Understanding gully blocking in deep peat.

Understanding Gully Blocking in Deep Peat

Moors for the Future Report No 4

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(Eds.)

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UNDERSTANDING GULLY BLOCKING IN DEEP PEAT

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. The report consists of three main studies of a successful collaboration of scientists and practitioners at the University of Manchester, the University of Leeds and the Moors for the Future Partnership.

The first study is an extensive evaluation of practical experience of gully blocking in deep peat, pioneered by the National Trust on three locations in the Peak District. Practical advice and guidance is collated regarding the choice of gully block location, material and technique. Financial implications of gully blocking, such as initial material and labour costs, and other variables such as practicality, logistics and maintenance and aesthetics are discussed to aid decision making processes. Furthermore, a monitoring programme was started with records for several key attributes regarding block and gully characteristics, and accurate GIS maps of the 1392 gully block locations on Within Clough, Kinder Scout and North Grain were produced.

The second study consists of three components, (i) an extensive photographic survey of natural re-vegetation on the Bleaklow and Kinder Scout plateaux, (ii) a quantitative field survey of natural re-vegetation at 149 gully sites in seven areas across Bleaklow and Kinder Scout and (iii) a survey of 357 existing artificial gully blocks installed on Within Clough and Kinder Scout by the National Trust. The photographic survey (i), provides important baseline material and has generated five hypotheses about mechanisms of natural re-vegetation which occurred in specific geomorphic contexts. The survey of natural re-vegetated gullies (ii) confirms that natural re-vegetation is widespread in the study area, and provided supporting evidence for mechanisms of colonisation of re-deposited peat surfaces, i.e. by *Eriophorum angustifolium* on peat flats and behind natural gully blockages and on bare peat floored gullies by *Eriophorum vaginatum*.

The survey also identified two classes of gully types in the study area: Type A that are steep and narrow and Type B that 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 survey of existing gully blocks (iii), demonstrated that 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 proving most efficient, plastic piling less efficient and the Hessian sack blocks working very poorly.

Combining the evidence from the naturally re-vegetated sites and analysis of the existing gully blocks by the first and second study, the following key recommendations are made for choosing suitable gully block sites and material, based on the current investigations:

- Objectives of gully blocking works need to suit chosen sites and gully types: Intact domes of peat on shallow gradients with minimal gullying may be targeted for raising water levels with water holding techniques such as plastic piling. On heavily degraded moorlands precedence should be placed on re-vegetation works and peat stabilisation, e.g. using wooden dams and potentially *Eriophorum* planting to reduce sediment loss from the system.
- Suitable Locations: Efforts should focus on blockage of sites with slopes less than 0.11 m/m (6º). Gully blocking should occur before extensive re-vegetation of interfluves.

- Blocking techniques:
  - Wooden fencing, plastic piling and stone walls are all effective gully blocking methods.
  - Block spacing should not exceed 4 m. Minimum spacings can be derived as a function of gully depth.
  - Target gully block height should be 45 cm. 25 cm should be a minimum height.
  - Maximum block widths should not exceed 4 m.
  - Planting of blocks with *Eriophorum angustifolium* once stable sedimentation has been achieved may aid peat stabilisation.
- Promotion of sediment deposition and re-vegetation in shallow Type B gullies, prevalent on Bleaklow plateau: experimental approaches, e.g. meander enhancing dams (groynes), should be developed based on the observation of natural processes.

As the current findings are a result of rapid survey of a poorly understood system and since the existing blocking programme was never planned as a controlled study, the recommendations outlined above are relatively conservative.

The third study in this report developed an approach that allows high resolution topographic data based on LiDAR to be coupled with hydrological predictions about hill slope saturation. A series of GIS data files were produced during the course of this research for an extensive coverage of 133 km^2 over the Bleaklow and Kinder Scout plateaux, containing vast numbers of gullies. The GIS data include (a) a merged digital terrain model (DTM), (b) merged aerial photographs, maps of (c) topographic index, (d) slope, (e) drainage network, (f) stream network and (g) flow accumulation map. Using (a-g) the location of existing gullies was identified and (f) mapped.

As a reliable indicator of how gullies may impact on hill slope saturation, the topographic index was derived. This spatially explicit parameter provides crucial information for management of areas that will be more sensitive to blocking compared to others. In a second step, predictions of potential change after gully blocking were estimated by simulation of a partial blocking (infilling) of gullies. By re-calculating flow accumulation and topographic index and subtraction of original maps, new maps of change in (h) topographic index and (i) flow accumulation were generated. These provide important information on consequences of blocking, which range from beneficial by enhancing hill slope saturation, to potentially detrimental by redirecting flow through new gully formation.

The novel GIS tool developed provides a valuable spatially explicit hydrologic decision tool for choosing strategic locations for gully blocking in deep peat. Combined with the advice on suitable locations and effective material for gully blocks, this report and associated maps provide the basis for efficient planning of gully restoration works in deep peat.

1 UNDERSTANDING GULLY BLOCKING IN DEEP PEAT

1.1. Introduction

1.1.1 Moorland erosion in the Peak District

The blanket peat moorlands of the South Pennines are some of the most severely eroded peatlands in the world. Over the past decades, the blanket bogs in the Peak District National Park have suffered a sharp decline in habitat quality with an overall reduction in plant cover and the exposure of the peat surface. This has lead to widespread erosion and the creation of a network of gullies. As primary causes of erosion, atmospheric pollution by acid rain (sulphuric acid deposition), past land management practices such as over-grazing by sheep, inappropriate burning management, drainage as well as trampling have all been identified. Furthermore, accidental fires have accelerated erosion processes, culminating in a loss of sediment and carbon as well as damage to local ecology, e.g. on ca 750ha of the centre of Bleaklow.

Currently, peat surfaces are frequently unsaturated during the summer, which presents unsuitable conditions for most blanket bog plant species and encourages decomposition of the upper soil layers. Furthermore the creation of gullies, further causes the peat to dry out, resulting in accelerated peat decomposition, leading to discolouration of local water sources and release of greenhouse gas emissions into the atmosphere. Substantial sediment transport in streams (up to 500 tons sediment/yr per km² in some catchments) and water discolouration are of increasing concerns for water companies. These processes lead to serious degradation and loss of moorlands.

1.1.2 Moors for the Future Partnership - Restoration Project

The **Moors for the Future** partnership is a major corporate partnership project, funded by Heritage Lottery, to provide an integrated sustainable approach to moorland conservation, understanding and enjoyment in the Peak District National Park. The partners include the Peak District National Park Authority (PDNPA), English Nature (EN), National Trust (NT), defra, Sheffield City Council, Severn Trent Water, United Utilities, Yorkshire Water, Country Land and Business Association, National Farmers Union and Peak Park Moorland Owners & Tenants Association.

The three principle objectives of the Moors for the Future project are as follows

- To restore and conserve moorland sites most damaged from access and recreational pressures.
- To enhance visitors' and local peoples' experience of moorland heritage and encourage greater care of it.
- To establish a learning centre to develop expertise about how to protect moorlands for the future and to meet the education and research needs of specific groups and the wider public.

With regards to the first objective, the project aims to restore 4 km^2 of the worst degraded areas of the Dark Peak areas which have been caused by accidental fires and which now present bare peat landscapes at risk from severe erosion. Restoration measures include active re-vegetation and gully blocking.

Active re-vegetation of bare peat is encouraged by application of lime and fertiliser, re-seeding areas with a grass nurse crop, and spreading of heather brash or geo-textiles to establish a vegetation cover and a peat stabilising root mat. The aim is to provide suitable habitat conditions for a natural re-colonisation by native blanket bog species, such as cotton grass and sphagnum species. To date, an area of 3 km² has been treated. These restoration techniques have been well researched and subject to field trials, and re-vegetation techniques have been applied in conjunction with stock removal to help the moorland recover.

Large-scale restoration works by blocking erosion channels are planned to aid the long-term recovery of the Bleaklow plateau to ‘active’ blanket bog. Restoration objectives for gully blocking are therefore to control and stop gully erosion, to reduce water (peak) discharge and to prevent sediment loss from peatlands. The ultimate goal is to raise the water table, promote re-vegetation and reduce water discolouration of streams. The National Trust has pioneered this restoration approach and has ample experience with different gully blocking techniques (see section 2). Since 1992, the National Trust High Peak Estate Team has put in place dams of heather, wool, wood, stone and plastic piling to block drainage gullies and the National Trust (co)fund several long-term research projects regarding effectiveness of gully blocks by consultants and universities.

However, to date little evidence-based research exists to aid informed decision-making on *where* and *how* to block gullies on the Bleaklow plateau by the Moors for the Future partnership. Therefore, this research collaboration has been set up to identify best locations for gully blocking and highlight tools for gully blocking best practise.

1.2 Research objectives

This research project 'Understanding Gully Blocking in Deep Peat' has been developed to assess and predict the hydrological and geomorphological impacts of existing and planned blocks in the Dark Peak. Specifically, this research will aid decision making on where and how to place gully blocks on Moors for the Future Partnership sites on Bleaklow in order to achieve the objectives listed above. It is hoped that results will also provide guidance for other future works in the Peak District and elsewhere in the UK.

This project consists of three sub-projects (Figure 1.1) by the Moors for the Future Partnership, in conjunction with the National Trust (project I), and the University of Manchester (project II) and University of Leeds (project III). In close collaboration these projects have arrived at specific advice for feasible and strategic gully block locations on Bleaklow, suggesting suitable techniques. Special focus was placed on developing a decision process for prioritising sites and materials to suit given objectives, and to lead to successful re-vegetation of sites and effective moorland erosion control.

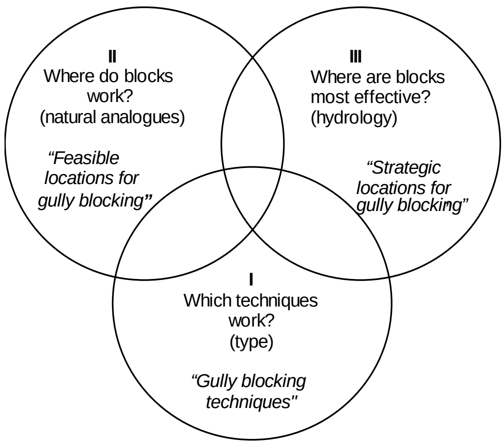

Figure 1.1 Diagram of the three projects

1.2.1 Project I – Gully Blocking Techniques

S.Trotter, S.Hodson, S.Lindop, S.Milner (National Trust), S.McHale (PDNPA), C.Worman, C.Flitcroft & A.Bonn (Moors for the Future Partnership)

This study formalised practical experience with gully blocks in the Peak District pioneered by the National Trust. Starting in 1992, the National Trust trialled different gully blocking techniques on several locations, including Within Clough, North Grain and Kinder Scout.

Within this study, the location of all gully blocks from these three sites were mapped and transferred into a GIS, and a monitoring programme was started. Furthermore, practical advice and guidance was collated regarding the financial implications of gully blocking, such as initial material and labour costs, and other variables such as practicality, maintenance and aesthetics influencing the decision making process.

1.2.2 Project II – Feasible Locations for Gully Blocking

M.Evans, T.Allott, S.Crowe & L.Liddaman (University of Manchester)

This study explored the feasibility of gully blocks by derivation of parameters from naturally re-vegetated gullies as well as technically blocked gullies subject to restoration works. Field surveys assessed the efficiency of existing gully blocks. General recommendations for gully blocking in deep peat have been developed, applicable also to other sites within the Peak District National Park. Furthermore, guidelines for monitoring Moors for the Future Partnership restoration works were established.

1.2.3 Project III – Strategic Locations for Gully Blocking

J.Holden, G.Hobson, B. Irvine, E.Maxfield, T.James & C.Brookes (University of Leeds)

This study investigated the spatial distribution of erosion patterns and gullies through the assessment of peat hydrology by use of LiDAR topographical data. The topographic index was derived to assess the likelihood of saturation, identification of catchment areas and analysis of connectivity between saturated areas. The developed maps aid decision making for the identification of strategic locations for gully blocks on Bleaklow to meet the above restoration objectives and to identify those gullies that are likely to erode the greatest. Maps of change were derived for effects of potential gully blocks for a scenario when gullies are partially infilled.

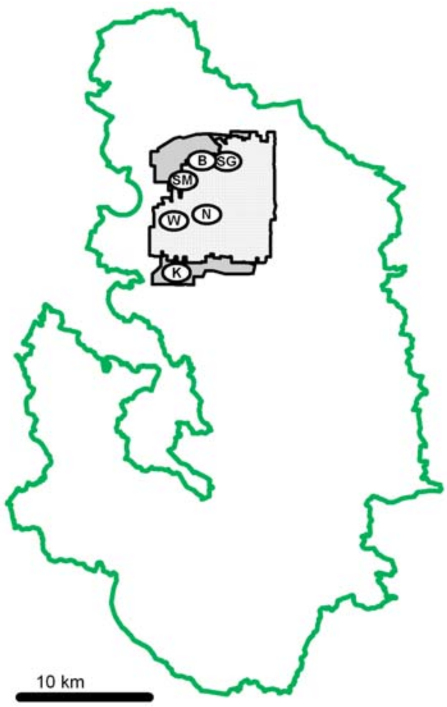

Figure 1.2 Location of the study sites in the Peak District (outline - National Park boundary; circles – natural and artificial block sites of project I and II: Kinder Scout (K), Within Clough (W), North Grain (N), Shelf Moor (SM), Bleaklow Meadows (B) and Swains Greaves (SG); polygon – coverage of 133km² LiDAR data and resulting GIS maps from project III, darker section - Moors for the Future Partnership data, lighter section - National Trust data). For detailed locations of block sites see Figure 3.14.

2 GULLY BLOCKING TECHNIQUES

Steve Trotter[1], Steve Hodson[1], Steve Lindop[1], Sophie Milner[1], Sheila McHale[2], Cass Worman[3], Catherine Flitcroft[3] & Aletta Bonn[3]

[1]National Trust, [2]Peak District National Park Authority, [3]Moors for the Future Partnership

2.1 Practical experience of gully blocking (National Trust)

This section describes the National Trust's experience of their gully blocking trials on the High Peak Estate, Peak District National Park. Funding was aided by a Nature for People Project (NFPP) by English Nature.

2.1.1 Decision making process

The key objectives of the National Trust's gully blocking are to protect intact peat domes, to promote re-vegetation, to reduce sediment loss from the system, to raise the water table, and to re-establish original habitats with active peat growth.

In order to decide on most effective works the following hierarchical decision making process was employed to identify priority areas, to choose suitable gullies within these and to choose the most effective material.

2.1.1.1 Choice of suitable areas for gully blocking works

A strategic review of the High Peak Estate was carried out by Haycock Associates (Haycock 2003) using LiDAR data (remote sensing high resolution topographic data) to identify key areas of intact peat domes based on geomorphological analyses. Gully networks and low slopes (<5°) were delineated and hydrological parameters were derived. Areas of blanket peat were detected and prioritised in the following way

- **Priority 1 areas** – large, intact domes of peat on shallow gradients, e.g. Within Clough, North Grain
- **Priority 2 areas** – blanket peat desiccated by gullies, e.g. Bleaklow Head (not described in this report)
- **Priority 3 areas** – heavily eroded areas, e.g. Kinder Scout

To assess the viability of gully blocking on deep peat the National Trust chose representative sites from each of the three priority areas. Kinder Scout, as priority area 3, was the first area to be addressed with new gully blocking experiments commencing March 2003, to see whether it was practical to block the deep gullies. Work on priority areas 1 and 2 followed with the aim to maintain the current 'good' health of these areas and to protect them from further desiccation in the future. Priority 1 areas with incipient gullies on the outskirts of the peat dome are targeted in the first instance to maintain the water table level. In this study we chose to focus on the extreme sites of priority 1 and 3 areas.

2.1.1.2 Choice of suitable gullies to block

Field studies were carried out before works commenced within the chosen priority areas to determine suitable gullies. The following parameters served as decision criteria

- **Peat depth** - Where possible deep peat gullies were blocked that had not yet eroded to the mineral rock, as mineral soil is difficult to penetrate with the materials currently used to build dams, except for stone.
- **Width of gullies** - Small gullies are easier (and cheaper) to block and were therefore targeted for initial blocking. The widest gully measured 3m in width towards the base of the main channel on Within Clough. Blocking the smaller, tributary gullies is seen as a 'first step' in slowing water supply to the main watercourse and helping to reduce the amount of sediment washed out of the system. With experience a "top down" approach has been adopted, i.e. if materials or other resources are limited, or if the lower reaches of the gully are too deep or wide to block, then the top of the gully (where it is eating up into the peat) is the highest priority for the installation of dams to prevent nick point migration.
- **Slope of gullies** - Steeply inclined gullies require more dams (see 1.1.5) and this was taken into consideration during the planning stages. The number of dams needed per gully was ascertained by walking the site. Early investigations have been confirmed that it is not very successful to block slopes steeper than 5-6° (see recommendation for targeting slopes <6°, sections 3.5.3.6, 3.5.4.3).

2.1.1.3 Choice of materials

Choice of dam material was based on the morphology of the chosen gully, mainly peat depth. In total five different materials were employed by the National Trust; stone, wood, wool and plastic piling and brash (on Bleaklow Head only). Below we also list coir and heather bales as suitable options.

- **Stone** – Stone walls work best on gullies eroded to mineral soil. It does not need to be 'driven into' the gully bottom and sides. However, this is an expensive option if materials cannot be sourced on site and have to be flown onto site (Figure App.1, Appendix III). Stone blocks relatively high maintenance.
- **Wood** – Wooden dams are discussed in detail in section 2.2.2.1 'Kinder Scout' (Figure App.2). They are very effective in sediment trapping but experience problems of undercutting. The National Trust is considering the use of recently felled trees from a local valley (Alport valley) as a gully blocking possibility.
- **Wool** - Hessian sacks of wool are suitable for mineral gullies as long as supporting stakes can be driven into the gully bottom (Figures App.3, App.4). Bags can also be forced into smaller gullies, requiring no supports, (Figure App.5). The source of natural materials also has to be carefully considered. Wool must be free of ticks to prevent their spread to local livestock and collected well after any dipping to prevent chemicals being released into water courses. Wool is difficult and unpleasant to work with. Wool inserted into a chicken wire mesh is another method being trialled by the National Trust (Figure App.6). However, this method is now abandoned due to Animal Health regulations.
- **Plastic piling** - This method is only suitable where the peat is deep enough to drive the dam into the gully sides and bottom. Plastic was also used to block where drainage tubes through the peat were thought to exist. Plastic dams have to be sited correctly into the gully sides and at the correct height to trap water (see 2.1.3.). A low point in the middle of each plastic

dam was created to allow water to overflow the middle of the dam preventing side-cutting (in places where this does not exist extra pieces of plastic have been installed where sides have been washed through). Lugs in the centre of dams have been installed to provide extra strength to the dams. The last dam downstream should be installed into mineral soil to prevent continual dam failure up-stream as dams are undercut. The National Trust is currently exploring the feasibility of splash plates at the bottom of dams to prevent scour to mineral soils to prevent undercutting. At present there is no guidance on the success of splash plates. As a guide, plastic dams are the tallest of all blocks, often installed to above knee height (see Tab 3.13).

- **Heather brash** – Heather brash as a local material can be used to block gullies when stabilised with wooden stakes. The National Trust employed this material in blocks at Bleaklow Head.
- **Heather bales** – Similar to brash, heather bales can be used to block gullies when stabilised with wooden stakes. Currently, English Nature is trialling this method on Saddleworth in the North Peak. It is important that the heather is free from pesticides.
- **Coir logs** – Moors for the Future Partnership are considering using coir logs (equivalent to sand bags used for flood prevention) in a similar way to wool bags. These can be used singularly or piled up and supported with stakes.

2.1.1.4 Landscape aesthetics

Different materials have differing levels of aesthetic effects on the landscape, much of which is of personal opinion. Wool, wood and stone are generally considered to be of a lower impact than plastic dams. The National Trust chose to use black plastic piling to reduce the visual impact on the landscape, although this doubled the cost per dam and was unfortunately not available in recycled materials at the time. However, the company who supply the plastic piling propose to change their manufacturing technique so that in future in excess of 98% of the dark brown piling (as close as possible in colour to peat) will be recycled. The dark brown, virgin material will be applied as a coating to the recycled core.

Depending on material, spacing of gully blocks may differ. Aesthetics (as well as costs) of a densely blocked gully system should be considered carefully. However, most of the dams are invisible unless people actually walk to them, e.g. the Within Clough dams close to the heavily frequented Pennine Way.

2.1.2 Logistics - Material delivery

Due to the remote locations of blocking sites, materials are delivered by helicopter. As a result of the nature of the terrain, moving materials by hand even short distances is hard work and time consuming – therefore helicopter drops were organised to reduce the distance materials had to be moved around on site. A large number of small, light drops were prepared at the lift site, enabling the helicopter to spread the materials evenly around the site as required. A typical lift would consist of 80 pieces of piling per lift (20 pieces of piling per bundle, 4 bundles per lift; Piling weighs 3kg per metre). Drops were made in the centre of each gully length so material could be spread up and down slope evenly. The National Trust’s experience show material lifts can be completed between a half and one full day. Lift costs could be reduced by using a larger helicopter which can carry a greater payload but the knock-on effects of then having to move materials around on site makes this a false economy. It has been suggested that twin helicopter lifting could be utilised to speed the delivery of materials without increasing costs excessively. Alternatively, material drops could be made in small short bursts to keep site events easy to manage and allow for changes in techniques/ material requirements etc during installation.

2.1.3 Construction Methodology

2.1.3.1 Technique

During installation, the National Trust Estate team tried to follow the following procedures

- **Dam spacing -** Dams were installed at intervals so that the top of the lower dam levels with the bottom of the upstream dam (Figure App.7). This should allow for a continuous water surface to be created between the dams. The rationale is, that any water flowing over the top of dams flows into water held by the dam further downstream as opposed to bare peat or mineral (Figures 2.1, App.8). This helps to prevent undercutting of dams (Figure 2.2), stops erosion of any trapped sediment and reduces disturbance to any established vegetation behind the dam. Water flow over the middle of plastic and wooden dams (as opposed to gully sides which would cause side cutting of peat) is encouraged by creating a small indent in the middle of the material. However caution is required, as this may also lead to increased water pressure and velocity at high flow due to diminished flow diameter (McGrath, pers. comm.).

  Initially, spirit levels and poles etc. were used to try and measure exact dam spacing but this proved to be time consuming and no more effective than spacing dams by eye.
- **Sequence -** Gullies are blocked in a 'top-down' approach. Installation begins at the head (highest point) of the chosen gully and dams are installed down the entire length of the gully until it reaches the main tributary into which the gully drains.

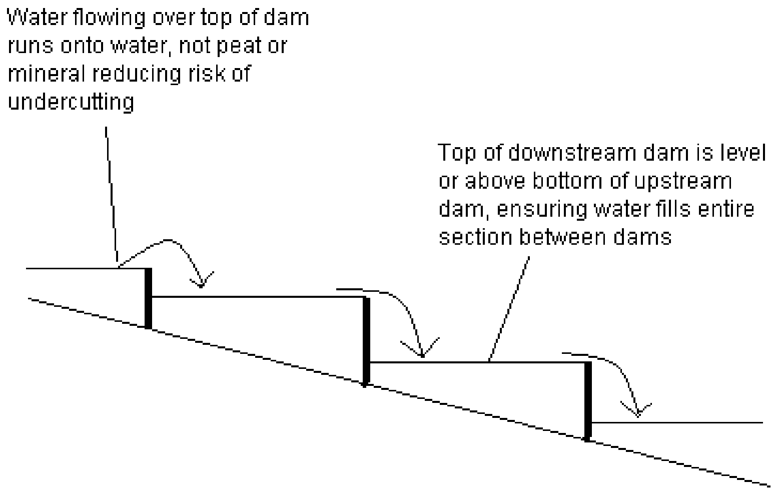

Figure 2.1 'Top to toe' approach of dam installation

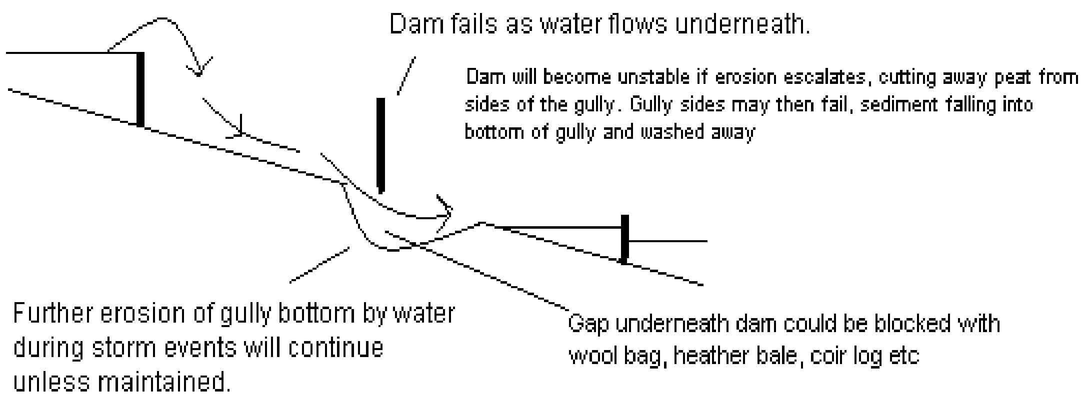

Figure 2.2 Undercutting of dam where gully bottom is not protected & water scouring under dam

This methodology results in denser spacing of dams on steep slopes, and sparser spacing of dams on gentle slopes. For this reason it is difficult to make method statements such as “install dams at 5m intervals”. The method of lining up dam top and bottoms should be employed wherever possible. However, a site with a relatively homogenous slope will produce dams at equal spacing, e.g. Within Clough dams are spaced 3 to 8 m apart, the average being around 4m. A more heterogenous site with a wider range of slope angles such as Kinder Scout has more varied dam spacing. Here, in steep gullies dams are as close as 2.5m apart, average spacing being between 3 and 4m (see also Table 3.9, section 3.4.3.2).

2.1.3.2 Difference between materials

The above described technique is only successful when using impermeable materials which trap water. Scouring and / or undercutting may occur when dam material is porous or when dams have totally filled with sediment and can therefore no longer hold water. This latter situation helps explain why wooden dams appear to be more prone to failure. Wooden dams silt up very quickly, with no protection downstream over the weaker, newly accumulated sediment. The use of experimental splash plates could be considered with materials which do not trap water as well as plastic (e.g. wood, wool). Other preventative methods could be employed such as installing Hessian bags or coir logs at the bottom of wooden dams at the same time the dam is built, to prevent undercutting occuring in the first instance.

Taller materials (e.g. plastic) can be spaced further apart than shorter materials as they can hold a larger volume of water. However, their long term ability to hold large pools of water should be considered. From an ecological point of view, pools may be desirable, but a series of smaller sized pools which hold less weight of water is to be preferred over a large pool that is more likely to fail catastrophically. For very shallow slopes, this implies a blocking at shorter distances than necessary when following the 'top to toe' approach.

2.1.3.3 Health and safety

Creating large pools of water over wet, boggy sediment may create a potential increase I risk for both people and stock I not managed carefully. For this reason, it has been suggested that gully blocking works at popular walking areas and dense sheep grazing should preferably use semi-permeable materials, such as wood or stone that lead relatively quickly to consolidated sediments (see Appendix III, Fig. App.1).

The National Trust Estate Team has also addressed the health and safety of staff installing dams after assessing the difficult nature of the work. Hard-arm vibration injuries are possible and therefore staff is only allowed to work on gully blocking sites 3 days per week. Short, frequent breaks are scheduled throughout the day to help prevent exhaustion and strain injuries. The National Trust Estate Team use a flat-pack garden shed they airlift to each site and take down once work is completed to act as a shelter or on-site storage. Work is scheduled for summer months with back-up jobs as alternatives if the weather or forecast are bad on any particular day.

Table 2.1 Summary of dam material attributes

Dam Type	Peat type	Cost	Method	Primary function(s)	Installation Issues	Landscape/ visual impact	Current location
Plastic piling	Medium to deep peat (not mineral soil)	£3 per metre white plastic (~£30-40 per dam) £6 per metre brown plastic (£50-£80 per dam)	Drive piling into peat using rubber mallet	Hold water, creation of large, often deep pools	Ensure plastic driven into sides of gully, dam lower than surrounding veg. height (not always possible, when dam hits mineral soil)	High-low, depending on location Less impact in black/brown colouring Persistent	Within Clough, Kinder Scout, North Grain, Bleaklow Head
Wood	Medium to deep peat, mineral soil	~£2 per metre (~£20 per dam)	Dams 5-6 planks high, with post support	Trap sediment, hold water (from deep pools to small puddles once filled with sediment)	Ensure prevention of under and side-cutting on mineral	Low	Kinder Scout, Bleaklow Head
Wool **no further use permitted**	Any, as long as supporting stakes can be driven into gully bottom	~20p per sack (~£2 per dam dependent on wool market) (n.b. possible arrangements with tenants)	Wool rolled and placed between stakes or rabbit netting Fleeces piled up and covered with bare peat	Trap sediment, creation of small pools and puddles	Can be washed out of place during high storm events	Low	Within Clough no further use permitted
Stone	Mineral soils / very shallow peat	~£60 per tonne (~£40 per dam) Ideally should be locally sourced	Build stone walls	Trap sediment	Can be washed away during storm events, prone to side-cutting. High repair maintenance	Low	Within Clough, Kinder Scout, Bleaklow Head
Hessian Bags/ coir logs	Any, as long as supporting stakes can be driven into gully bottom	£10 per meter (~£20-£60 per dam)	Bags filled, then stacked up with post support	Trap sediment, possible creation of small pools	Not trialled to date	Low	
Heather Bales	Any, as long as supporting stakes can be driven into gully bottom, high sediment supply	£2-6 per round bale (£6-30 per dam)	Bales (tied with twine) stacked up with post support	Trap sediment, possible creation of small pools	Ensure prevention of under & side cutting. Ensure bales extend to width of gully	Low	Saddleworth Moor
Heather Brash	Any, as long as supporting stakes can be driven into gully bottom	~£70 per tonne (~£20 per dam)	Stakes driven in and brash weaved	Trap sediment, possible creation of small pools	Ensure prevention of under & side cutting.	Low	Bleaklow Head

2.1.4 Costs

Costs for gully blocks depend on the morphology of gullies (size, slope) and choice of materials. For example, steeper gullies will require more dams (see 2.1.3.1.) and therefore they will be more expensive to block.

- **Material** – Table 2.1 lists approximate costs for the National Trust gully block materials.
- **Transport –** Helicopter drops need to be calculated at £450/h (ca £6000/d). Weight does not present a problem as air lifts should consist of many small drops (see 2.1.2.).
- **Labour** – Dams can be built within 45min–1h per dam by two people, with little difference between materials employed. Therefore, 6-8 dams can be completed within 1 day by 2 people (£15/h or £105/d per person).
  For the National Trust the labour costs were internal as the Estate Team carried out works. At Within Clough a total 820 dams were built in 137 person days. As the site is close to the road, no significant time was spent travelling to site.
  Walking time to the sites may however be substantial. For the Moors for the Future Partnership sites on Bleaklow a 2-2.5h walking time/day should be calculated.

In total the works for the four National Trust sites at Within Clough, North Grain, Bleaklow Head and Kinder Scout calculate to £160,000 with significant funding through a Nature for People Project (NFPP) by English Nature.

2.1.5 Long-term effectiveness of gully blocks

Gully blocks need to withstand a range of weather conditions, e.g. to resist heavy storm events and to continue holding sediment in high flow conditions. Their effectiveness during dry summers also needs to be considered in helping to maintain water table levels. Current PhD studies address these and other research questions (S. Crowe, Manchester University, H. O'Brien, Nottingham Trent University, see section 7). As the National Trust sites have only recently been established, the long-term success of gully blocking remains to be seen. Continual monitoring will be required to establish whether these aims have been met.

First results indicate that all materials trap sediment, with plastic piling taking the longest to fill, probably due to its water holding capacity. There are several hypotheses as to why plastic piling appears to trap sediment more slowly than other dams. Plastic dams are generally taller and therefore appear to hold more water and less sediment. The large amount of water trapped behind the dam creates eddies which scour out any trapped sediment. Also, it is difficult to measure the exact sediment deposition behind dams as the sediment is less consolidated and longer kept in suspension (see also section 3.5.3 and Table 3.13.).

A risk of gully blocking is the opening of new soil pipes and a potential risk of peat slides due to peat re-saturation on hill slopes. The latter depends on the magnitude of works and needs to be considered carefully. At the present scale of the National Trust works to date, this is not seen as a major risk. However, the risk of soil pipe development is a problem. Therefore the probability of redirection of flow paths is incorporated in the model predictions presented in section 4.4.2. After evaluation of model results with National Trust data, this model may help avoid targeting sites prone to development of soil pipes.

The desired effects of dams should also be considered during the planning stages. Decisions need to be made on whether water or sediment trapping is of greatest importance.

2.1.6 Maintenance

Table 2.2 lists maintenance problems that occurred and strategies for their repair.

Table 2.2 Gully block maintenance problems and their repair

Type	Description	Solution	Requirements	Time	Costs	Frequency of maintenance required
Side-cutting of plastic dams	Dams no longer retain water, wash occurring around sides of gully, eroding gully sides away which worsens if problem not addressed	Extend plastic piling further into gully sides	Spare piece of shallow piling, normal installation equipment and expertise	½ h or less	£6/m piling	Once only
Split plastic dams	Dams no longer hold water to their full height. If splits enlarge, dam could break and shatter causing a health and safety risk.	Uncertain how to mend this damage. When broken dams still help retain water in the gully system by easing pressure of water on downstream dams and slowing water flow (e.g. where splits are small, water trickles slowly through the dam)				
Undercutting of wooden dams	Loss of sediment and failure of dams to hold water	Extend wooden slats downwards into mineral soil when possible, though may be difficult to achieve; block gap with coir log, wool bag etc.	Wooden slats or wool bag or coir log, stakes, normal installation equipment and expertise	ca ½ h	£5 - £20	Once only or after every large storm event (possibly 2-8 times per year)
Infilling of wooden dams	Dams no longer hold water or trap sediment	Extend wooden slats upwards, install new dams in between in filled dams, re-vegetation of accumulated sediment to stabilise dam.	Wooden slats, stakes, normal installation equipment and expertise, *Eriophorum* seedlings.	ca ½ h	£5 - £60	Possibly twice yearly, requires monitoring to assess how quickly dams infill.
Washing away/ dislodgement of wool, Hessian or heather brash bags, heather bales	Dams no longer serve any constructive purpose (Figure App.9)	Re-stake bag in place; create larger dam using extra materials; entirely replace dam with stronger material more suited to gully conditions.	Extra original materials, stakes, new materials, normal installation equipment and expertise	10min - 1h	£2 - £60	After large storm events (possibly 2-8 times per year)
Collapse of stone wall dam	Water washes around sides creating erosion problems both on gully sides and washing away any accumulated sediment. Sediment is no longer trapped or held by dam.	Re-build wall with original materials, rebuild wall with extra supporting stones or other materials for added support (e.g. coir logs, wool bags, supporting stakes), provide support with re-vegetation works.	None, if using original materials (but will probably require continual maintenance until gully is stable and re-vegetating), stone, supporting stakes, wool bags/ coir logs, stakes, *Eriophorum* seedlings.	10min - 1h	£0 - £20	After large storm events (possibly 2-8 times per year)

2.2 Case Studies - Within Clough, North Grain & Kinder Scout

2.2.1 Within Clough

2.2.1.1 Site description

The Within Clough site comprises an intact peat dome and is therefore a National Trust priority 1 area (see 2.1.1.1). This gently sloping site has a network of small gullies running into the large, main gully of Within Clough (see Figure 2.3). Despite these gullies, the site is largely uneroded, supporting a dwarf shrub mosaic vegetation cover dominated by bilberry (*Vaccinium myrtilus*), crowberry (*Empetrum nigrum*), heather (*Calluna vulgaris)* and cotton grass (*Eriophorum angustifolium* and *Eriophorum vaginatum,* the latter in wetter areas). Cloudberry (*Rubus chamaemorus*) is also widespread in this area and was flowering during spring/summer of 2004.

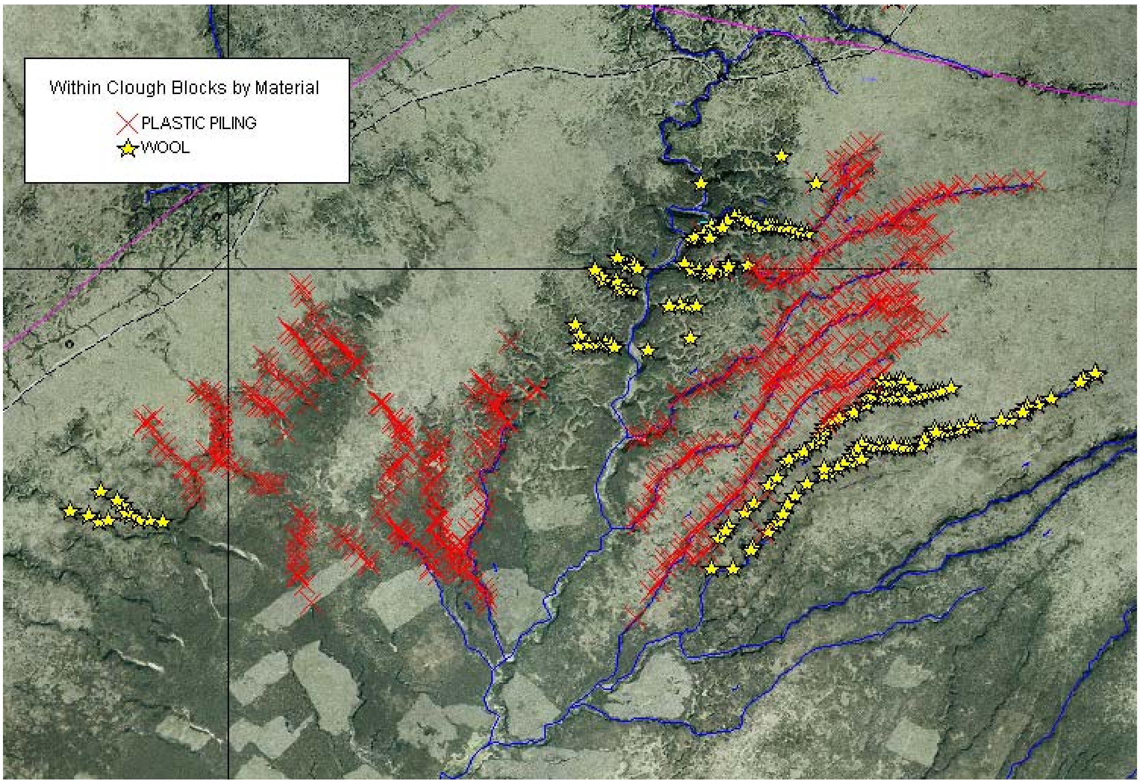

Figure 2.3 Dams on Within Clough (imagery by UKPerspective)

2.2.1.2 Dams on Within Clough

- **Plastic Piling -** Most dams on Within Clough are positioned in shallow, narrow gullies and are blocked using black plastic piling (Figure 2.4). The majority of plastic dams do hold water, except where the level has reached the top of the piling, where the dam has split, broken or where side cutting around the dam has taken place. The water level is often so high it is impossible to see if the dam is trapping sediment (unlike wooden dams on Kinder Scout).

Figure 2.4 Plastic dam on Within Clough. Gully sides range from well established dwarf shrub, *Eriophorum* patches and bare peat.

In some areas natural re-vegetation of blocked dams is taking place, mostly by *Eriophorum angustifolium,* especially where the water is shallower or absent. As there is a high colonisation potential from surrounding banks, it is envisaged that *Eriophorum* swards or possibly Sphagnum beds as well as rhizoms of bilberries will colonise the gully sides, as pictured in Figure 2.5 (natural re-vegetation, see also section 3.3). The primary effect of plastic dams on this site is to hold water. From an ecological point of view, the ponds may enrich habitat and species diversity, and in summer 2005 dragonflies and water striders among other invertebrates were observed at the pools. A proper survey would need to establish actual colonisation of invertebrates.

The amount of sediment accumulation will not be known until the monitoring surveys carried out during Manchester University Project II is repeated (but see Tab 3.13). The difficulties of measuring this attribute in the field using simple probing techniques may make results difficult to interpret and repeat.

Figure 2.5 *Eriophorum angustifolium* behind plastic dam at top of gully. This dam was installed in a vegetated area possibly to protect the already established vegetation or to prevent upstream erosion.

Figure 2.6 Wool bags anchored with wooden stakes. The majority of these dams are positioned in downstream locations where gullies are deep and wide bottomed.

- **Wool bags -** In larger, deeper gullies, wool bags have been used in attempts to stem the flow of water (Figure 2.6). The bare, steep sides of the gullies indicate a stream flow coupled with high erosion potential of the water. Small bags of wool appear not to have much effect in stemming this flow. Small puddles (Figure 2.6) have developed in some areas, but the dams do not hold a large amount of sediment and they are often scoured (see 3.4.6). Small dams would probably not prevent the wash of sediment in a heavy rainfall event and therefore do not support much re-vegetation of the gully sides (the steepness of gully sides will also hinder natural re-vegetation).

- Similar to wool bags, **heather brash** or **heather bales** can be employed. The brash has been employed by the National Trust on Bleaklow Head, the bales are currently used by English Nature on Saddleworth Moor. Both brash and bales are recommended as a 'progressive/phased' method, returning to site to add more intermediate dams in between existing ones and building up their height as they fill with sediment. They are best suited to areas with a high sediment supply (i.e. large % cover of bare peat, see 3.5.3.8). As water trickles through the brash/bales, the heather traps the sediment, infilling the gully. Like the wool bags, they are probably not effective for water trapping objectives or in downstream areas of increased stream flow, such as in Within Clough.

2.2.2 North Grain

2.2.2.1 Site description

North Grain is a National Trust priority 1 area (Figure 2.7). Gully blocks were installed during March – July 2003 to protect the peat dome.

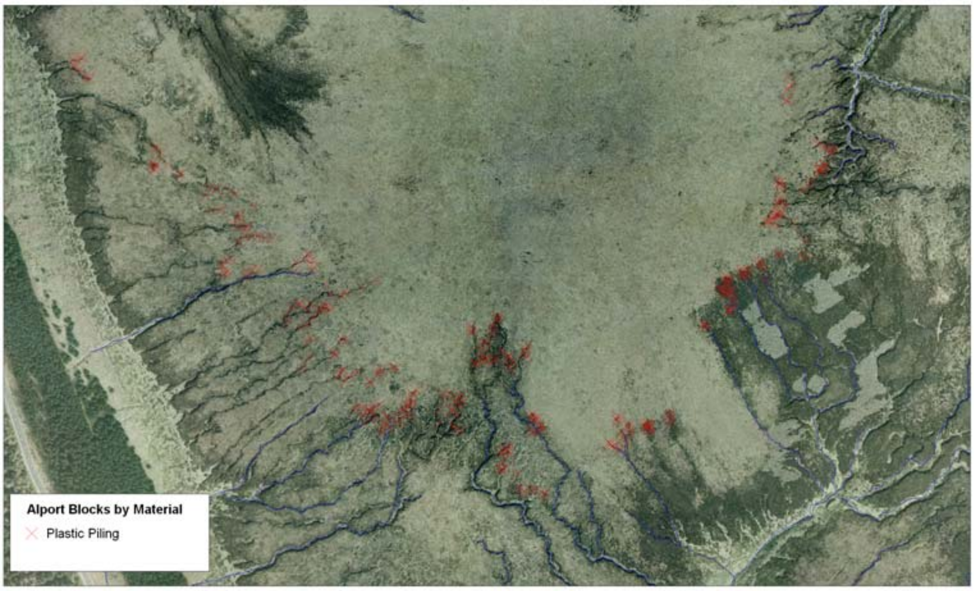

Figure 2.7 Aerial photograph of the North Grain area showing artificial dams installed by the National Trust Estate Team, March-July 2003 (imagery by UKPerspective)

2.2.2.2 Dams on North Grain

- **Plastic Piling -** Most dams on North Grain are positioned in shallow, narrow gullies and are blocked using black plastic piling (Figure 2.8). The strategy was to block the very tops of the gullies where they are eating into the peat as the gradient steepens on this site, making the lower reaches of the gullies less suitable for blocking. In general, the areas blocked were more vegetated than the other two sites (Kinder Scout and Within Clough).

Figure 2.8 Plastic dam on North Grain. Gully sides are generally well vegetated with established dwarf shrub and *Eriophorum* patches, but locally bare peat is present. The banks provide a good source for plant colonisation by e.g. rhizomes.

2.2.3 Kinder Scout

2.2.3.1 Site description

This heavily eroded area with vast expanses of bare peat (Figure 2.9) is a National Trust priority 3 area. Gully blocks were installed during March – July 2003.

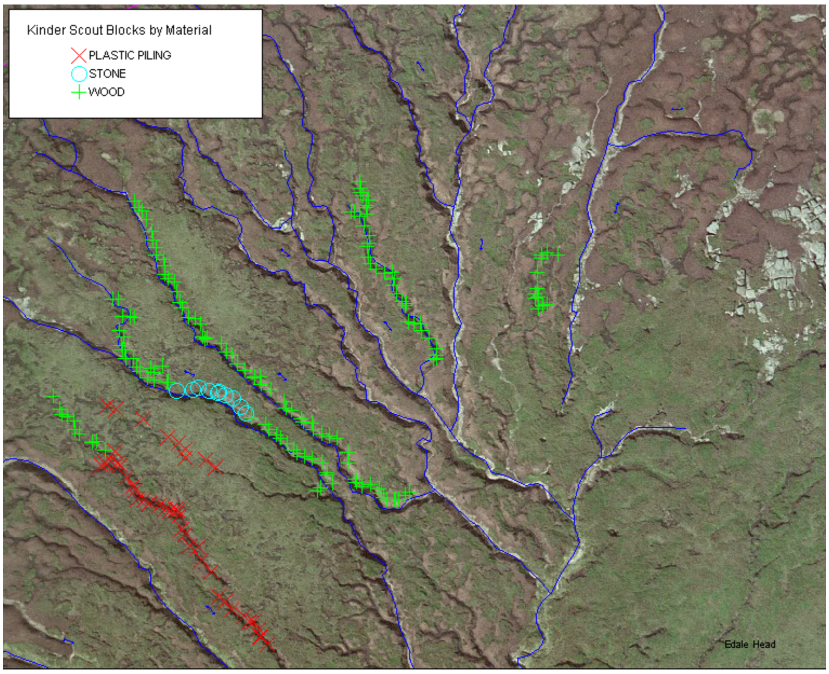

Figure 2.9 Aerial photograph of the Kinder Low area showing artificial dams installed by the National Trust Estate Team, March-July 2003 (imagery by UKPerspective)

2.2.3.2 Dams on Kinder Scout

As Kinder Scout was the first National Trust site, three types of materials have been trialled:

- **Wooden dams –** Wooden dams on Kinder Scout hold sediment and water (Figures 2.10, 2.11) very well. Sediment behind many dams is very consolidated with small pools of water and in many cases sediment has accumulated up to the top of the dam (Figure 2.11). *Eriophorum angustifolium* is colonising well in some gullies where there are pools of water.

The firm sediment build up may be benefited with *Eriophorum* planting to further stabilise the peat and initialise natural re-vegetation of the gullies.

Figure 2.10 (left) Wooden piling on Kinder Scout is strong enough to hold water as well as plastic piling

Figure 2.11 (right) Sediment build up behind a wooden gully block on Kinder Scout

The success of these wooden dams could be further improved by installing more wooden slats to extend the height of existing dams, encouraging further sediment and water build up. Similarly, plastic piling could be placed between wooden gully blocks to encourage further infilling of sediment and to retain some water. Where algae have established on wooden dams, their aesthetic effect on the landscape is minimal.

Sediment is building up in front of some wooden dams but in some cases, water is flowing over the consolidated sediment and over the top of the wooden piling and creating large ‘pools’ of erosion in front of the dams (Figure 2.12). At some locations this has caused undercutting of the wooden dam at its base and water is now undermining the sediment build up behind. Where dams are built on or near to mineral sub-soil, the wooden piling has not been installed deep enough and peat and any sediment caught behind the dam has been washed or blown out (Figure 2.13). Gaps could easily be blocked using coir logs or wool bales etc (see Figure 2.2). In 2005, failing dams have now been repaired or replaced. Blocking gaps has generally not been successful.

Water in some dams is also cutting peat away from the sides of the gully and in some cases, the gully sides are now in danger of collapsing, causing the dam to fail and any sediment built up to be lost and perhaps further erosion of the gully itself (Figure App.12).

Figure 2.12 Water erosion in front of a wooden dam. Sediment is still held behind dam, as scouring has not yet reached bottom of dam.

Figure 2.13 Undercutting by water of a wooden gully block. Any sediment trapped behind dam has been washed away underneath dam.

On the area of Kinder Scout that has been blocked, it seems likely, that sediment is probably drained from a large area of bare peat further upslope. It is thought that to reduce the ‘stress’ of a large sediment and water supply on dams further downstream (causing blow outs, side cutting, scouring and other dam failures), steps should be taken upslope to reduce water and sediment flowing down the blocked gullies. Ways of diverting water away from gullies would prevent gully erosion worsening, making dams more effective and less susceptible to damage. The National Trust has addressed this problem by blocking gullies further upstream (from the head of each gully already blocked). Currently, they are looking into methods of stabilising silted dams, such as *Eriophorum* planting.

- **Plastic Piling -** The piling has not been placed in smaller channels to hold water and help raise the water table. As this was the first experimental site for trialling plastic piling, several recommendations can be given. Care should be taken to ensure dams are installed at an appropriate height and evenly to reduce the visual impact of gully blocking works, however it is not always possible to install dams below the vegetation level if the depth of the peat is insufficient. Once a mineral base has been hit it is not possible to drive the piling any further. If peat depths are not sufficient, alternative materials should be used. Plastic is holding some water in this area but no re-vegetation is occurring to date. This could possibly be due to the steep gully sides and the low colonisation potential from surrounding bare peat flats. Given the short-time span since blocking to date, long-term monitoring will better inform the re-vegetation process. To initiate and accelerate natural re-vegetation, the National Trust considers *Eriophorum* planting as suggested in section 3.5.4.6, once the deposited peat is more consolidated.

In some areas on Kinder Scout, poor seals in some plastic dams causes them to leak. Water is not being held by these dams and is flowing through them, so that the gully is not benefiting from gully blocking work with regards to raising water table or trapping sediment. Plastic piling used on Within Clough has proven to be successful in trapping water, so this method can be very effective. However, the Kinder Scout dams are difficult to compare to the Within Clough dams due to the very different nature of the topography of the two sites. The shallow sloping, well-vegetated nature of Within Clough, allows using plastic dams to assist in raising the water table as a feasible objective. However, the steep sloping terrain with deep, wide and bare gully systems on the Kinder Plateau seems too degraded to raise the water table with plastic dams without first tackling the continual erosion of bare peat. First steps here should be to stabilise the peat with more semi-permeable gully blocks and possibly with re-vegetation work helping to reduce peat loss from the system. Gully blocking work here should therefore concentrate on trapping sediment and reducing its movement through gully systems. Field studies on the National Trust's work on Kinder Scout show wooden and stone dams to be the most successful sediment trapping method (see also 3.4.7).

- **Stone** – Stone walls appear to work well on wider gullies eroded to mineral soil. They appear to be effective at trapping sediment but ineffective at holding water as small gaps allow the water to filtrate through the blocks. To date little re-vegetation of the gully sides had occurred, possibly due to wide gullies and little connection to vegetated areas as well as yet little time to colonise. In some areas, further collapse of the gully sides had occurred and a build of peat on the gully floor was evident but little material had passed through the gully block. Some collapse of the stone blocks was also evident and care needs to be taken to ensure dams are installed to withstand possible storm events. The stone blocks had little visual impact and were very effective at trapping sediment. Larger stones may be more effective and in narrower gullies but expense and feasibility should be considered.

2.3 Conclusions

Objectives of gully blocking works should be carefully considered to suit the chosen site. Priority 1 areas with minimal gullying targeted for raising water levels seem to suit water holding techniques such as plastic piling, while heavily degraded priority 3 areas appear to require re-vegetation work and peat stabilisation. Here, semi-permeable barriers are optimal to help reduce sediment loss from the system. The National Trust's preferred materials are stone and/or timber. Once peat has accumulated and consolidated, *Eriophorum* planting may complement the peat stabilisation and initiate re-vegetation. No planting has yet been tested to this respect, but *Eriophorum* seems to be among the first natural colonisers for re-vegetation (see also section 3.2.3.2). Table 2.1 outlines the suitability and implications of all materials tested by the National Trust Estate team.

The sheer size and remoteness of sites requires careful planning and thorough site visits should be made prior to ordering materials and helicopter lifts to ensure the materials are distributed correctly. Time can be saved by organising helicopter drops at the lift site with clear directions as to which dams should be sited in which locations.

Considerations of installation of dams must also be considered. If using contractors, detailed methodology may have to be provided, along with some training and supervision by experienced persons. Working conditions must also be considered. Detailed risk assessments with a suitable work schedule are necessary.

Finally, it is important that ongoing maintenance of gully blocking works are programmed from the onset of the works. Continuous maintenance is required (see Table 2.2) and work needs to be scheduled with regards to staff/contractors, time commitment and occurrence of any extra material costs.

3 FEASIBLE LOCATIONS FOR GULLY BLOCKING IN DEEP PEAT

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3.1 Introduction

3.1.1 Background to the Project

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 for the most 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 2005) suggests a series of key parameters that 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 that 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 over-steepening 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 artificial 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 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 (as in section 2). 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 re-vegetated 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 re-vegetation 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 re-vegetation. 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 field walking 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/Kinder Scout 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 stored in digital format at the Moors for the Future office. The file 'Photo catalogue.xls' lists and categorises the available photography. The photographs comprise two main datasets. The first is photography derived from field walking 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, 3.4). 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 field walking 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.

- **Peat Flats -** Where there are extensive areas of low angled bare peat, 'peat flats', such as found on fire scars, re-vegetation 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.

- **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).

- **Peat deposition and re-vegetation 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 insides 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 Kinder Scout

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* re-vegetation**

   One interesting pattern apparent in several gullies is a hybrid form of re-vegetation 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 re-vegetation 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 Re-vegetation 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 plateaux. The aim is to evaluate both the patterns of re-vegetation 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 3.14). 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	Unit
Gully width (from top of gully walls)	m
Gully floor width	m
Gully depth	m
Gully floor slope (local slope)	$m\ m^{-1}$
Depth of redeposited sediment	cm
Block width (where relevant)	m
Block height (where relevant)	m
Block depth (where relevant)	m
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

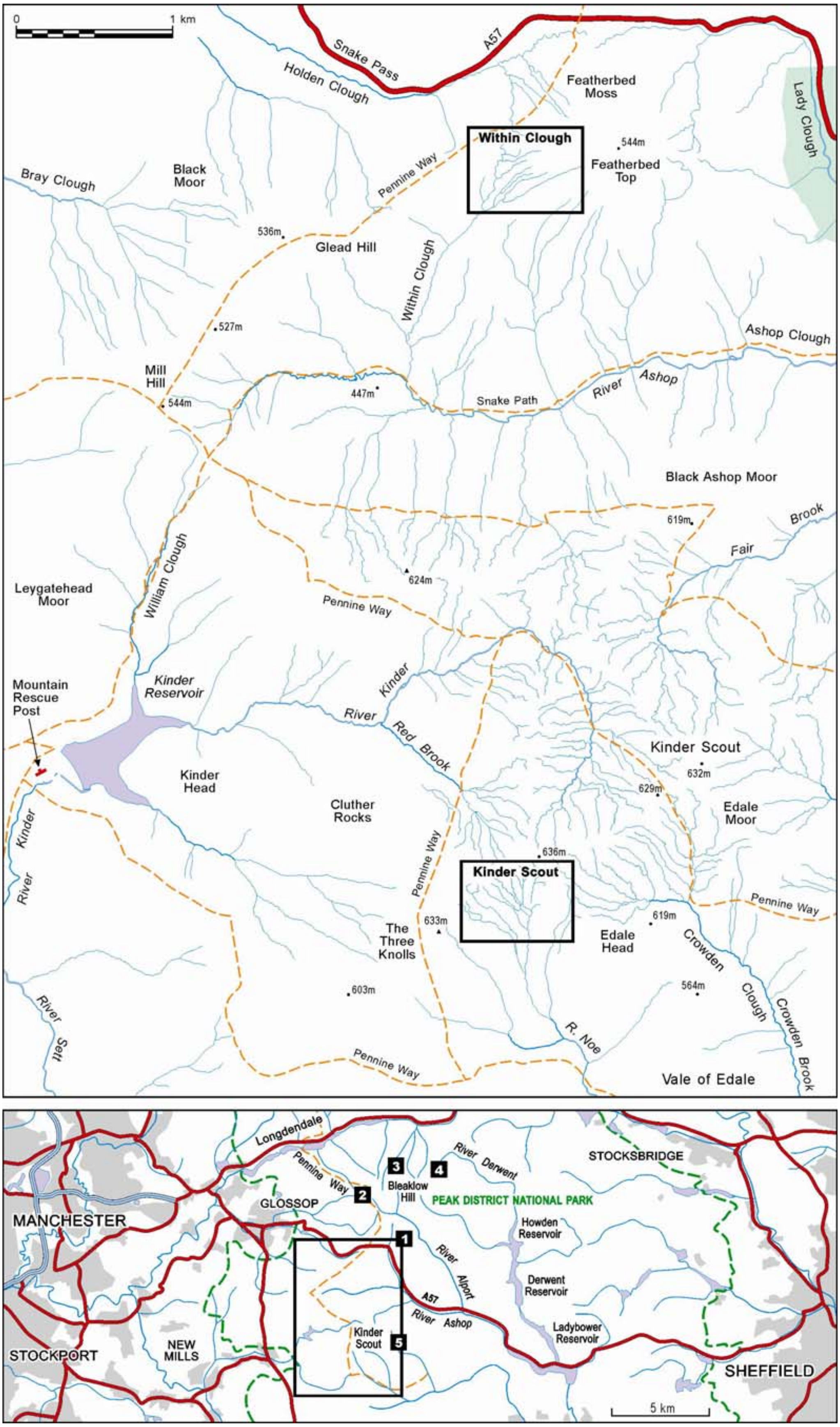


Figure 3.14 Study Locations The upper map is a detail of the box on the location map showing artificial gully block sites. Key to natural re-vegetation sites on location map 1) Upper/Nether North Grain / Doctors Gate. 2) Shelf Moor. 3) Bleaklow Meadows. 4) Swains Greaves. 5) Kinder Scout.

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 was 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 3.2 Plant species recorded in the gully survey

Full name	Common name	Abbreviated 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 effusus	Soft rush	Jeff
Juncus squarrosus	Heath rush	Jsqua
Nardus stricta	Mat grass	Nstri
Deschampsia flexuosa	Wavy hair grass	Dcaes
Agrostis tenuis	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 that 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 that 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

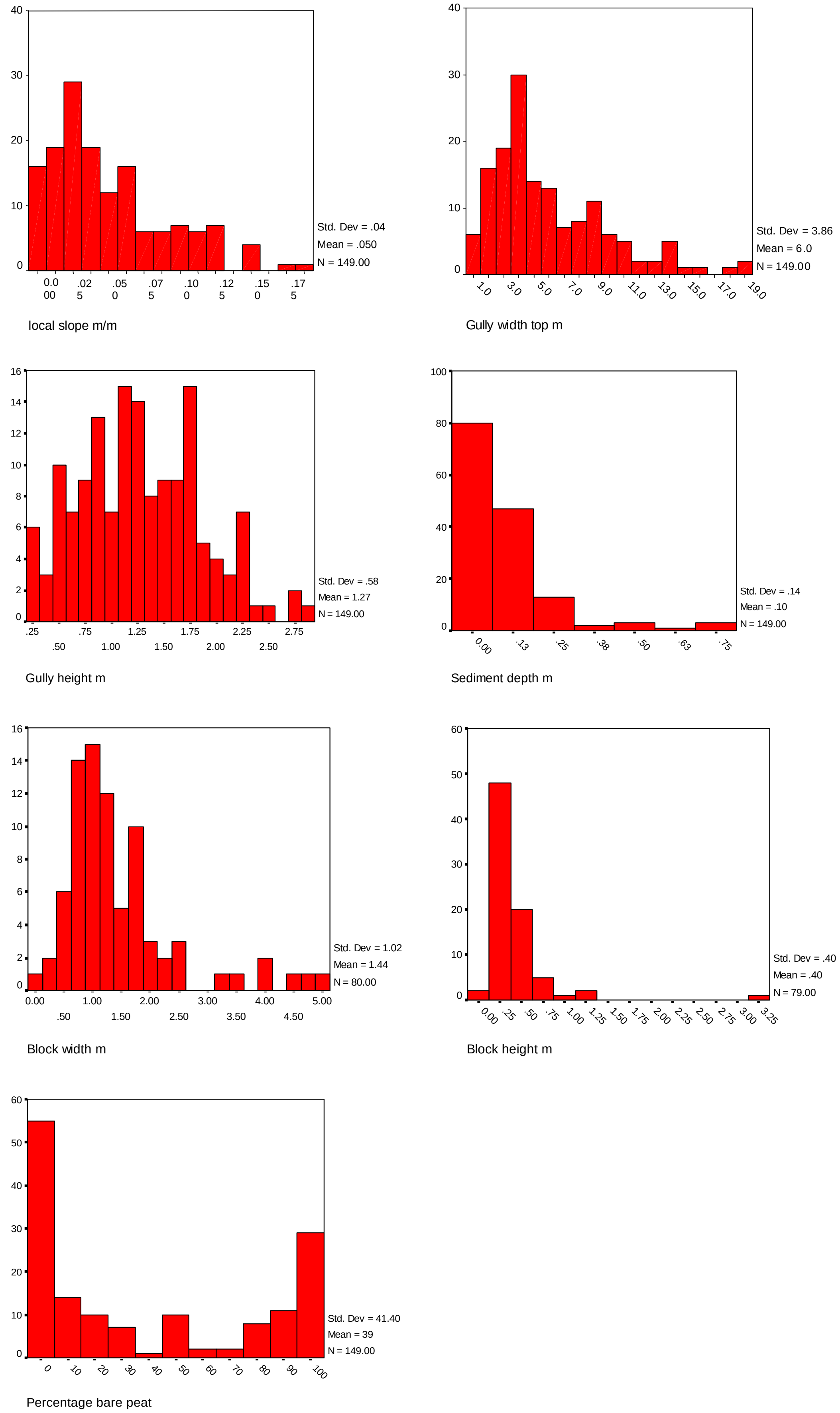


Figure 3.15 Frequency distributions of physical characteristics for the 149 gully sample sites

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 narrower gullies with steeper local slopes, relative to those of type B gullies. Type A gullies tend to be shallower 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 wider systems, with lower relative slopes. These gullies tend to be deeper and are associated with lower 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. Over-steepening 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.

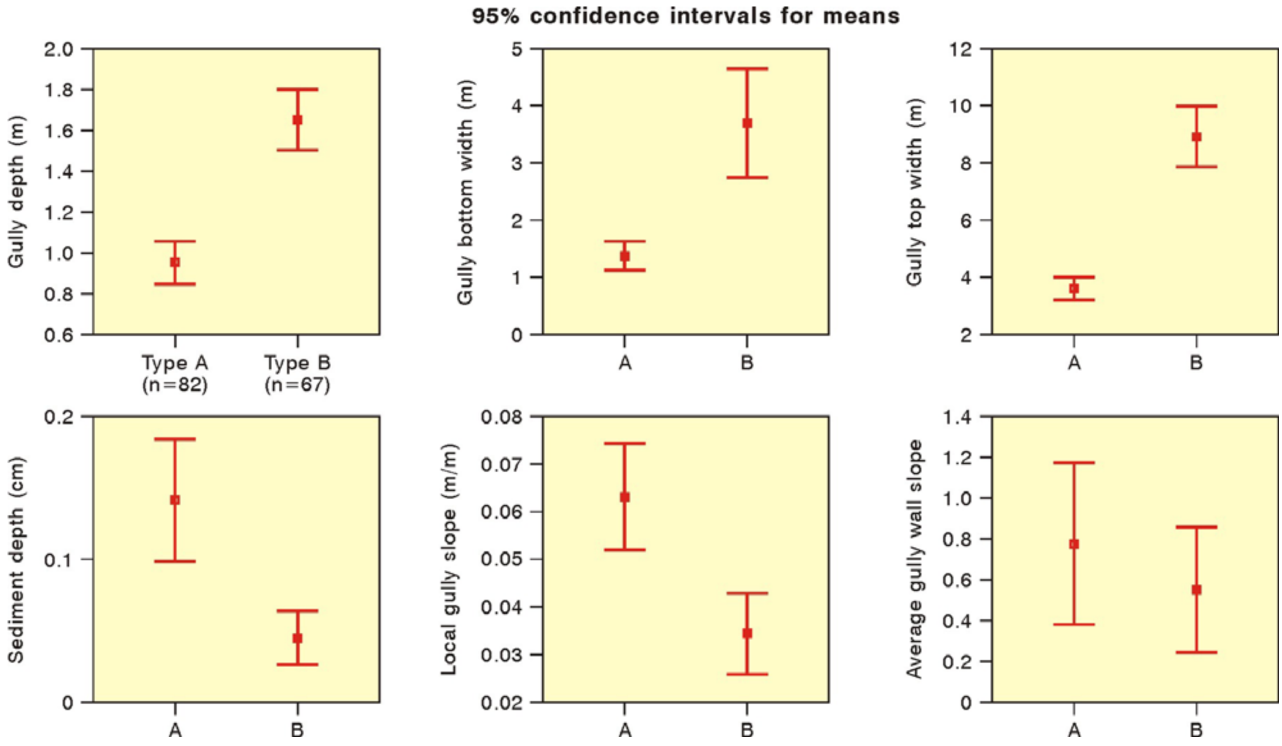


Figure 3.16 Boxplots of key physical variables for Type A and Type B gullies

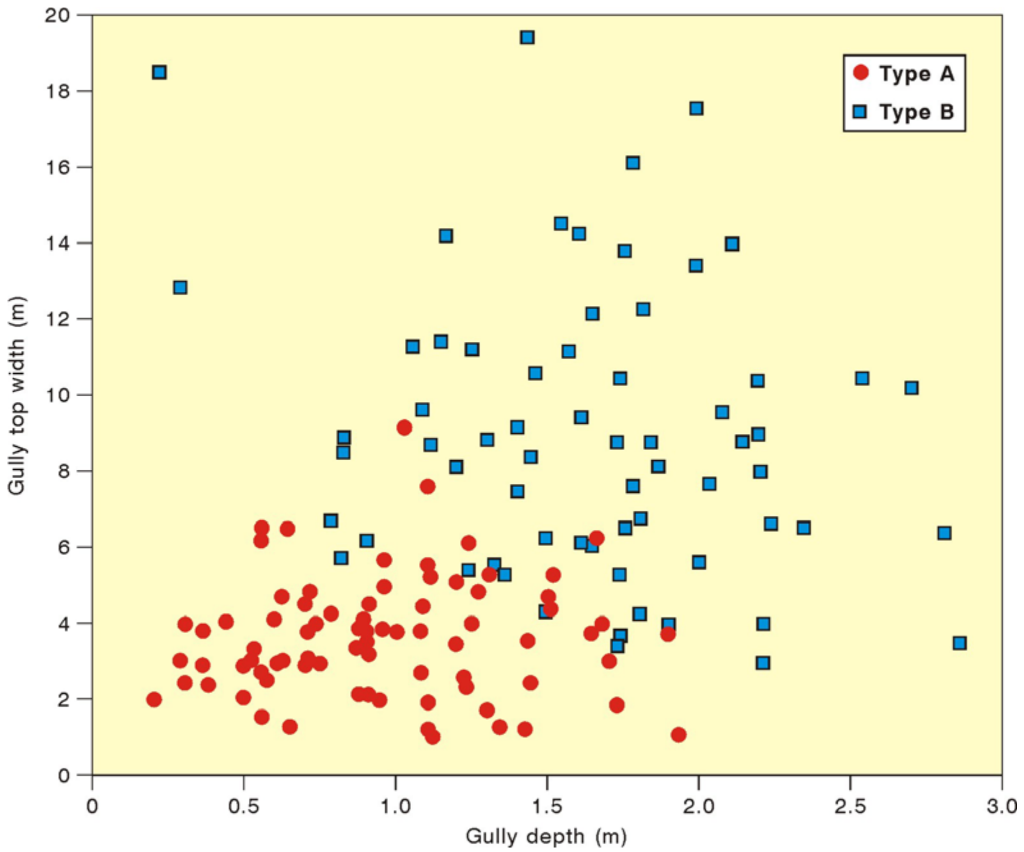


Figure 3.17 Scattergraph of gully width against depth, indicating Type A and Type B gullies

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*, *Sphagnum* spp., *Juncus effusus* 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	

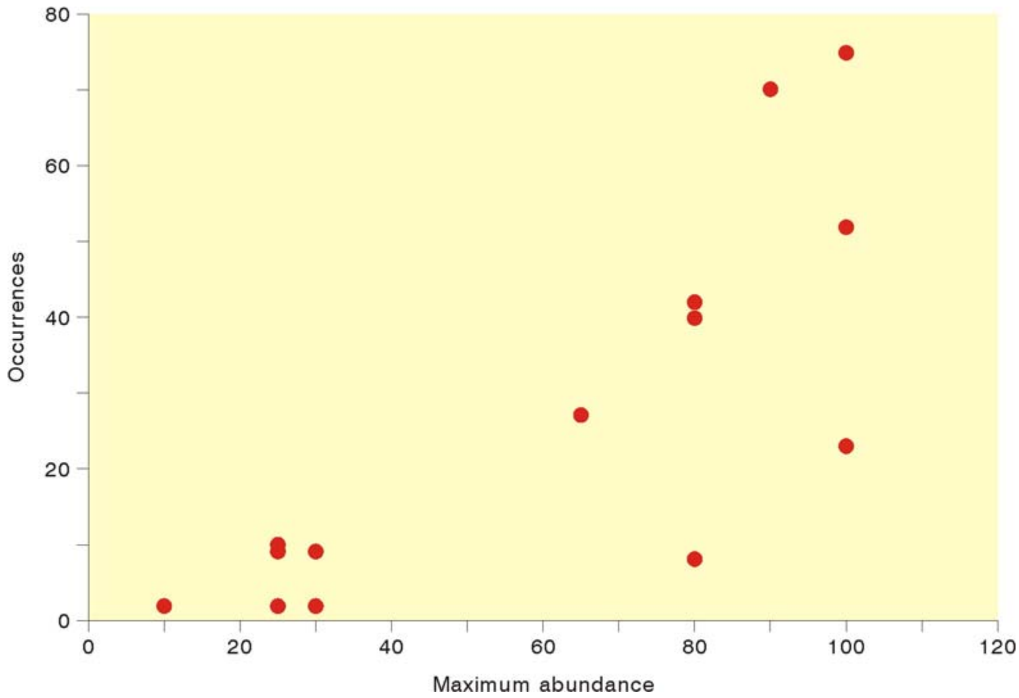


Figure 3.18 Scatterplot of species and cover type occurrence against maximum abundance on the gully floors

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 cut-off of 50% effectively separates gully floors which are predominantly 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 *Eriophorum* 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 re-vegetated 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. myrtillus* and *E. nigrum* *E. vaginatum* and *E. angustifolium* occasionally present

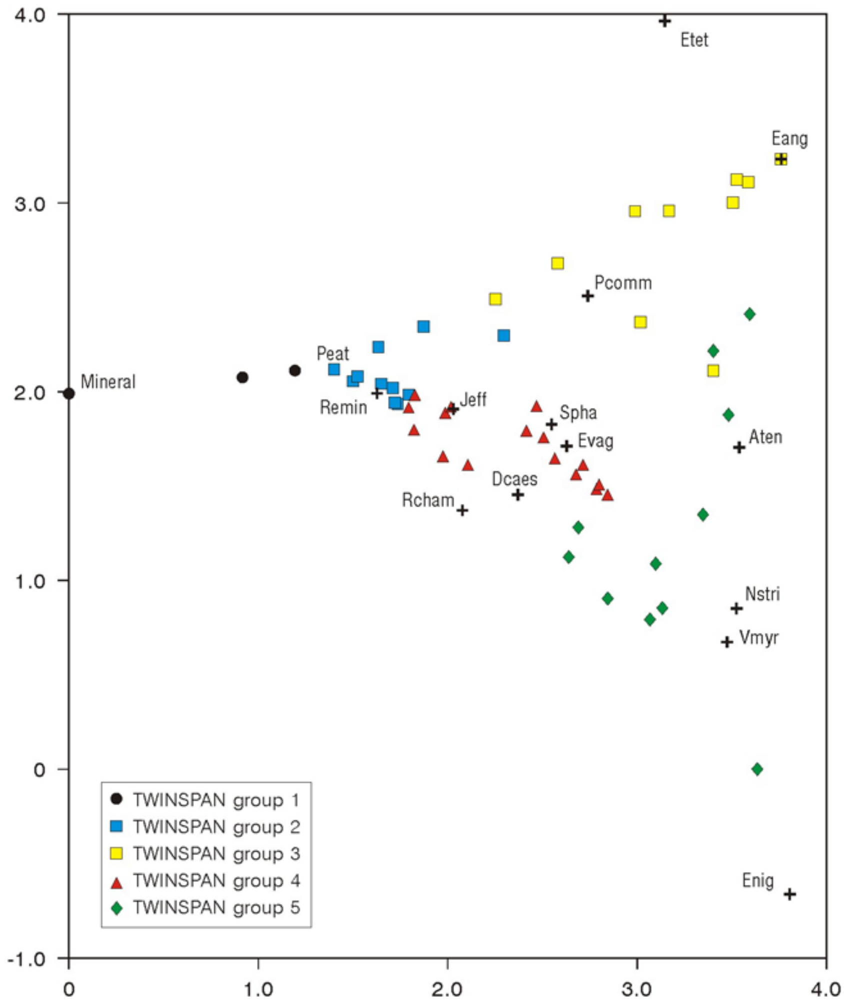


Figure 3.19 DCA joint plot of vegetation cover types in Type A gullies
Cover types and species are labelled with abbreviations (see Table 3.2)

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 re-vegetation 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 dominated 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 characterised 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. myrtillus* and/or *Empetrum nigrum*)

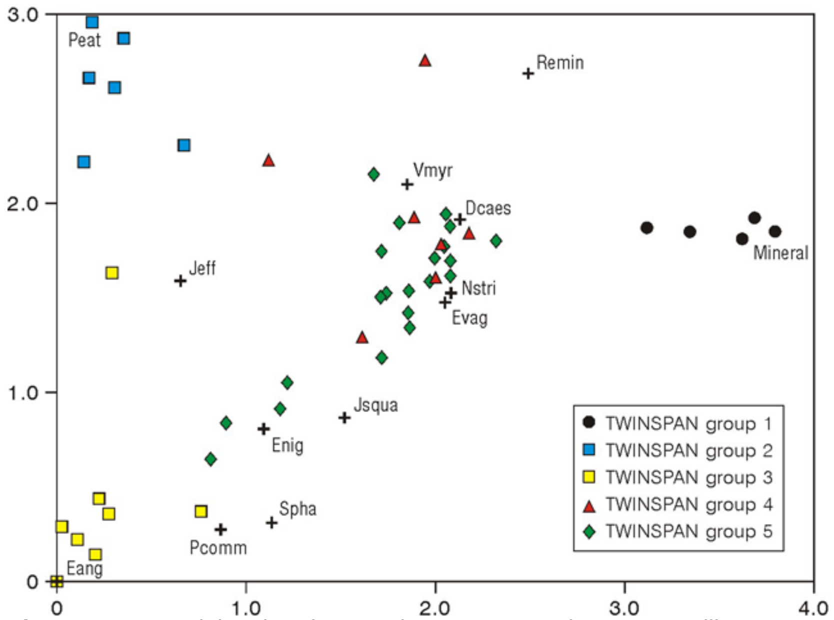


Figure 3.20 DCA joint plot of vegetation cover types in Type B gullies
Cover types and species are labelled with abbreviations (see Table 3.2)

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 interpretation 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 that 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 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 assessing block effectiveness in the context of strategy for artificial blocking, *E. angustifolium* is a potential target assemblage 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-re-vegetated 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* re-vegetation 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.

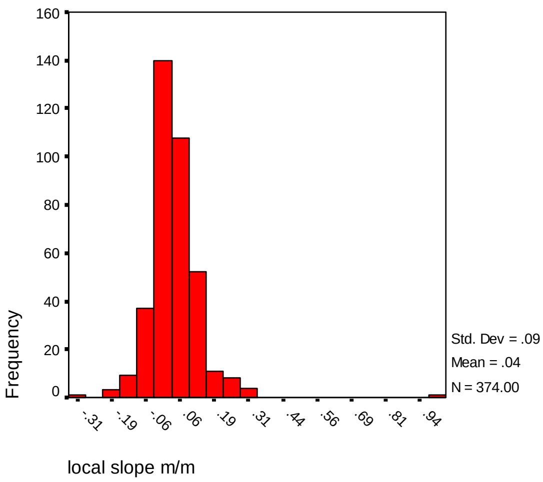
3.4.3 Patterns of key parameters

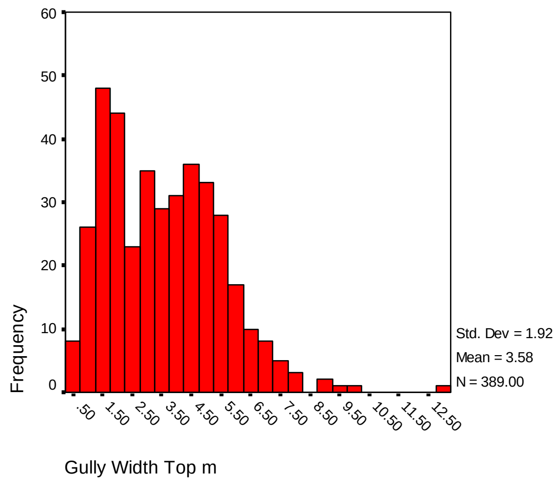
3.4.3.1 Gully vegetation

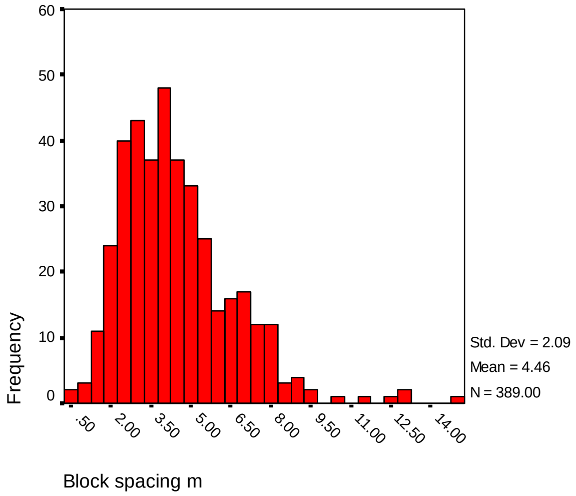
One immediately obvious pattern emerges from initial inspection of the data which is that almost all of the gullies at all of the sites have no vegetation cover established on the gully floors or on the gully walls. This is unsurprising given the relatively recent blocking of the sites. Consequently, 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.

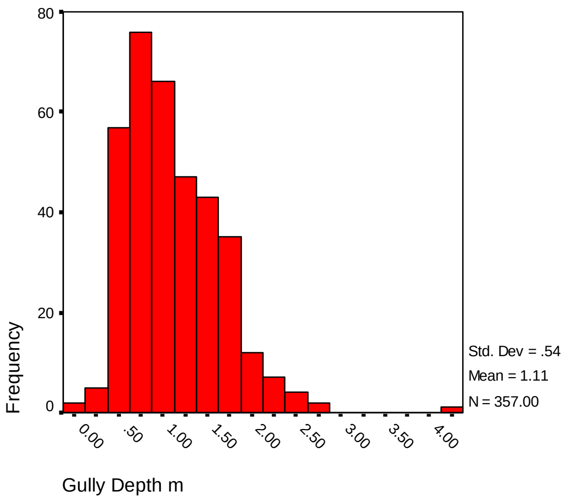
3.4.3.2 Gully and block parameters

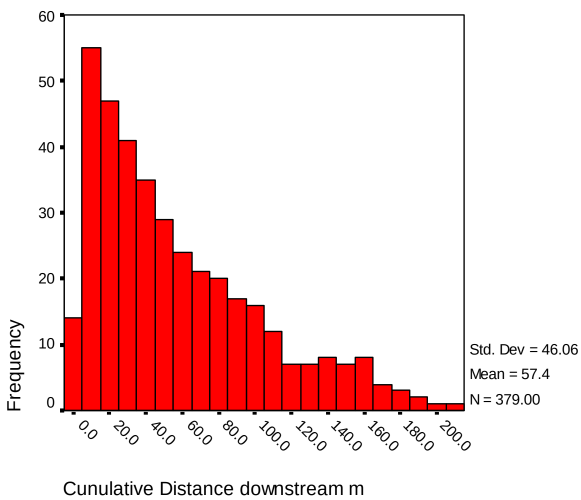
Distributions of gully, block and sedimentation parameters are plotted in Figure 3.21. Most of the parameters are approximately normally distributed; an exception is sediment depth which is closer to a log normal distribution with a majority of sites having low sedimentation and a tail of sites which 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.

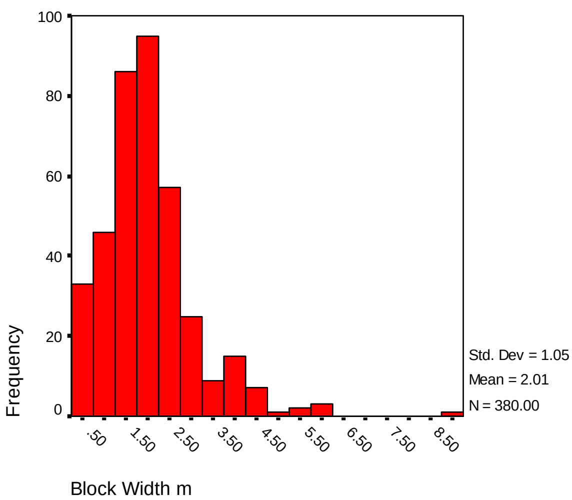

Frequency
Std. Dev = .09
Mean = .04
N = 374.00
local slope m/m


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

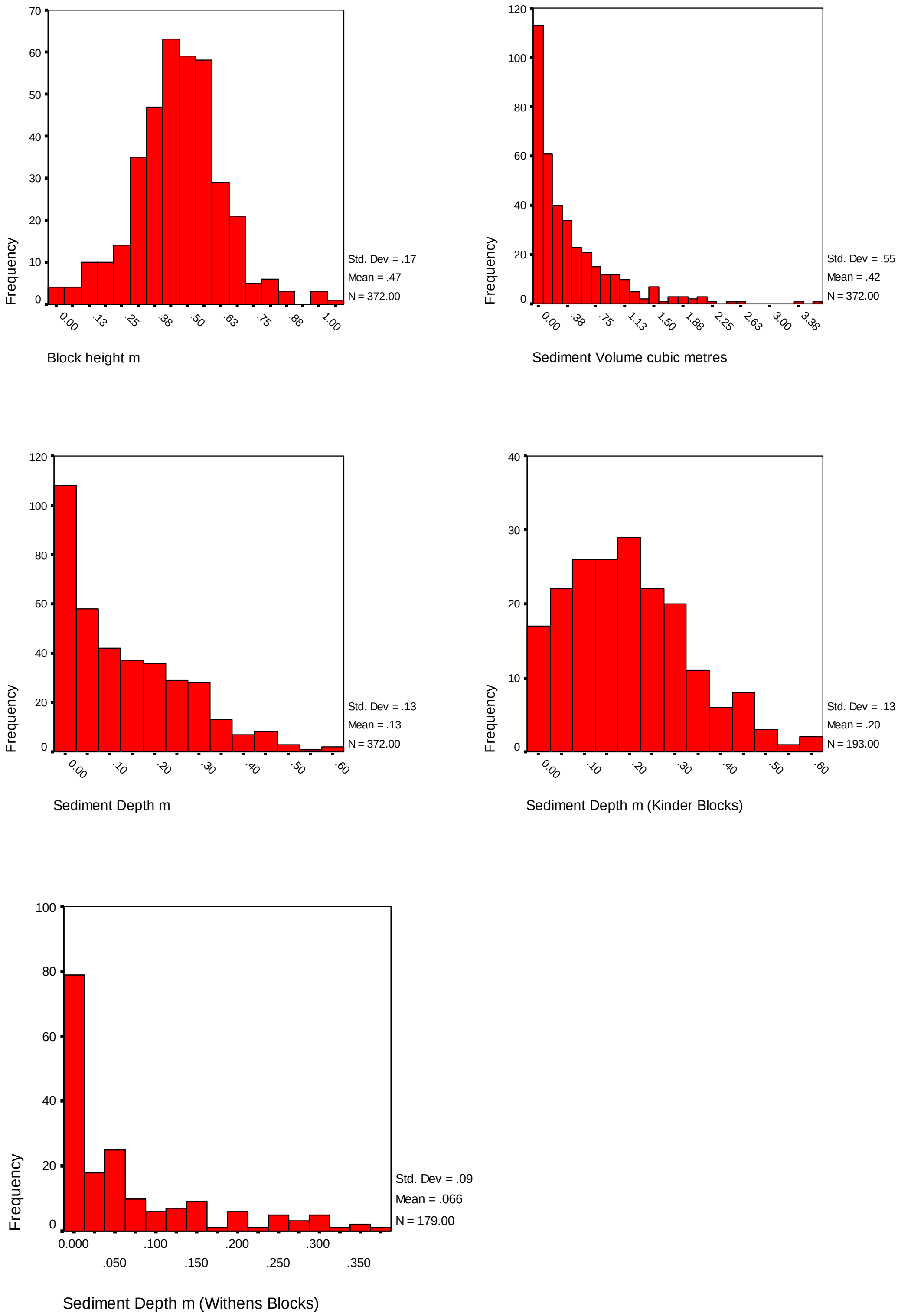


Figure 3.21 Distributions of morphological characteristics of blocked gullies

Table 3.9 provides 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 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 Top Width(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 (m m^{-1})	0.059	0.015	-0.16 – 0.27	0.02	0.01	-0.12 – 0.16
Block Spacing (m)	3.94	0.22	0.68 – 7.20	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 – 0.46	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

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.

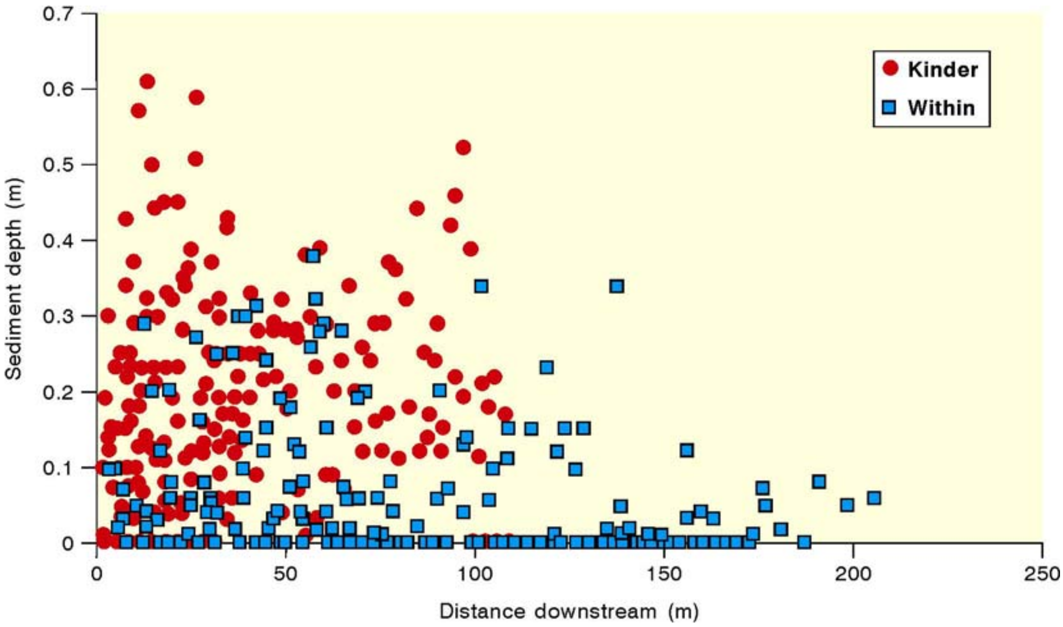


Figure 3.22 Change in sediment accumulation behind gully blocks with downstream distance

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 Scout and Within Clough 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 Clough gully (WC5). The lower reaches of this gully are blocked with the Hessian sack technique, which field observations suggest 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. 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.

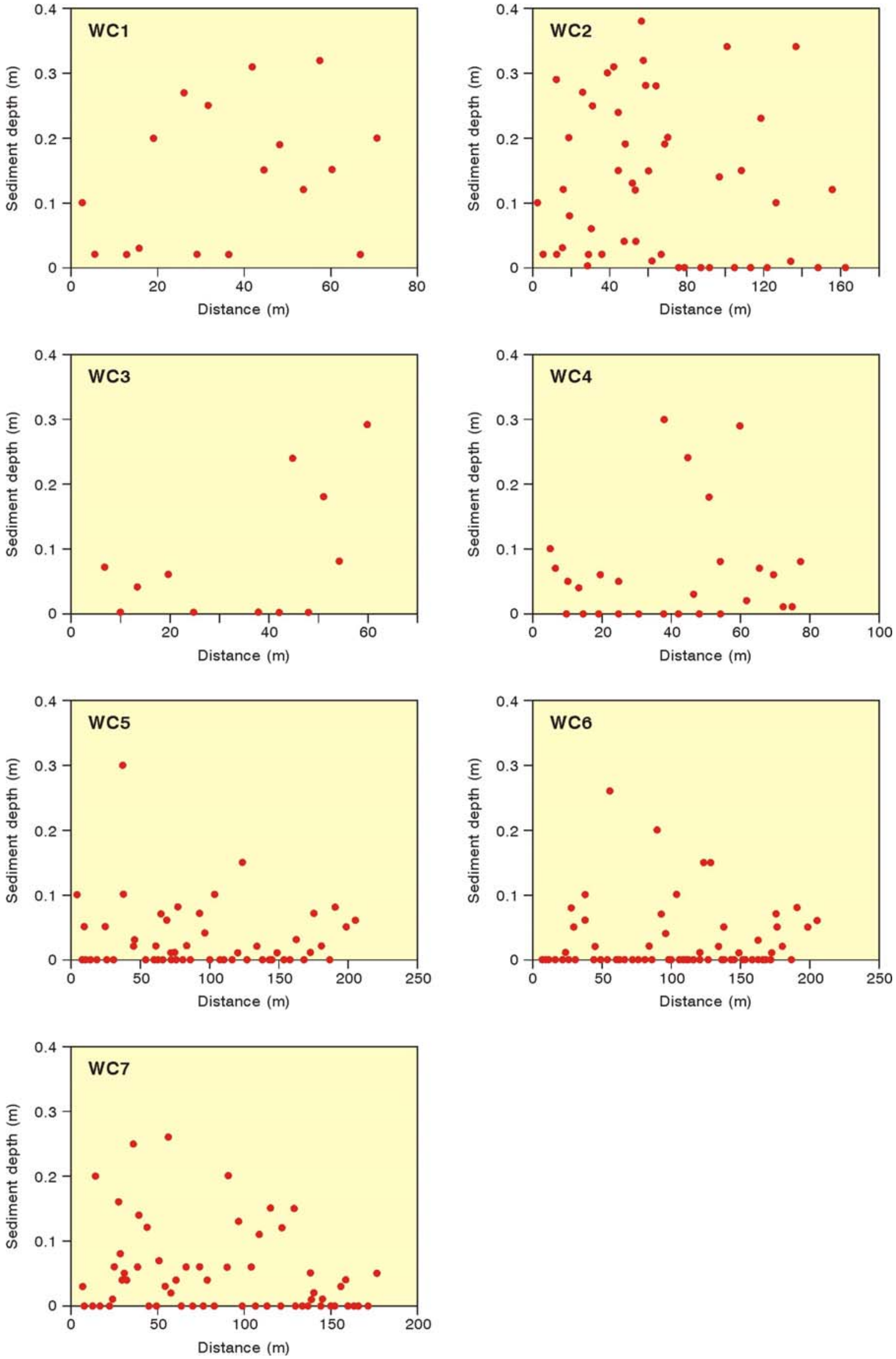


Figure 3.23a Distance downstream plotted against sediment depth Within Clough Gullies

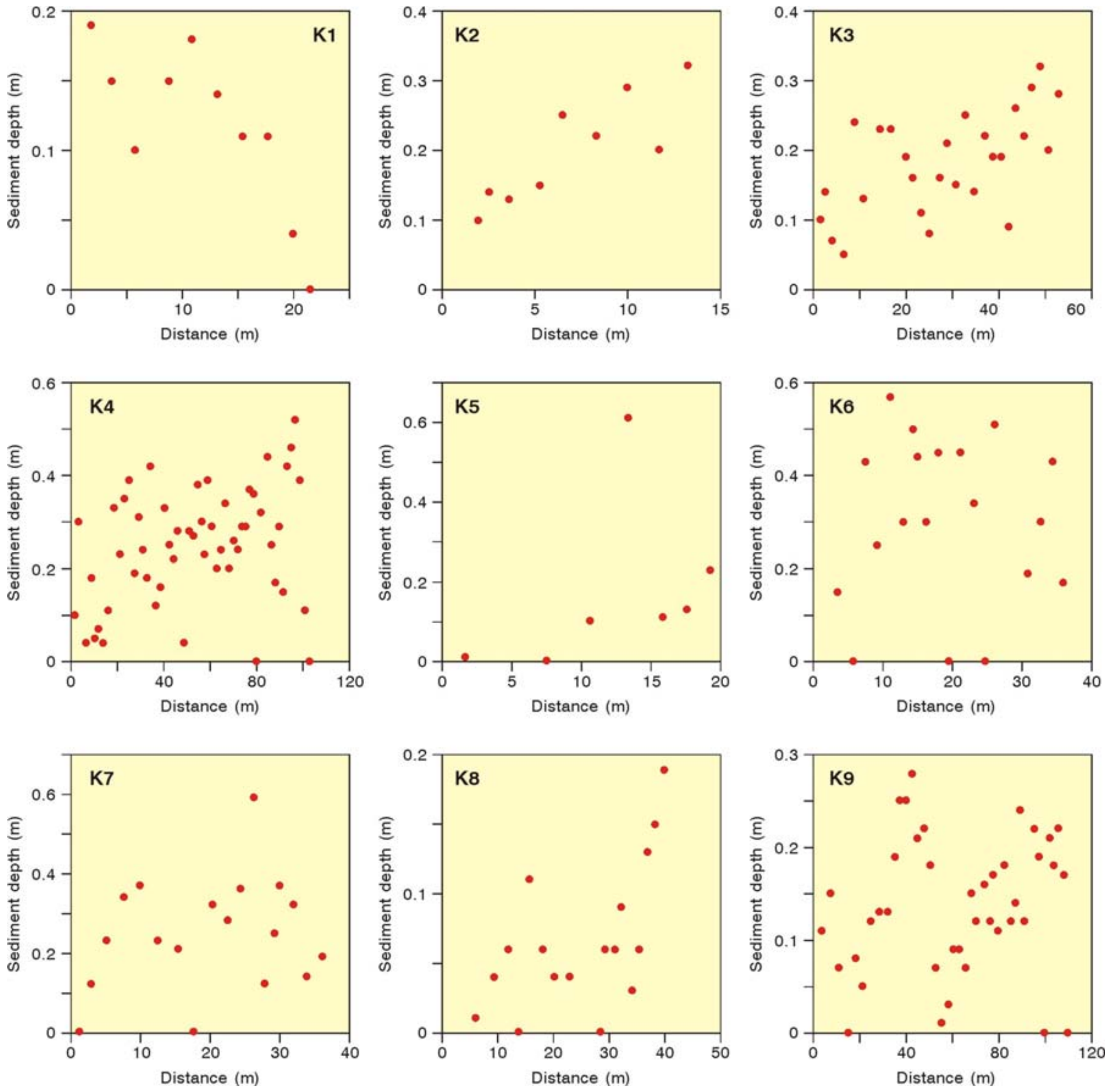


Figure 3.23b Distance downstream plotted against sediment depth Kinder Scout Gullies

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 gullies 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 [m]	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
Dist. 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 (Kinder Scout and Within Clough)

		N	Mean [m]	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 Scout only

		N	Mean [m]	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 (Table 3.11 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 is used for comparison but 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 Scout 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 Scout 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 gullies 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 [m]	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 [m]	Std. Deviation	Std. Error
Gully Width Top	Wood	134	4.749	1.419	.123
	Stone	18	6.803	1.544	.364
	Plastic	58	3.687	1.582	.208
	Total	210	4.632	1.680	.116
Block Dist.	Wood	134	3.9731	1.583	.137
	Stone	18	4.9433	1.272	.300
	Plastic	58	3.5752	1.731	.227
	Total	210	3.9463	1.633	.113
Cumul. Dist. downstream	Wood	124	34.489	27.727	2.490
	Stone	18	19.641	11.174	2.634
	Plastic	58	50.530	31.463	4.131
	Total	200	37.804	29.211	2.066
Block Width	Wood	125	1.968	.635	.057
	Stone	18	2.004	.561	.132
	Plastic	58	2.572	.974	.128
	Total	201	2.146	.788	.056
Sediment Depth	Wood	134	.212	.142	.012
	Stone	18	.247	.144	.034
	Plastic	58	.116	.075	.010
	Total	210	.189	.135	.009

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

		N	Mean [m]	Std. Deviation	Std. Error
Block Spacing	Plastic	157	4.921	2.334	.186
	Hessian	22	6.085	2.638	.562
	Total	179	5.064	2.396	.179
Cumul. Dist. downstream	Plastic	157	71.501	48.841	3.898
	Hessian	22	135.340	29.520	6.294
	Total	179	79.347	51.334	3.837
Block Height	Plastic	157	.475	.181	.014
	Hessian	22	.608	.192	.041
	Total	179	.491	.187	.014
Sediment Depth	Plastic	157	.072	.094	.008
	Hessian	22	.025	.052	.011
	Total	179	.066	.092	.007

Table 3.16 Correlation matrix of site and block characteristics for the complete dataset of artificial gully blocks for a) total data set, b) Within Clough, c) Kinder Scout

a) 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

b) Within Clough	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

c) 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 0.05 level (2-tailed), ** Correlation is significant at the 0.01 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 large 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 failed.

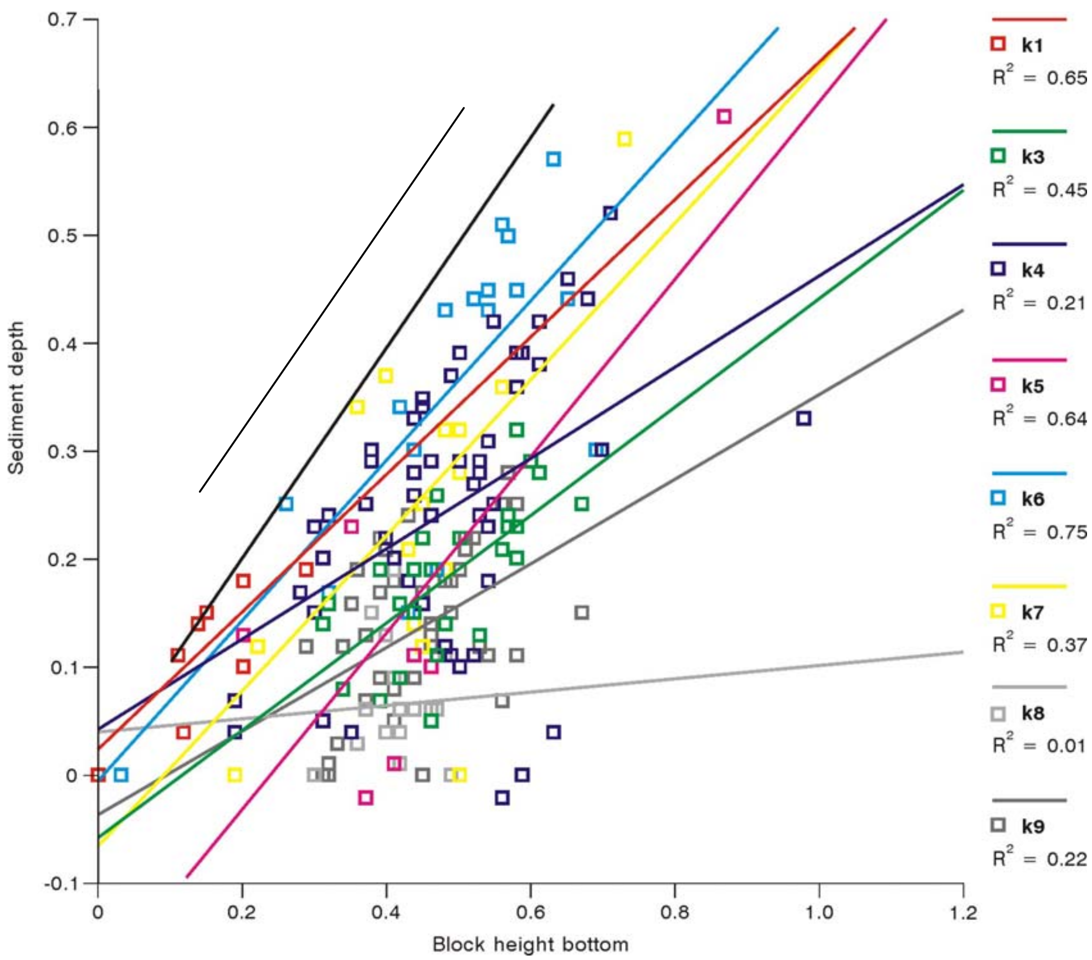


Figure 3.24 Relation between block height and sediment accumulation, Kinder Scout blocks

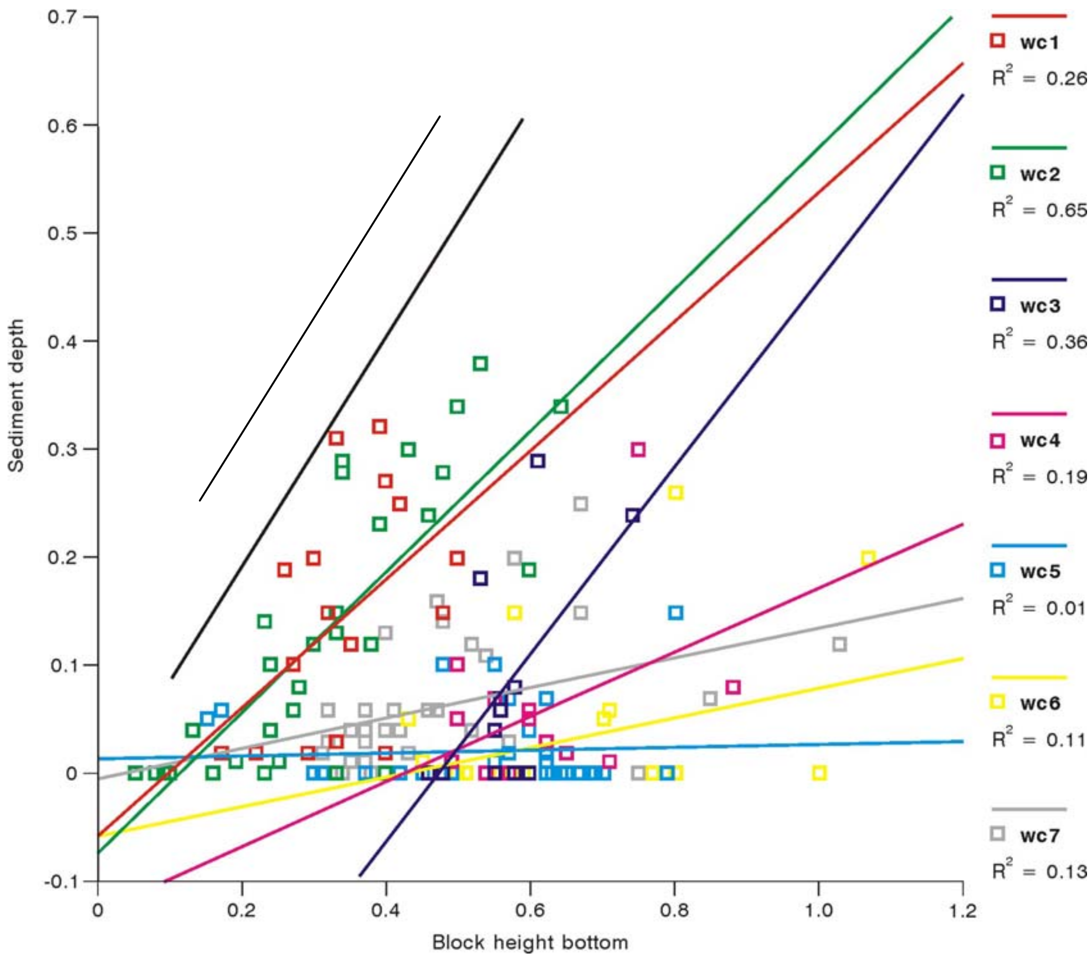


Figure 3.25 Relation between block height and sediment accumulation, Within Clough blocks

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 site.

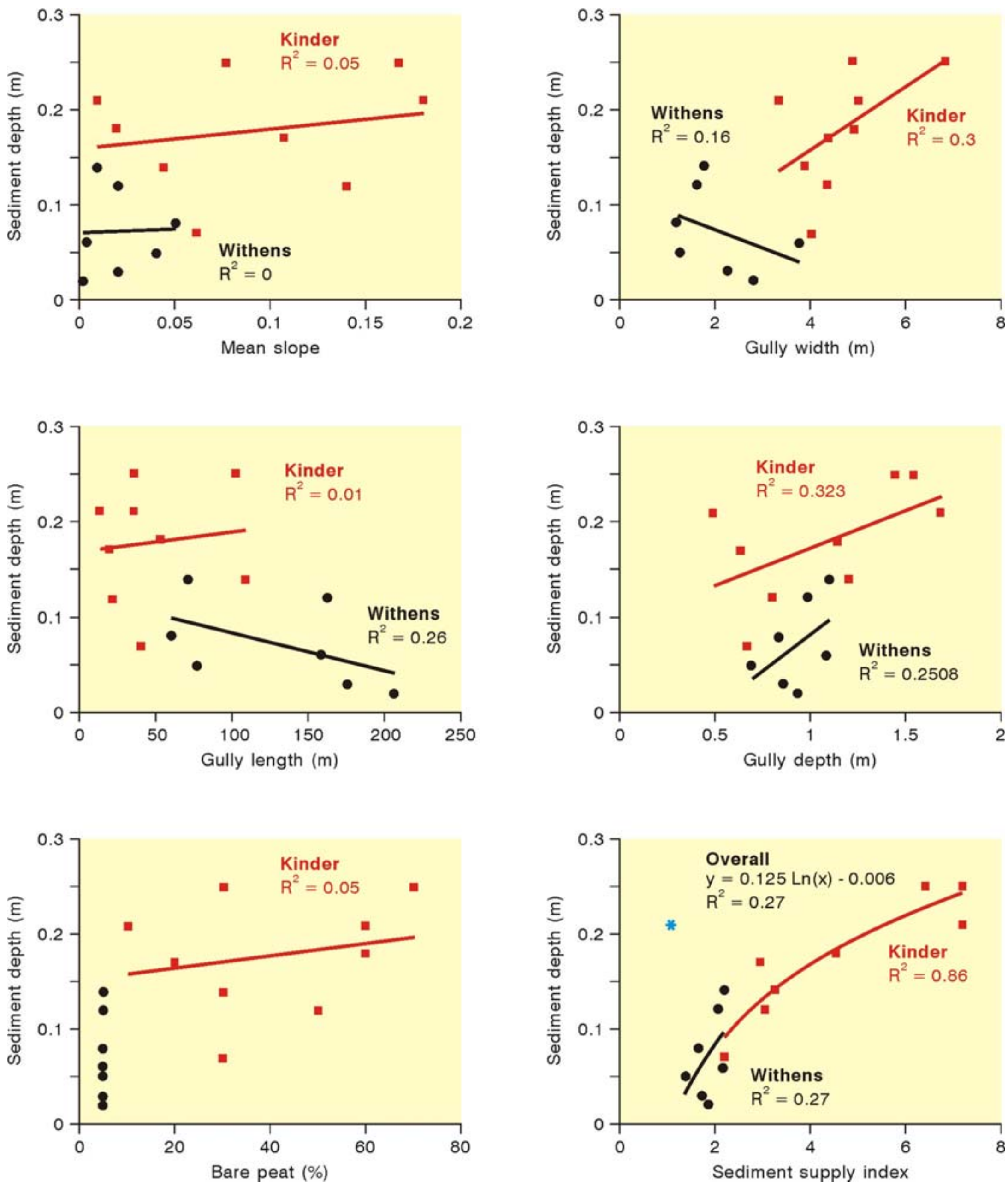


Figure 3.26 Association between site and gully characteristics and sediment accumulation at the gully scale

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 in 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 Time scales

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 re-vegetation. 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 time span 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 re-vegetation 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. myrtillus* 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 re-vegetation; i) Peat deposition and re-vegetation 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. myrtillus*, *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 re-vegetation (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 re-vegetated.

Although initially surprising, there are a number of explanations for this finding. First, the issue of equifinality – different processes of re-vegetation may lead to similar vegetation assemblages. In particular *E. angustifolium* re-vegetation 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 re-vegetation processes have been acting. There is some evidence of vegetation gradients within the survey data, and these suggest possible trajectories of re-vegetation 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 that 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 year's 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 the lowest mean sediment accumulation, possibly due to their inappropriate placing lower downstream and therefore to high water pressures. 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 and 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.

3.5.3.4 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 guideline. If sediment accumulation is continuing at the study sites then they are a conservative estimate of minimum spacings.

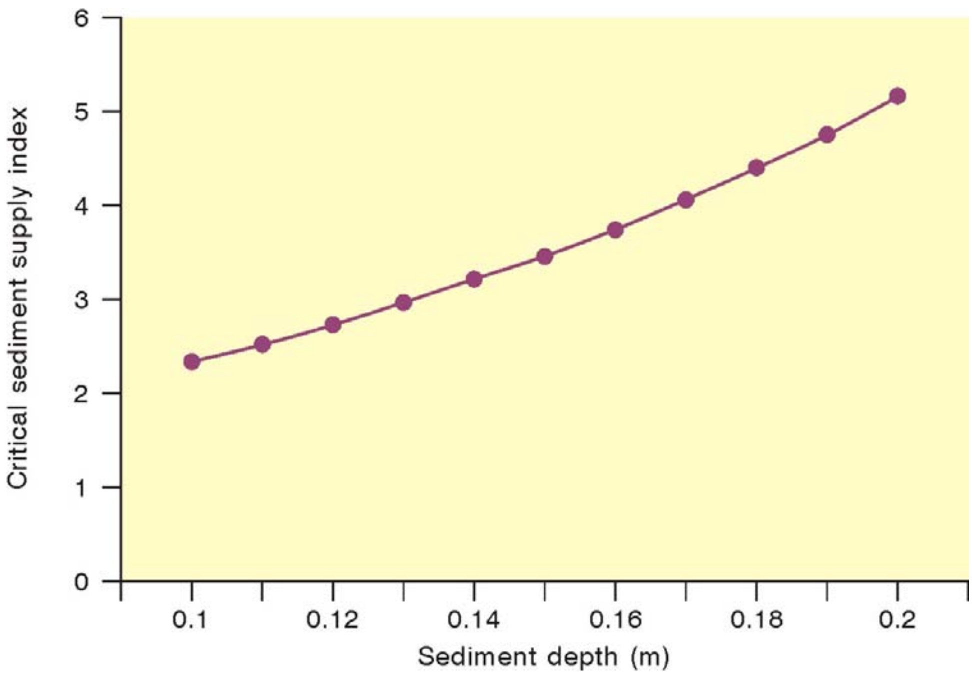


Figure 3.27 Critical values of sediment supply index required to achieve a given sediment depth

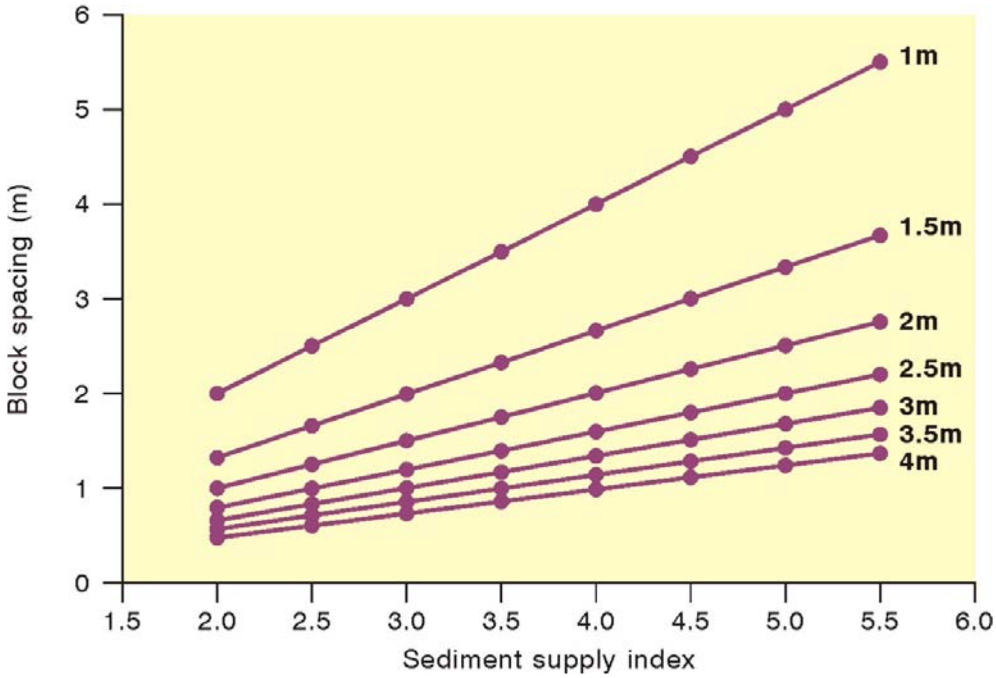


Figure 3.28 Block spacings required to achieve sediment supply index values for gullies of varying depth

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 created 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 re-vegetation of these large gullies. Observations of naturally revegetating gullies suggest that once initial vegetation is achieved, sediment trapping promotes upstream migration of the vegetation cover. Successful downstream re-vegetation 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-vegetated sites that re-vegetation tends to initiate 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 experimental approaches to promoting sediment deposition and re-vegetation 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 re-vegetation of interfluves.

3.5.4.6 Planting

The work on natural re-vegetation clearly suggests that the natural re-vegetation 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.

4 STRATEGIC LOCATIONS FOR GULLY BLOCKING IN DEEP PEAT

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4.1 Introduction

Gully restoration objectives in the Peak District include the control and prevention of gully erosion, a reduction in peak water discharge, a reduction of sediment loss from peatlands, to raise the water table, to promote re-vegetation and to reduce water discolouration of streams. However, a tool is required in order to inform decision making on where to block gullies on the in order to achieve these aims. This is because with limited resources it is not possible to block all gullies within the 133 km^2 study area. In addition, there may be detrimental hydrological effects of blocking some gullies, such as development of further gullies or soil pipes. This research aims to assess the peat hydrology of Bleaklow and Kinder Scout and provide a tool to predict the impacts of gully blocking in order that strategic gully blocking locations can be identified. The primary objective is to produce a guide for decision-making for efficient restoration works.

The Leeds Team have developed an approach that allows high resolution topographic data based on LiDAR to be coupled to hydrological predictions about hill slope saturation (e.g. Lane *et al.,* 2003; 2004). Such information is important in blanket peat uplands because even very small changes in topography on gentle gradients produce marked differences in hydrological response (Holden and Burt, 2003a). It is often assumed that there are uniform water tables in peatlands and managers often strive to recreate this scenario (Holden *et al.,* 2004). However, Holden and Burt (2003a, 2003b) have shown that runoff production in blanket peat is spatially distributed such that more gentle slopes, and particularly footslopes are dominated by saturation-excess overland flow, whereas steeper slopes are more often dominated by shallow throughflow just below the surface. Small changes in topography will route water across and through hill slopes in different ways and at different rates. Thus the impact of a gully on local saturation may be very different depending on where the gully is located on a hill slope. Some gullies may divert water from the hill slope into the stream very rapidly. This may reduce the amount of water that travels for long distances downslope responsible for maintaining peat saturation. Thus, travel times to the stream are reduced and some gullies may reduce downslope saturation by preventing water from reaching that part of the hill slope. This change in saturation extent (spatial and temporal) is crucial for wetland ecology, peatland growth and carbon sequestration. Desaturated peats are likely to be ones that produce more discoloured stream water (dissolved organic carbon) and release carbon dioxide and methane into the atmosphere. To lessen adverse effects of peat desaturation and to favour increase in peat saturation on hill slopes is one basis for selecting gullies to target for blocking and the basis which is advocated and presented in this research.

It should be noted that it is difficult to present the provided GIS data in this written report without significant simplification and the full extent of our work and data provision is best assessed viewing the maps in a GIS package. Data are available for non-commercial use from the Moors for the Future office and Joseph Holden.

4.2 Summary of approach

The topographic index is a measure of the drainage area per unit contour length (a) divided by the slope ($\tan\beta$). Essentially a point at the foot of a long, gentle gradient slope is more likely to be saturated than a point on a short, steep slope. The topographic index is therefore used as an indicator of topographic drainage.

A gully may reduce the length of slope that is draining into a point on a hill slope and thus change the topographic index. Hence the topographic index is a very reliable indicator of how gullies may impact on hill slope saturation. Thus utilising the LiDAR data it is possible to tell how gullies are impacting on saturation extent which is so crucial for peatland survival and habitat. This requires:

- a digital terrain model to be constructed from LiDAR data (checked for errors)
- the topographic index to be calculated on LiDAR for the area of interest.

LiDAR data is thus required for complete hill slopes (i.e. from top to bottom) otherwise the topographic index calculated for a given point will be false and results may be misinterpreted. In this case it was necessary to mesh existing LiDAR data for some of the study site (December 2002) with a newly acquired data set for other parts of the study site (May 2004). The following steps were:

- identification of gullies on the terrain model
- a simulation of gully infilling
- calculation of the impact of gully infilling on the topographic index
- comparison (or subtraction) of the topographic index maps produced for the current environment and the gully filled environment.
- development of maps of flow accumulation

Flow accumulation maps are based on the area draining to a given point and the local slope direction and are therefore closely coupled to the topographic index (see below).

Such an approach is entirely novel and yet provides crucial information for management on areas that will be more sensitive to blocking compared to others. This chapter does not report on whether gully blocking itself would be successful at any site and so results from the two partner studies discussed in chapters 2 and 3 should be assessed with this in mind. While our approach is novel, it is also numerically and computationally very demanding. In particular the coverage of 133 km^2 is huge and the area contains a vast amount of gullies, which does not allow a straightforward automated approach.

It was our original intention to simulate the complete blocking of gullies. This would provide data on which gullies are most important in the landscape and therefore which should be targeted for restoration. This would be useful information even if complete infilling was not likely over a short time period. This is because it allows us to justify why we are attempting to block certain gullies on the basis of protection and restoration of the peatland as a whole. However, on request of Moors for the Future, we specially devised a technique that would simulate a partial blocking of gullies that might be more realistic and then to compare results. As shown in chapters 2 and 3, gully blocks do not usually block the gully to its full height and a partial filling seems to be realistic and advisable.

Finally, it may be the case that some gullies are very active because they have a large drainage area feeding into them whereas other gullies are inactive due to a small drainage area and are thus not likely to erode further. In order to establish such effects (and so that this could be utilised as a secondary decision-making criteria) flow accumulation maps were produced. These can be used to show the distribution of active and passive gullies. The size of a gully can be viewed from the aerial photographs. However, whether they are passive relic features or active gullies capable of transporting large quantities of water (and therefore likely to be at high risk of rapid erosion) depends on the amount of flow being drained into the area. A flow accumulation map calculates the amount of flow that would come into a pixel if each pixel across the entire study area were to start with a value of 1 and then follow the steepest descent for flow routing (i.e. water must flow down the path of steepest descent and is therefore entirely based on the natural topography of the landscape as depicted by high resolution LiDAR).

4.3 Detailed methodology

The methodology involves:

- Generating a DTM covering the entire area
- Calculating flow accumulation and topographic index
- Identifying and digitising gullies
- Interpolating over areas of gullies and recalculating flow accumulation and topographic index
- Buffering around gullies to different degrees as a proxy for partial infilling of gullies and calculating topographic index and flow accumulation
- Generating maps of change in topographic index and flow accumulation (new map subtracted from original unmodified version)

4.3.1 The digital terrain model (DTM) for the area

The two sets of LiDAR data collected on different dates (December 2002, May 2004) were provided by the Environment Agency. These data were used to produce a DTM for the whole area. This is available in digital format for viewing. However, on close inspection of the DTM (e.g. Figure 4.1), some data problems were identified and it was necessary to rectify or interpolate over some missing data points before any further analysis could proceed. The corrected DTM for the whole area is shown in Figure 4.2, although in order to see the fine detail it is necessary to zoom in on such data in a GIS package.

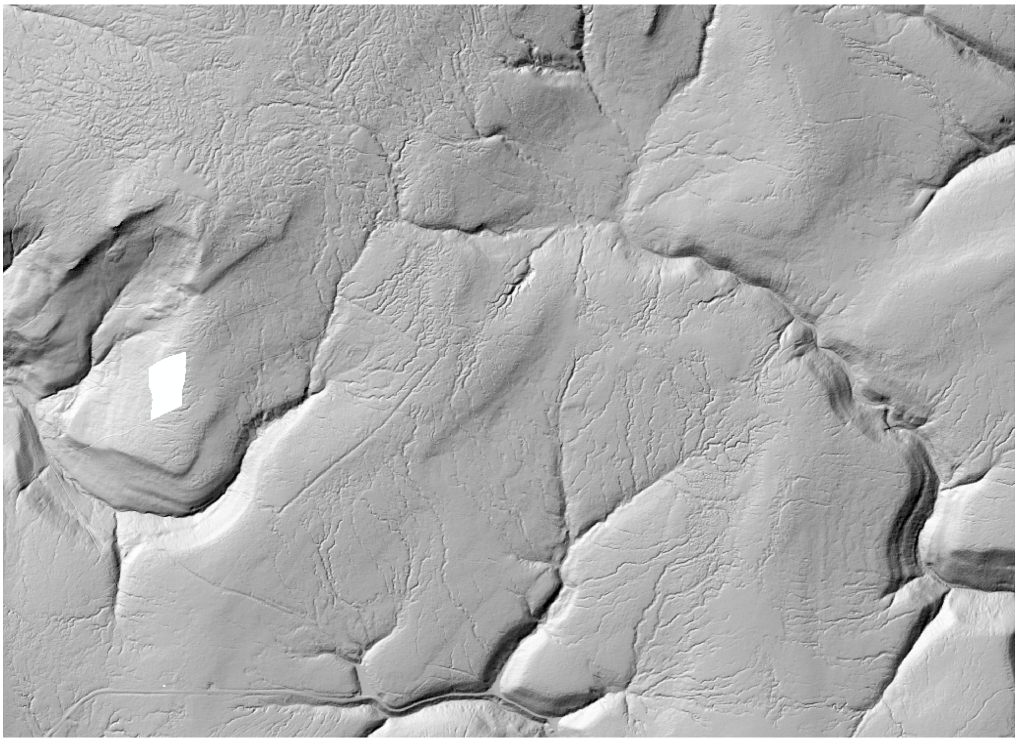


Figure 4.1 The DTM for a small part of the study area. This shading provides a useful way of observing the DTM, as the streams and gullies become clearer. However, as seen on the left edge, there were some areas with no data that had to be interpolated with before progressing.

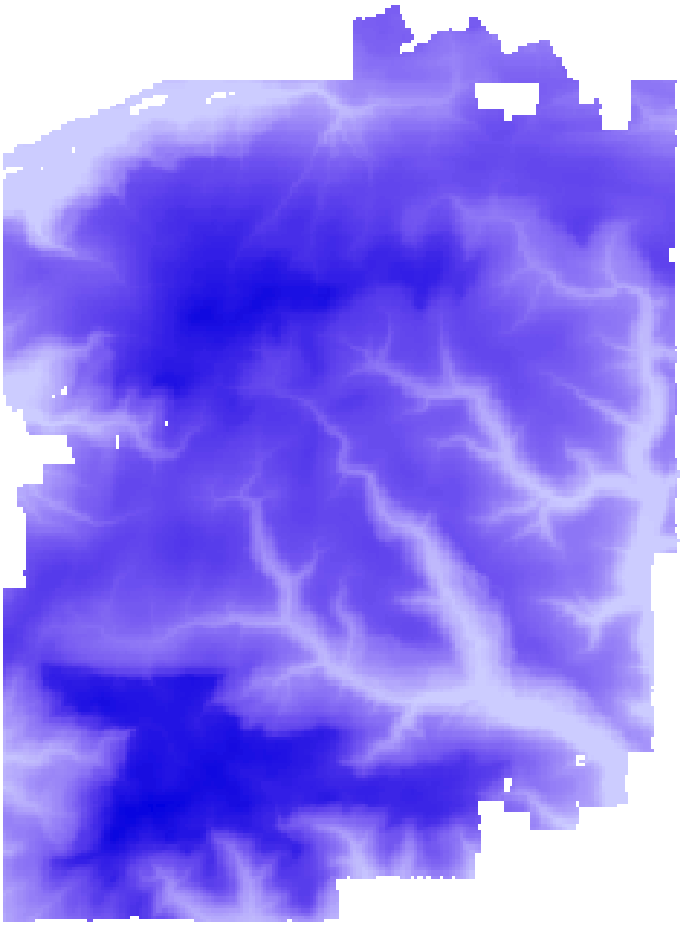


Figure 4.2 DTM for the whole study area

4.3.2 Calculating flow accumulation and topographic index

Following DTM production it was necessary to infill any pits to allow flow accumulation and topographic index map production. The topographic index for the whole study area is shown in Figure 4.3. Dark areas are those more likely to be saturated. A closer view of the topographic index of one part of the study area is given in Figure 4.4 as an example.

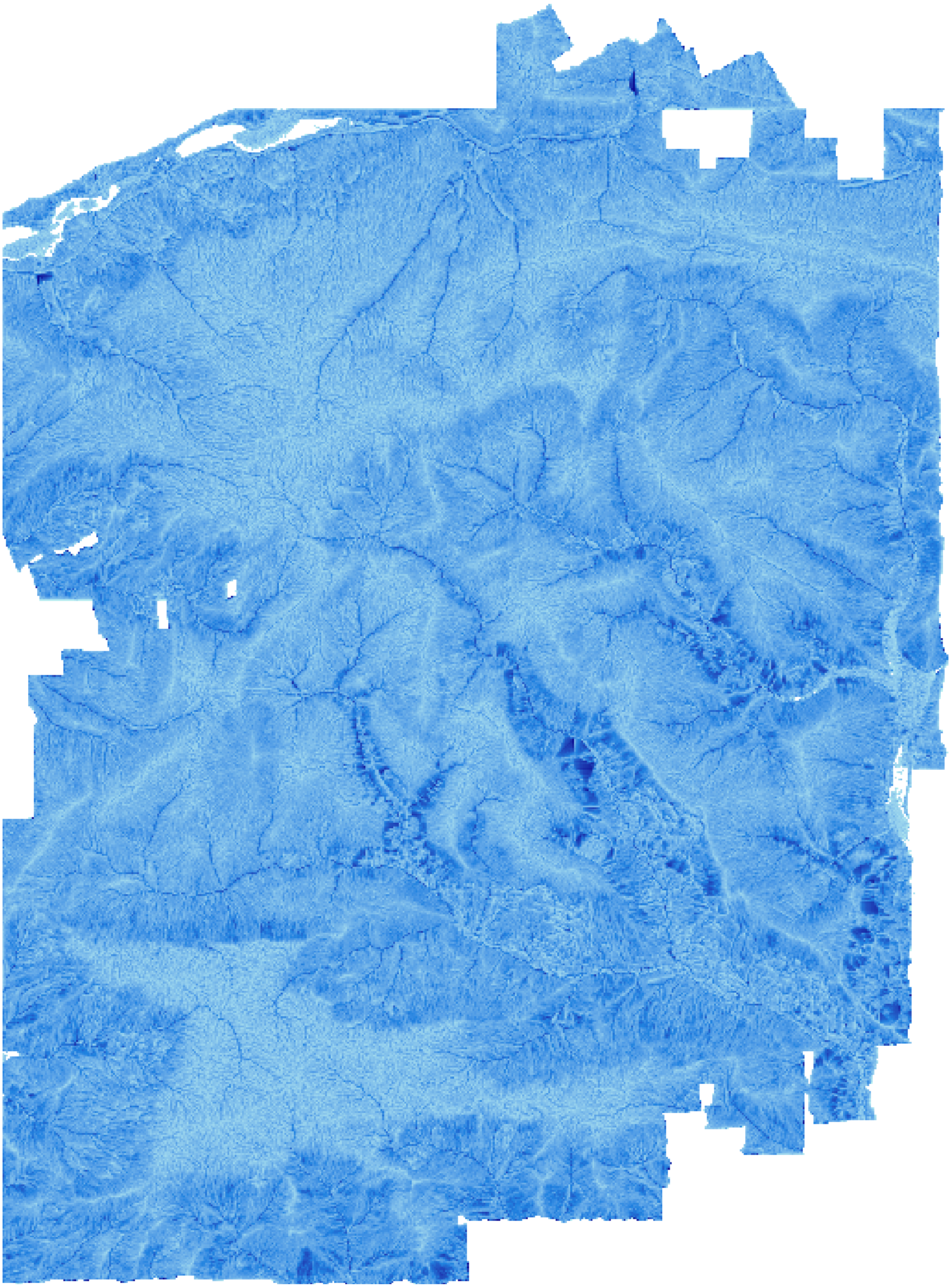


Figure 4.3 The topographic index for the whole survey area. Darker areas are those with a higher index and thus more likely to be saturated, e.g. on the foot of hill slopes.

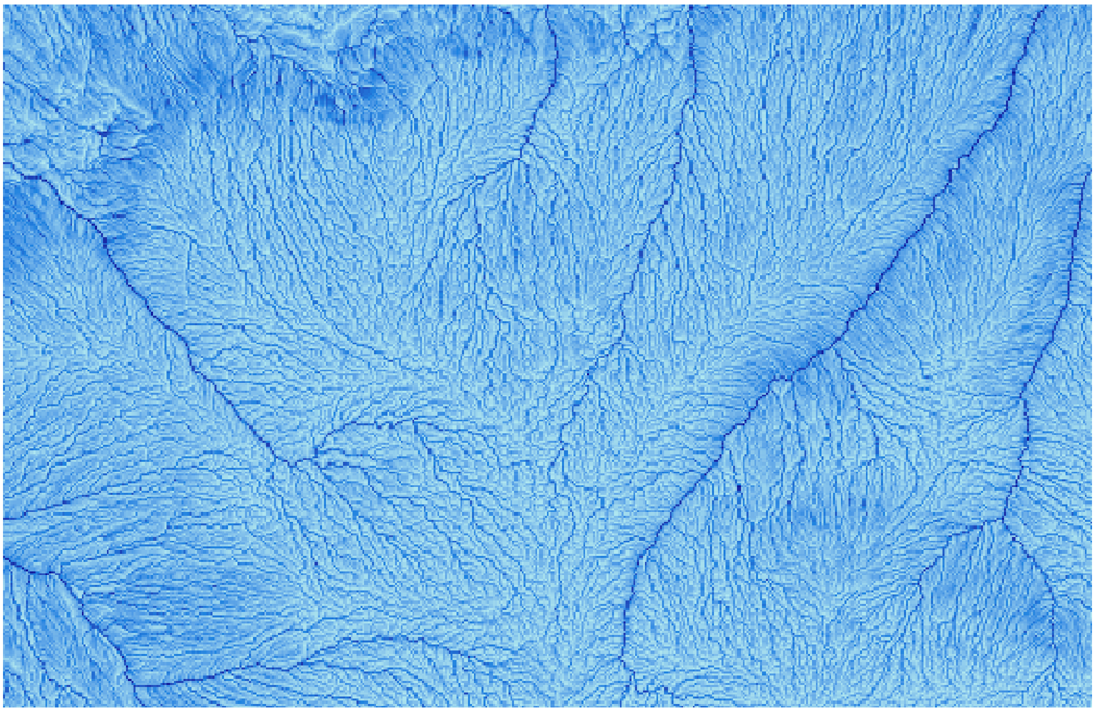


Figure 4.4 Topographic index for one part of the study area

The flow accumulation maps can be produced in a similar way and use of shading will allow to visually compare relative flow accumulation in different parts of the system (Figure 4.4, 4.5 – n.b. figures not for same area). This reflects the drainage network. The main benefit is the speed with which information can be gained about the characteristics of whole of the 133 km^2 area. By clicking on any part of the GIS map value of flow accumulation can be obtained. This is useful when wanting to know the flow accumulation that reaches the head of a gully and for differentiating more active and passive gullies.

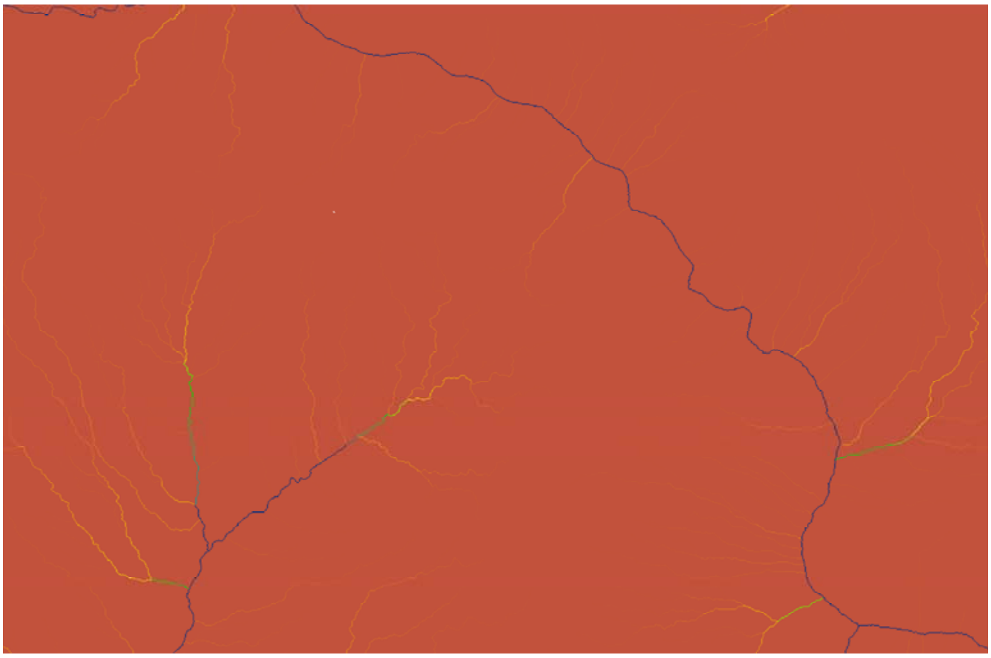
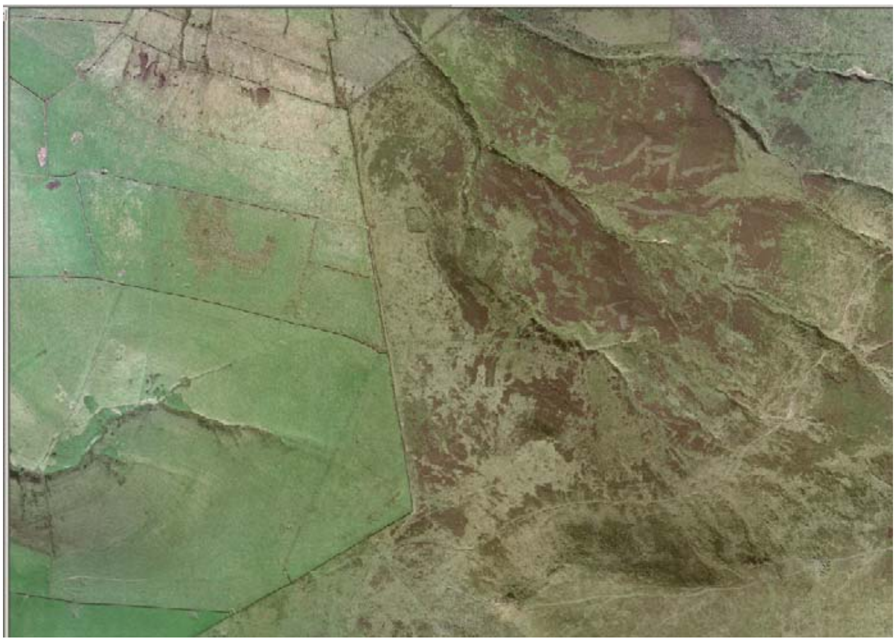


Figure 4.5 Flow accumulation map for part of the Bleaklow system. Red indicates low accumulation whereas yellows and green indicates a medium to high accumulation through to dark blues that indicate high accumulation.

4.3.3 Identifying gullies

Any approaches to identifying ground features on digital data were assisted by air photos of the area that were available. Considerable time was spent in decompressing the air photo files and then converting all 156 images into grid format for overlaying in ArcGIS format. These data are now available for use in digital format and represent an additional output of the research process. In some areas there are very few gullies, e.g. on the moorland fringe (Figure 4.6a) whereas in other areas, as on the top of Bleaklow, there are dense gully networks (Figure 4.6b).

a)



b)

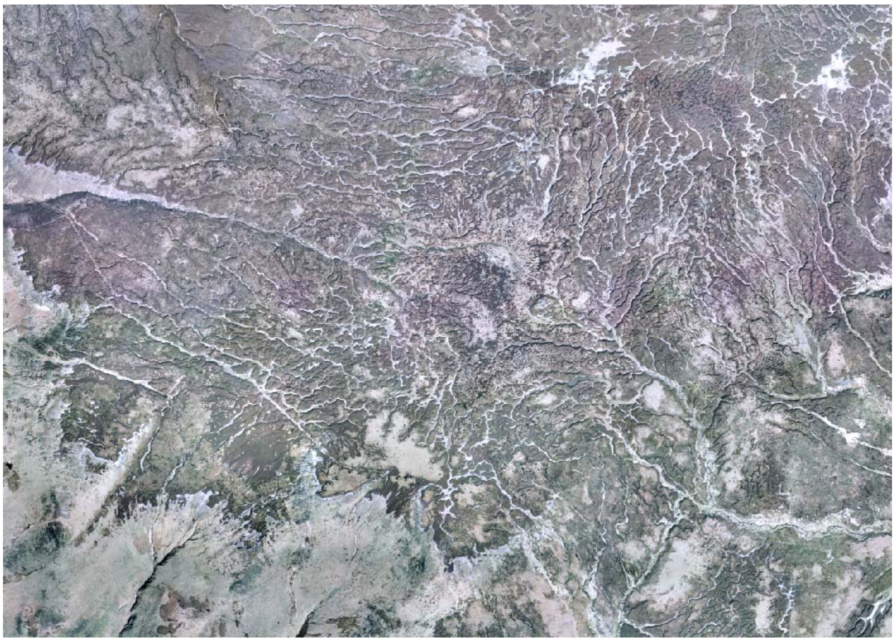


Figure 4.6 Air photos of gullying: a) area with very few gullies, b) area with dense gully networks (imagery by UKPerspective)

The first major challenge was to develop a method by which gullies may be identified over the large area of study. In search of such a method a number of different approaches were considered:

4.3.3.1 Automated process using an algorithm

The development of an automated process in which gullies can be identified based on a number of criteria is possible in theory and is an obvious choice. For example, an algorithm that searches across the DTM for breaks of slope (one of the most defining features of a gully), in addition to other features, could be written. However, in reality the method would i) be extremely time consuming to develop from scratch and ii) requires set criteria values. There are insufficiently clear and definable criteria from which to identify the gullies and hence we could not justify this form of development of an automated process.

4.3.3.2 Multiple Criteria Evaluation (MCE)

MCE is very similar to generating an automated process. It highlights potential areas of gullies. However, it does not involve generating a unique algorithm as above. MCE theory can be defined as "investigating a number of choice possibilities in the light of multiple criteria and conflicting objectives" (Voogd, 1983). The process involves generating a series of layers that are defined on specific criteria; these are standardised and multiplied to produce an output that underscores only areas that meet all criteria. Weights can also be attached to the layers in relation to their relative influence on the decision. The MCE method is predominantly applied to decision-making processes in the environmental sciences such as land suitability mapping, highway routing and nuclear waste disposal site location. In this respect it could be developed for the current project objectives. It would require a set of specific criteria (minimum of three) with a spatial context.

When applied to the current problem of trying to identify gullies, the most reliable use of an MCE process is as follows:

- **Buffers** - Rather than the entire study area, a more realistic space on which to apply the MCE process can be defined by buffering around a very high-density drainage network (generated in ArcMap or DiGem). This is advisable since the nature of this natural landscape results in a number of steep devegetated slopes outside of gully zones; much of this is avoided with the newly defined workspace.
- **Map Transfer** - The resulting map cannot be directly transferred for gully infilling since the criteria are not sufficiently rigid (i.e. there are no reliable threshold values for the criteria). Instead, it should be used as a basis that narrows down the search for gullies; its significance is to eradicate areas that do not fill the criteria and therefore simplify the process of identifying and manually digitising gullies.
- **Gully Definition** - From accepted definitions of an active 'gully' and the current project objectives the most important gully characteristics appear to be slope (gullies are channels with steep side slopes), limited or ephemeral flow (very different flow conditions to streams), and devegetated conditions (flow, whether ephemeral or permanent, is sufficient to strip natural vegetation and halt regrowth). An MCE could therefore include:
    - **A reclassified slope map** - the threshold slope of interest (i.e. one that relates to gullies) could be identified though a calibration process in which a number of sites that clearly represent potential problem gullies are identified on aerial photographs. Slope values can then be identified from an overlaid slope map (generated and reclassified from a DTM). From these samples a threshold value is taken from the low end of values (to ensure small, but still important gullies are not overlooked; the aim is to eradicate slopes that are clearly not gully locations).

- **NDVI map for identifying of areas of limited vegetation** - A map of Normalised Difference Vegetation Index (NDVI) could be generated which uses an algorithm based on light wavelengths to indicate type of vegetation cover by identifying the density of green leaves. The threshold value could again be taken from samples found during a simple calibration process as above.
- **Removal of streams** - To ensure that only gullies are being highlighted streams can be removed by defining a threshold flow accumulation for streams and removing these areas from the potential output. Values for stream heads (to be reclassified) can be found through a similar calibration process again involving the identification of flow accumulation at stream heads using a flow accumulation map and aerial photographs.

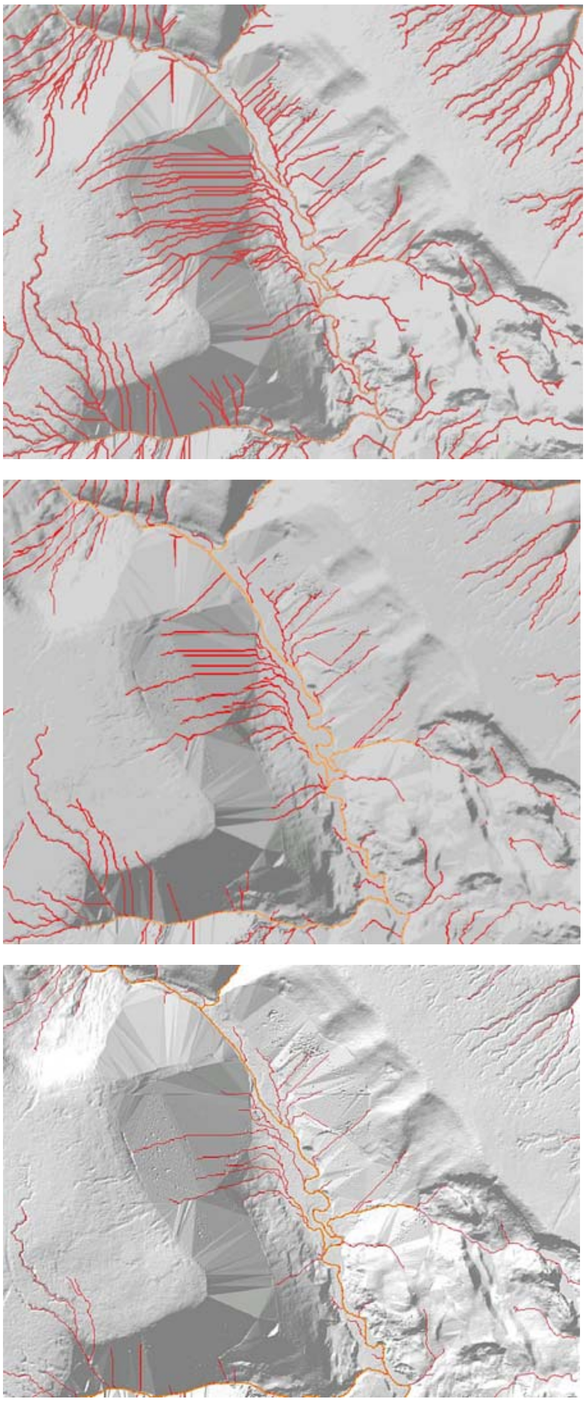
In theory this process provides an enhanced scientific rigour to the identification of gullies since it is based on defined criteria in addition to value judgements of those individuals digitising the gullies. However, there are some limitations to this process which inhibit its use:

- **NDVI calculation** - To calculate the NDVI requires not only data on the distinct wavelength of visible light but also near-infrared sunlight (that is absorbed and reflected by plants), which are available only from satellite data and not LiDAR data alone. Another reliable method of classifying gully vegetation cannot be found within the current project framework (due to data availability and time).
- **Criteria** - At least three layers must be applied for any credible use of an MCE method. However, there are fundamental difficulties in finding specific criteria that can be applied to the definition of gullies. On the ground, gullies of concern may be easy to identify by the experienced eye. From those criteria that can be specified from the field, however, they may appear to have very different characteristics yet still cause concern. For example, values of flow accumulation, slope and vegetation as defined above may in fact differ remarkably between gullies.

4.3.3.3 Manual digitising

By considering the limitations associated with the above methods, and the project framework and specifications, the best method to ensure gullies of interest are actually identified and removed is described below. The method predominantly involves manual digitisation of the gullies. However, it does take some elements from the MCE method into account.

Generation of a drainage network - A drainage network is developed using ArcInfo based on the single flow algorithm (FRho and other 8-flow direction algorithms have difficulty computing over such a wide area). Through a process of trial and error a threshold value of flow accumulation for the network was found which covered most gullies by minimising error. Error will develop for a number of reasons in such drainage networks (e.g. a single-flow algorithm often results in streaky lines of flow since all flow in one pixel must flow to the pixel of steepest descent rather than being proportionally divided between all surrounding 8 pixels). The flow accumulation thresholds do not represent reality unless they are calibrated to do so; hence trial and error methods are used to meet gully flow. Figure 4.7 shows three threshold values; the threshold value over 3000 reduces the proportion of artificial network generated.



DN > 1000

DN > 2000

DN > 3000

Figure 4.7 Flow accumulation thresholds for small part of the study area (DN: drainage network threshold). The bigger the threshold value the smaller the proportion of artificially created drainage network.

Generation of a stream network - A stream network has been generated so that only actual streams are highlighted. This is preferable to the drainage network which identifies pathways of flow accumulation and therefore has no realistic stream threshold. The threshold flow accumulation value for streams was found using the method described in the MCE section above. A basic calibration process was applied in which flow accumulation values were found for a series of different stream heads identified on the available aerial photographs; samples cover a range of streams throughout the study area. The values for stream heads are concentrated between 6,000 and 10,000. It was found that gullies were best mapped between 30, 000 and 3,000; anything with a flow of above 30,000 was deemed to be a stream. Anything below 3,000 was either a gully with low flow or an error. Hence the 3,000 threshold was chosen to reduce the number of errors. Any gullies with flow under 3,000 were digitised by hand.

Digitising gullies - It was not realistically feasible in the time available to manually digitise every gully across the entire study area. Instead the stream network was removed from the drainage network to create a gully network layer; this should, by subtraction, identify only gullied areas. To remove much of the error flow, the drainage network flow accumulation threshold was increased; this unfortunately resulted in some gullies not being picked out by the drainage network. As such, another vector layer was added and those tops of gullies not highlighted by the drainage network (visible on the aerial photographs) were manually digitised. This layer was then also added to the new gully network layer. In this way much of the time spent digitising gullies was saved, thus allowing more efficient use of resources. At the same time the entire area was carefully checked and compared with aerial photographs to ensure accuracy in the method.

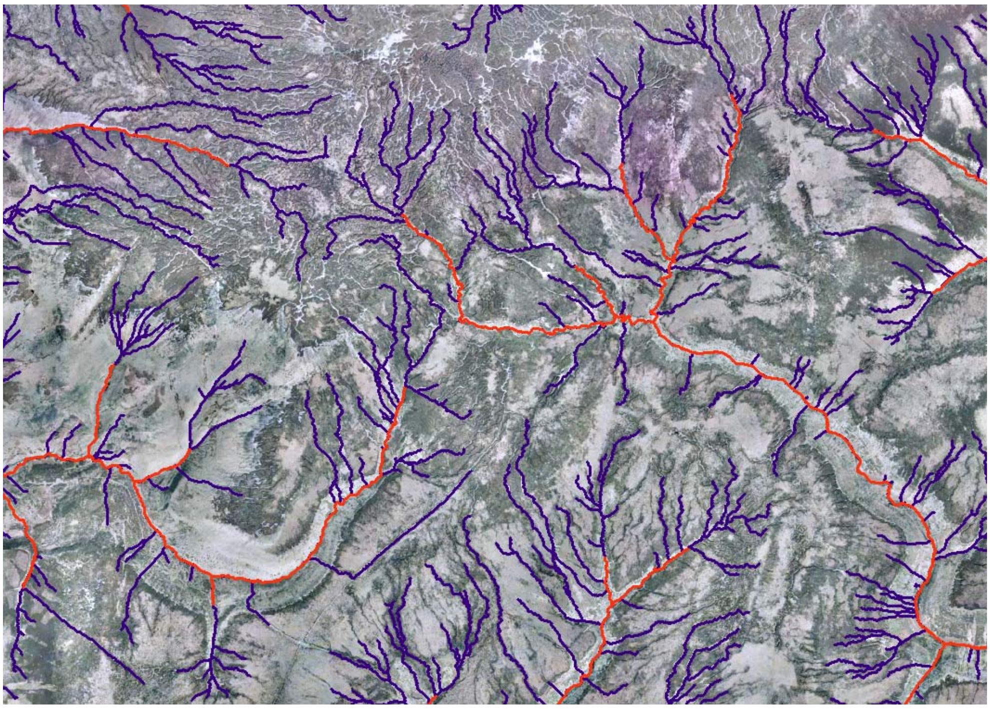


Figure 4.8 Gully and stream network (purple – gullies, red – streams) (imagery by UKPerspective)

Figure 4.8 shows how the stream network (red line) has been overlaid onto the drainage network (purple line). The purple lines are taken to represent gullies. The example area shown here represents one of the more gullied sections of the study area. Closer inspection shows a dense network of branching gullies at the top of Figure 4.8 that are not picked out by the drainage network. These are shown more clearly in Figure 4.9. These gullies were manually digitised onto a separate layer and later added to those gullies already highlighted using simple ArcMap functions.

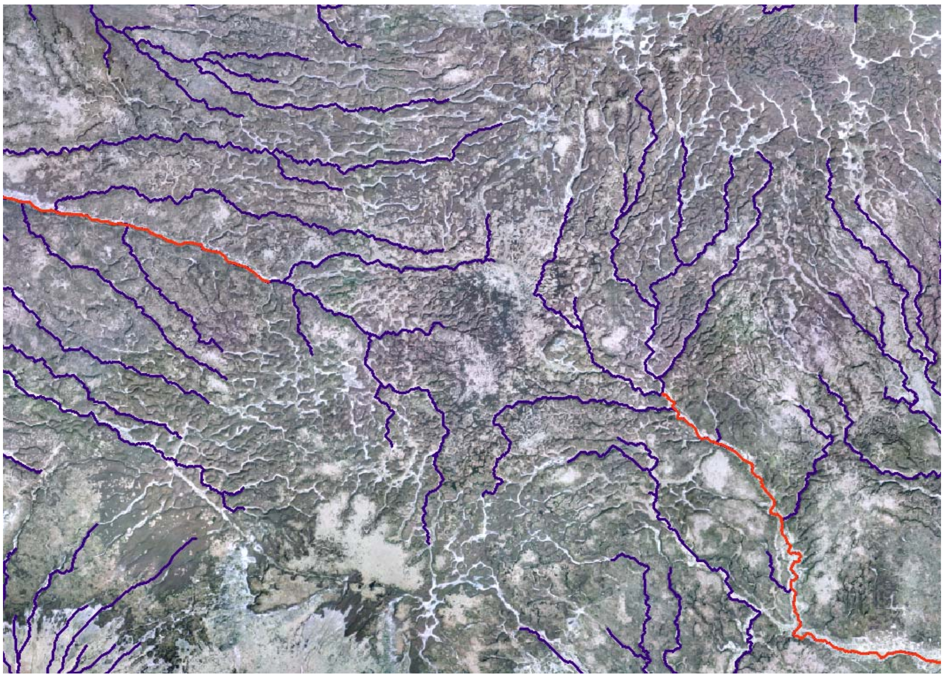


Figure 4.9 Close up of the northern portion of Figure 4.8 where it was necessary to manually digitise gullies. These were then added as another layer at a later stage. (imagery by UKPerspective)

4.3.4 Simulation of gully infilling

A process was required in which gullies could be 'filled' within GIS software. A function was required in which it would not be necessary to write a specific algorithm and where limited information would be required about the individual gullies to be filled (the vast number of gullies means they must be filled in bulk rather than individually). The only real way to do this is to remove the values and interpolate over them. A function for such purposes can be found in ENVI software (primarily used for remote sensing purposes). The exact method is as follows:

- Convert the Arc vector layer with the digitised gullies into a raster file
- Use Arc command line to specify all areas of 'no data' to a value of 1 (use the 'con' function), gully areas now having a value of 0
- Multiply raster gully layer with the DTM to create a new DTM
- Convert gullied DTM to ascii file in Arc Toolbox
- Import external ascii file to ENVI, save as ENVI standard file
- Use ENVI 'replace bad values' topographic function; replacing and interpolating over all values of 0
- Export as a new ascii file. Open in wordpad, remove header information and replace with header information from the original (non-interpolated) ascii file
- Convert the new ascii to raster grid in Arc Toolbox, topographic index can now be applied to the new DTM without gullies

A small example area is given in Figure 4.10. This image shows the DTM once gullies have been digitised, set to raster, given values of 0 and then multiplied by the original DTM. After the gully areas (shown in black with values of 0) have been interpolated over in ENVI, the resulting DTM will look as shown in Figure 4.1. It is very similar to the original DTM (despite the slightly different colour bands), but the gully values have been removed.

Figure 4.10 DTM with digitised gullies shown in black for a small part of the study area

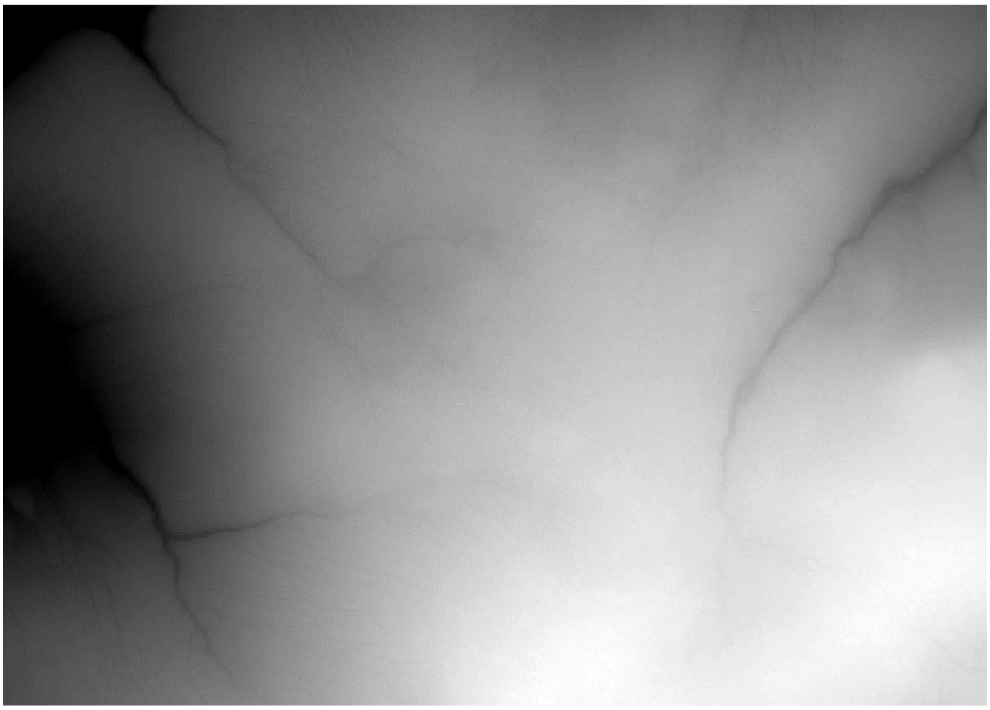


Figure 4.11 Resulting DTM after gullies have been interpolated over in ENVI, as shown for part of the study area in Figure 4.10

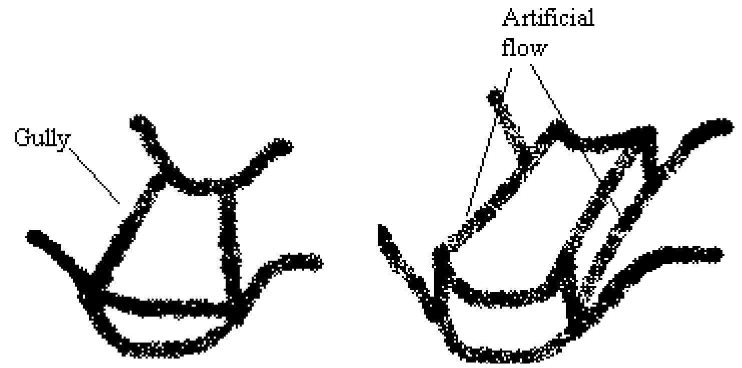
4.3.4.1 Partial infilling of gullies

This project concentrates on comparing the relative significance of various gullies on surrounding hill slope flow conditions. Therefore by entirely filling various gullies, the degree to which they are 'active' and their significance on surrounding saturation conditions can be assessed. This provides information on which gullies to target for blocking in the field. However, in reality the gullies may not be entirely filled over short timescales; sediment will slowly accumulate over the years following blockage. For this reason Moors for the Future have requested that it would be informative to partially infill gullies and re-calculate the topographic index and flow accumulation maps to assess whether this alters the resulting significance of individual gullies.

4.3.4.2 Method

A method was required that would represent reality as much as possible, would create a useful output for decision making processes and was feasible for GIS software functions. The chosen method of infilling gullies involves buffering polylines digitised to represent the gullies. This buffering process allows the gully, and the area around the gully, to be removed and then interpolated from surrounding height values. This buffering technique also provides a useful opportunity to fill the gullies to different extents. A wider buffer zone will remove more of the gully, filling the gully to a great degree, whereas a narrow buffer zone will only partially fill the gully, and the topographic indent of the gully will remain. A major advantage of this process is that it does not allow the introduction of artificial flow as in other methods. The only major limitation is the inability to specify the exact amount that gullies are being filled by. Instead it gives a relative indication of the impact of partial blocking.

Another method is possible in which the area that has been buffered (the gully floor) can be raised by a set amount that may represent reality a little better (e.g. 30-50 cm). However, this will cause a number of problems. Firstly, it requires knowledge of the size of the smallest gully to avoid raising the gully to the point where a mound is created. Secondly, such a method would create artificial flow conditions (see Figure 4.12). By lifting the base of the gully, the edges of the new gully floor would sit higher than its surroundings and a ridge and furrow would be created. Water will be channelled into the furrows on either side of the new gully floor (Figure 4.12). The advantage of using a specific value/percentage is also lost when gullies cannot be filled on an individual gully-by-gully basis (this requires gully depth). The influence of setting a specific value will depend on the size of the gully in question. If we are arguing that the influence of partial filling is important since over the next ten years, for example, gullies will not be entirely filled, we then also need to consider that gullies of different size will fill at different rates.



a) Gully before filling

b) Gully after being raised by a set value. Artificial flow is created at the boundaries.

Figure 4.12 a,b Schematic diagram of artificial flow creation when raising the gully floor. Hence a polyline buffering method has been adopted which will be more representative of reality.

In view of the above, the method in which gullies are buffered to different extents represents the simplest method. The degree to which gullies should be buffered is flexible. For example, the most appropriate amounts appear to be 1 m, 5 m and 10 m. However, greater and lesser extents of buffering can also be provided and analysed depending on the outcome.

4.3.5 Recalculation of topographic index, flow accumulation and subtraction maps

This involved comparing the original topographic index or flow accumulation map to the new maps produced after gully infilling has been performed. Each type of gully infilling (or buffering; 1 m, 5 m etc) can be followed by a production of the topographic index or flow accumulation for comparison. The new maps can be subtracted from the original and then spatially it is possible to see which areas suffer the biggest changes in hill slope topographic index as a result of gully infilling. Careful choice of colour classification must be used here in order to make the changes clear.

4.3.6 Complete procedure

A detailed presentation of the procedure performed in GIS software is given in Appendix IV. This breakdown of steps/instructions used to produce the maps may be beneficial for practitioners to be able to run through the procedure on these data or any other data.

4.4 Results & Analysis

4.4.1 Output files

An extensive series of GIS data files were produced during the course of this research. These include:

Before the removal of gullies

- Merged DTM
- Merged aerial photograph
- Topographic Index
- Slope map
- Drainage network
- Stream network
- Flow accumulation map

Following gully interpolation

- Map showing location of gullies
- Topographic index maps of change
- Flow accumulation maps of change

Important file or data layer names and information is presented in Appendix IV-2 including some information about colour classification used in the final maps which show the likely impacts of gully blocking and which are described in the following sections.

4.4.2 Final maps- description, analysis and examples

Maps of change in flow accumulation and topographic index have been produced for the entire 133 km^2 study area. These are easy to navigate in ArcMap. An example of part of the final maps produced is shown in Figure 4.13. This illustrates the change in flow accumulation when gullies are blocked. The gullies are shown in black on the figure. Blue lines running from the gulling indicate that the flow accumulation in the stream has been reduced because of the blocking. Thus water has been allowed to spread out across the hill slope which is an important goal of gully blocking and will allow peat growth. However, gullies where there are lots of red and orange lines emerging following blocking indicate that flow would be redirected such that it does not spread out across the hill slope. Instead the flow follows a new concentrated flowpath and flows into the stream. These are cases where flow may cause surface erosion and further gully development and in some examples flow is redirected into the head of other gullies which may cause them to extend (e.g. Figure 4.14). In other cases there are no blue or red lines emerging from the blocked gully (e.g. Figure 4.15). This suggests that there would be little benefit to the streamflow or to the hill slope if it were to be blocked and it is likely that the gully is inactive.

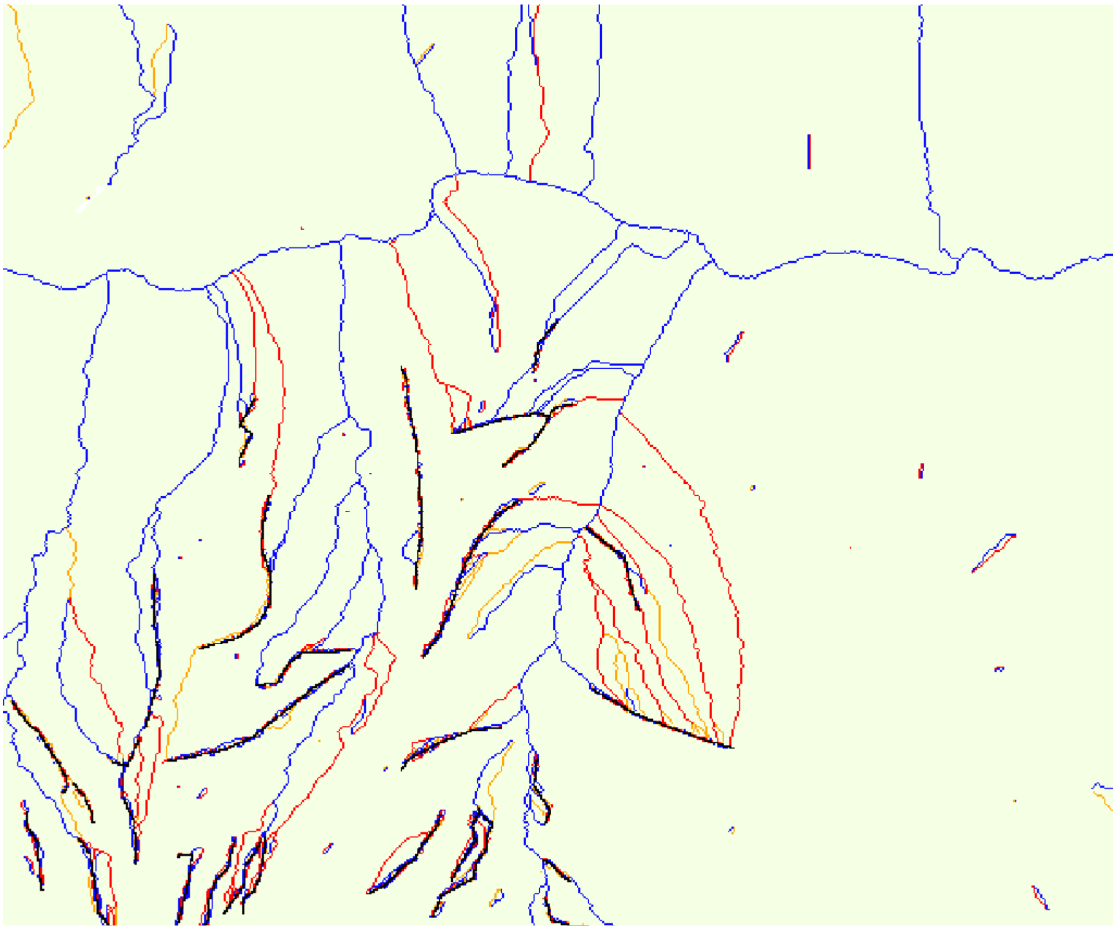
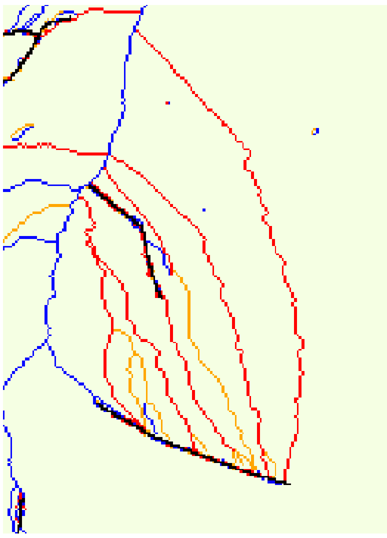


Figure 4.13 The impact of gully blocking on flow accumulation. The figure is a map of the natural flow accumulation as it occurs on part of Bleaklow today minus the flow accumulation once gullies have been blocked. It is therefore a map of change. Change is indicated by blue which suggests that flow through the drainage network is decreased by gully blocking and red which suggests that flow is increased along concentrated flow paths due to blocking. Thus gullies followed by red should not be blocked and gullies followed by mainly blue should be blocked.



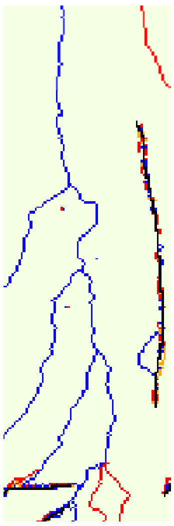


Figure 4.14 (left) A gully where blocking would have detrimental consequences (from part of Figure 4.13). Slope is from the bottom of the figure to the top. One of the red lines even indicates that flow would be redirected into the head of gully (black) near the top of the screen which would be detrimental to that gully.

Figure 4.15 (right) A gully (black) which has no major blue or red lines flowing from it. Thus this gully would have a very limited impact on hillslope resaturation or streamflows if it were to be blocked.

The additional benefit of the maps we have produced is that they allow not only decisions to be made about individual gullies but also whole areas of gullies. Following discussion with the project partners at Moors for the Future and the University of Manchester it was decided that this would be an appropriate management decision-aiding tool. Thus if it was decided that an area should be targeted for blocking rather than whole gullies, then by clicking on the blue flow accumulation change lines on the map, values of change are provided. It is therefore possible to click on the outlet of a small gullied catchment area and determine the predicted change in flow accumulation. This can then be compared to changes that may occur in another area if whole areas were targeted for blocking (Figure 4.16). Because it is a map of cumulative change the actual values only change at a junction of the coloured lines. Hence if a flow route meets no other ‘changes’ along its course then the values along that route will remain the same. In order to ensure that comparisons are fair between areas it is recommended that values are divided by the catchment area draining to that point. That will allow determination of the relative merits of blocking one gullied area to another. Nevertheless decisions could still be made without recourse to catchment area calculations if it was decided that an area which has the maximum impact on overall streamflow should be blocked.

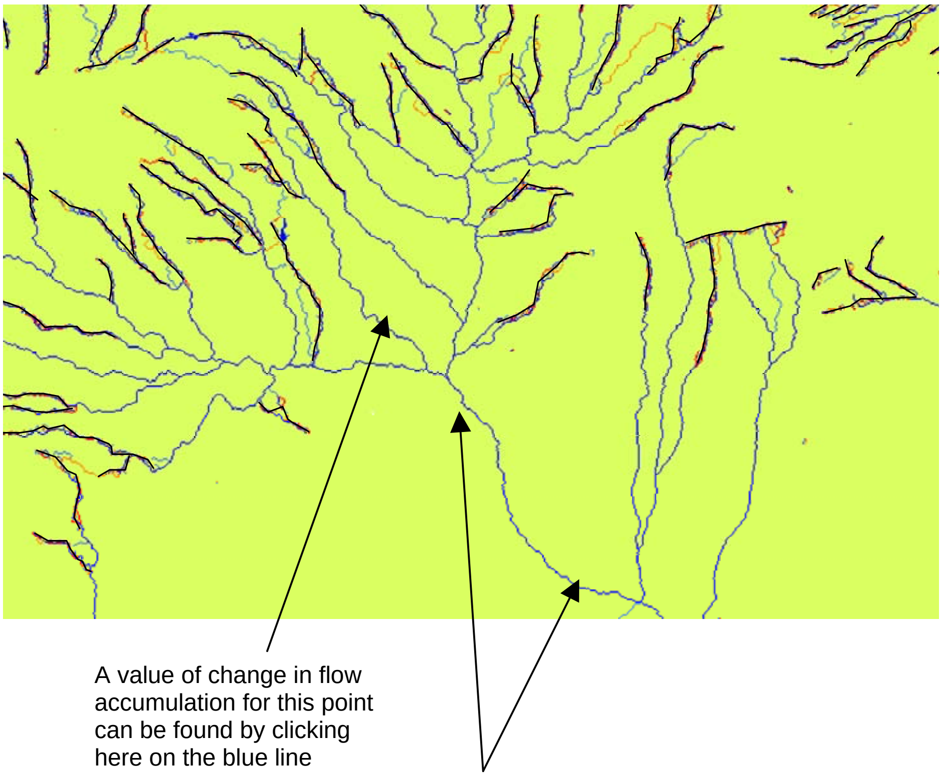


Figure 4.16 Another example of a flow accumulation change map. By clicking on the lines the relative values of flow accumulation change can be determined.

4.4.3 General Comments

When using the maps for the study area, the x-y co-ordinates are provided in ArcMap as the cursor is moved around. Additionally, the air photos can be easily underlain to provide additional layered information to guide the viewer about the on the ground location of the map area they are viewing on screen.

The main outcome of the processes highlighted above is a map of change in flow accumulation following gully filling for a 133 km^2 area of the Peak District. The map of change in topographic index has also been produced and this provides additional information. However, the topographic index map is in a form which is almost identical to that of the flow accumulation maps and it was decided that in order to avoid confusion just the flow accumulation maps would be presented above and we recommend that these are used as a basis for decision-making.

From the maps of change, the influence of blocking individual gullies on the surrounding levels of saturation can be assessed. It can sometimes be difficult to pinpoint the influence of individual gullies in those areas of very dense gully networks. Nevertheless the maps we have produced perform well in such circumstances. However, in these areas it may be decided that it is better to assess the significance of the entire regions of gullies by using the flow accumulation information.

Chapter 3 identified slope as an important factor in any gully blocking strategy. It is possible using GIS software to highlight those areas with slopes within any specified range. This can then be added as another layer to the maps presented in this present chapter allowing the viewer to focus only on areas where the slopes will allow feasible blocking success to be entertained. The aerial photograph, slope map, flow accumulation, drainage network and shaded DTM are useful additions to analysing the influence of gully blocking to put each place and its characteristics in context rather than simply basing all decisions on digital data alone.

A number of decisions are involved in the gully blocking process for the area under consideration. The most important of these is which gully to block and which method to use, with the aim of ensuring that the chosen method has the desired effect in as many places as possible. Chapters 2 and 3 have involved a temporal approach to gully blocking, examining change over time in naturally revegetating and blocked systems. It should be noted that our approach in this Chapter has not included a temporal factor. Instead it defines a generic ‘importance’ to the gully, based on the flow characteristics derived from the local topography. It therefore simplifies the definition of the gully, rather than complicating it with the transient nature of gully, which would require a complex analysis that involves the meteorological conditions of the site (i.e. degree and type of rainfall control, whether the gully is ephemeral etc). Instead, the relative amount of flow that the gully can accumulate and the influence this has on local saturation has been derived. This is given by the topographic index and the flow accumulation maps. By utilising this information on the flow size of the gully in context of its topographic surroundings, decisions over the most effective blocking methods will be better placed.

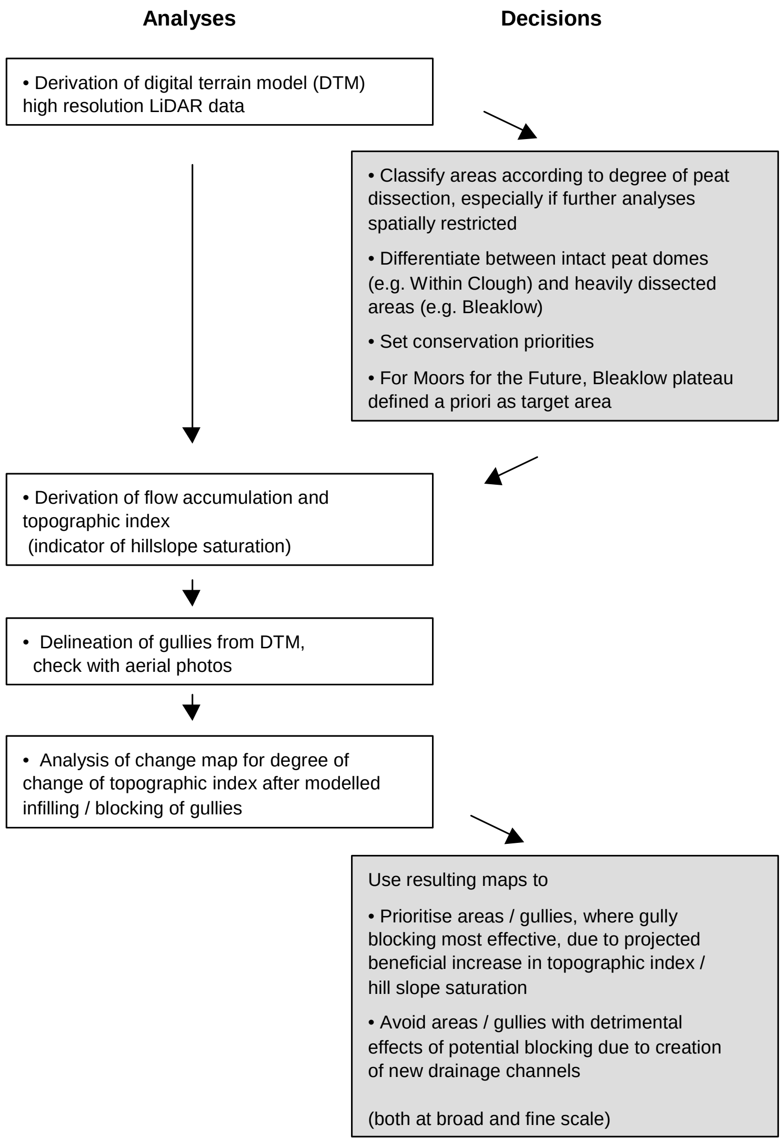
The tool we have developed is entirely novel and is a major scientific step forward in environmental modelling with implications for a wide range of environments far beyond the Peak District National Park.

5 CONCLUSIONS & RECOMMENDATIONS

Results from the three projects provide evidence based guidance and advice for gully blocking in deep peat. This will allow the Moors for the Future Partnership to efficiently target strategic restoration sites in the Peak District by making informed planning choices based on the spatially explicit flow accumulation maps provided by project III, to allow for maximum beneficial change to hill slope saturation. Advice and explicit recommendations from project I and project II will guide the choice of suitable locations and techniques within these areas to effectively place gully blocks. As gullies on the Bleaklow plateau resemble largely wide, shallow Type B gullies, novel techniques for promoting sediment accumulation may need to be trialled, as suggested by project II following observations of natural re-vegetated gullies. Practical advice regarding financial implications, technical implementation of works as well as maintenance issues collated in project I, will greatly aid planning of the restoration works.

To accomplish the planned gully blocking works the following flow charts visualise the recommended decision and action process for the Moors for the Future Partnership.

5.1 Choice of most effective gully blocking sites



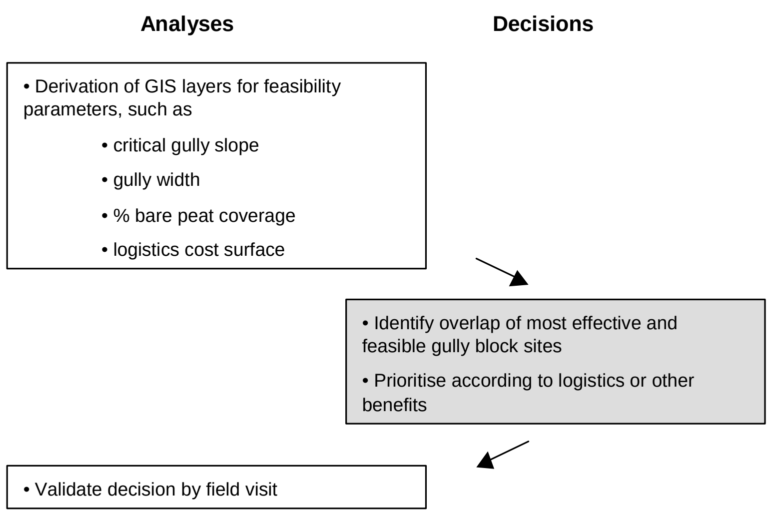
For conservation activities with tight budgets the described decision making process above may seem expensive and time consuming. Flight dates for LiDAR imagery capture need to be booked 4-8 months in advance and imagery can be expensive. Subsequent professional data analyses will add further cost and time resources. However, set against the fact, that gully blocking in deep peat on remote moorlands will always be very expensive (e.g. helicopter at £6000/d), an expenditure of 10-15% of the total costs for careful planning to ensure maximum benefit may well be justified and cost effective.

For small areas, the delineation of gully networks may also be feasible by manual digitisation of aerial photos or by ground surveys with geopositioning systems (GPS). However, any further derivation of topographical variables such as e.g. slope, gully depth, width in the field would be labour intensive. However, for the 133 km^2 area of LiDAR coverage, such geomorphological data can be easily obtained from the digital terrain model (DTM). At a large scale and indeed for any automated calculation of complex topographic parameters, such as gradient diversity (Haycock 2003), a high resolution DTM is essential. More important, local topography allows the derivation of valuable hydrological parameters. Important parameters such as topographic index, flow accumulation and area of drainage can be derived from the DTM and can indicate the contribution of gullies to the drainage network. These parameters aid prioritising target moorland areas for gully blocking at a landscape scale (see also Haycock 2003).

At a medium spatial scale, the developed GIS tool, modelling the effects of gully blocking, helps to assess maximum beneficial and potential detrimental effects of choice of gullies to block. Although the novel GIS tool remains to be tested on the ground, these assessments cannot be achieved in the field and may be crucial for ensuring effectiveness of the works. In practice, the developed maps of change (e.g. Fig 4.13) can now be used by the Moors for the Future Partnership to identify areas of gullies and individual gullies with highest influence on surrounding levels of saturation (for more detail see section 4.4.2, 4.4.3). (N.B. the presented analyses are not exhaustive of the analytical use of LiDAR data). In order to test some of the GIS model predictions, it is suggested to assess the existing National Trust gully block sites using the provided maps.

In general, these steps help in the decision making process to prioritise which areas of gullies / individual gullies to block at a large landscape scale and medium gully scale. Therefore, they are vital to maximise efficiency of works and expenditure.

5.2 Choice of feasible gully block sites



Following the choice of effective areas of gullies to block, it is necessary to focus on those gullies where gully blocking will be feasible, both at a medium gully scale and a fine tuned individual blockage scale. Clear recommendations for feasible block sites are provided in section 3.5.3 and summarised into brief guidance notes in section 3.5.4. Another important parameter may be logistics, if costs or health and safety issues will not permit appropriate work completion.

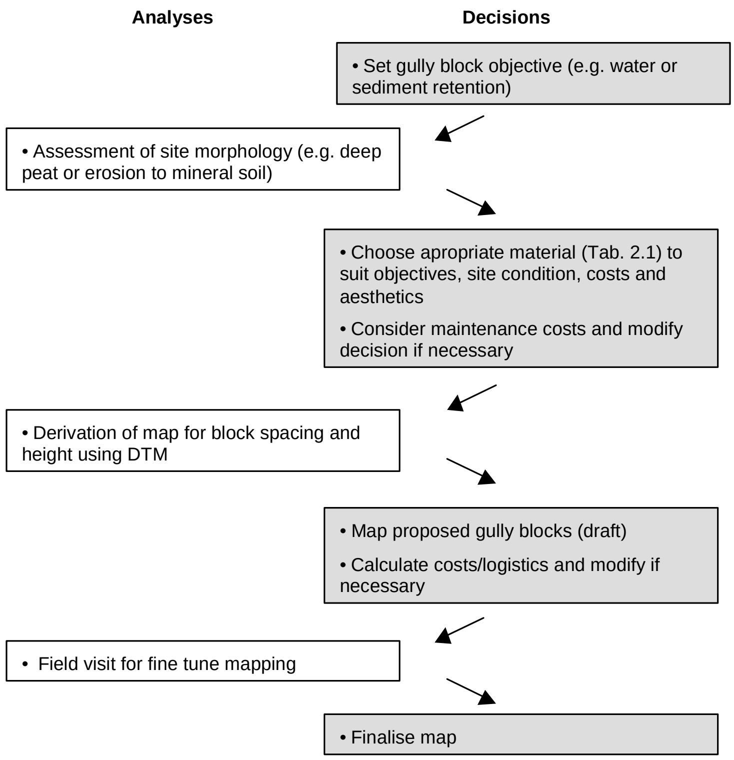
In practice, it is advised for the Moors for the Future Partnership to derive GIS layers from the LiDAR DTM, aerial photos and OS maps for parameters such as:

- critical gully slope (< 6°)
- gully widths (≤ 4m)
- headwaters (<130m from gully head)
- areas of bare peat (greatest sediment supply)
- cost surfaces, e.g. approximate cost of transport of materials and labour by distance to roads

These GIS layers can then be overlaid on the flow accumulation change maps and identify effective and feasible gullies to block. A subsequent field visit should validate these decisions.

In addition, experimental approaches should be developed on Bleaklow for wider, deeper type B gullies by potentially using low baffles to encourage reduction in stream power, local sediment deposition and initiation of re-vegetation (see 3.5.3.7).

5.3. Choice of appropriate gully block types & installation



Depending on objectives of gully blocking (e.g. sediment or water retention) as well as site attributes, different materials will be favoured (see Table 2.1, section 3.5.4.1). For the Bleaklow plateau the prevention of sediment loss will most likely be the first priority in order to stop further loss of habitat and to reduce turbidity. However, in order to ensure long-term restoration of the functioning of the blanket bog ecosystem and to reduce water discolouration, the water table needs to be restored and peat saturation increased.

As a result of this study, wooden fencing, stone walls and plastic piling are all effective. It should be noted that while wooden and stone blocks are water permeable and therefore seem to encourage faster sediment accumulation, the creation of pools using plastic piling may lead to different microhabitat characteristics. The different habitat characteristics may be desirable from an ecological perspective potentially enriching invertebrate biodiversity.

Depending on material cost and weight, labour intensity, logistics and projected maintenance requirements (Table 2.2), the resulting costs may also determine choice of material. Aesthetics will especially be important in areas of high recreation access.

The design for block heights and spacing can be derived using the high resolution DTM (see Figure 2.1, 2.2 and sections 3.5.3, 3.5.4). Draft maps will then need to be fine tuned in the field. Close supervision in the field during block installation will need to ensure most efficient gully blocking on the sites.

5.4 Monitoring

Monitoring programmes of the existing National Trust gully block sites as well as any new sites will be crucial to further assess the success of the gully blocking techniques with regards to water and sediment retention. Monitoring will be necessary to evaluate the newly developed decision tools for strategic and suitable gully block locations. The employed monitoring protocols used in this study are listed in section 3.3.2.1 and Appendix I. Recommendations for further monitoring are provided in section 3.5.5 and Appendix II. Possibly, a modified monitoring protocol will need to be devised for the suggested experimental blocking of Type B gullies with baffles.

Next to the developed rapid assessment monitoring programmes, monitoring of peat hydrology before and after implementation will be necessary to assess the developed GIS tool, as well as to test the effectiveness of techniques in long-term water retention, and therefore raising of the water table (see also other research, section 7).

In conclusion, we hope the decision tools and advice developed in this research collaboration will not only form an invaluable basis for the Moors for the Future Partnership restoration works but also for further moorland restoration projects on deep peat elsewhere in the world.

6 DATA AVAILABILITY & COPYRIGHT

Data and files are available from the Moors for the Future Partnership for non-commercial research. This includes

- Photo library of naturally re-vegetated gully sites
- Photo library of National Trust gully block sites
- Rapid assessment monitoring protocol for hand held computer in FastMap, and monitoring records by project I and II
- GIS maps derived by project III (see 4.4.1)

Copyright of data and the GIS tools remains with the authors and the Moors for the Future Partnership. Research on the existing and future gully blocks is greatly encouraged. Please contact the Moors for the Future Partnership.

7 ASSOCIATED RESEARCH PROJECTS

Gully blocking in deep peat, as distinct from blocking of artificial drainage ditches within peatlands, is an approach to moorland restoration and erosion control that has only very recently been contemplated. Further research projects on erosion and gully blocking in deep peat and associate research include:

- The effects of gully blocking as an erosion control measure
  Sarah Crowe, Martin Evans, Tim Allott, Manchester University, in collaboration with the National Trust
- Discolouration of water supplies in the Peak District; the effect of moorland management
  Helen O´Brien, Jill Labadz, Nottingham Trent University in collaboration with the National Trust and Severn Trent Water
- Pattern analysis to assess connectivity of sediment systems and predict sediment flux in eroding blanket peat catchments
  Laura Liddaman, Julia McMorrow, Manchester University
- Uncertainty in channel networks derived from LIDAR DTMs
  John Lindsay, Manchester University
- Sediment budgets of upland blanket peat
  Martin Evans, Jeff Warburton, Manchester University and University of Durham
- Modelling sediment flux from eroding blanket peat in the southern Pennines
  Juan Yang, Martin Evans, Manchester University
- Hydrological, fine sediment and water colour response of managed upland wetlands
  Joseph Holden, Leeds University
- Heavy metal storage and flux in eroded peat catchments of the Peak District
  James Rothwell, Tim Allott, Martin Evans, Manchester University
- Hyperspectral remote sensing of blanket peat moorlands
  Julia McMorrow, Martin Evans, Amer Al-Roichdi, Manchester University and University of Dundee.

Links

http://www.sed.manchester.ac.uk/geography/research/uperu/projects.htm
http://www.sed.manchester.ac.uk/geography/research/uperu/fieldwork.htm
http://www.geog.leeds.ac.uk/people/j.holden/researchinfo.html

Related Moors for the Future Partnership small research grants

- An assessment of changes in moorland erosion and sediment delivery following gully blocking on upland blanket peat
  Helen O'Brien, Jill Labadz, Nottingham Trent University (2004)
- Mapping and encoding the spatial pattern of peat erosion
  Julia McMorrow, John Lindsay, Manchester University (2005)
- Carbon flux from eroding peatlands in the Peak District
  Martin Evans, Manchester University (2005)
- Suspended sediments in High Peak moorland streams: status, ecological effects and indices of sustainable erosion
  Tim Allott, Manchester University (2005)
- An investigation of the impact of prescribed moorland burning in the Derwent catchment upon Discolouration of Surface Waters
  Jill Labadz, Nottingham Trent University (2005)
- Flux of heavy metal pollution from eroding Pennine peatlands
  James Rothwell, Martin Evans, Manchester University (2004)

Please note this list is far from exclusive. We would be grateful to hear from any other projects.

8 ACKNOWLEDGEMENTS

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The PDNPA ranger team and Moors for the Future Partnership research team assisted fieldwork for project I. The fieldwork for project II was carried out by PhD students in the Upland Environments Research Unit, Sarah Crowe and Laura Liddaman. Their hard work in a range of weather conditions is gratefully acknowledged. The intensive data manipulation for project III was mainly conducted by Gemma Hobson and Bryan Irvine. Their thorough approach to the GIS analysis was key to the success of the research. Andrew Jones assisted in map production and report editing.

The Moors for the Future Partnership would like to thank Martin Evans, Tim Allott and Joseph Holden for their strategic research, their advice and active project development such as hypotheses building regarding gully types and the development of novel techniques such as partial gully infilling. We are also grateful for their excellent communication of results to our partners.

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APPENDIX