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Windermere Catchment Restoration Programme

Environment Agency

Windermere Fluvial Audit

Report A - Catchment Scale Geomorphology - Technical Report

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Executive Summary

Windermere has been identified as having a water quality issue with regard to Phosphorus. One potential pathway for Phosphorus to reach the lake is via the stream network, particularly in the suspended sediment load. The catchment draining into Windermere functions as a potential source, pathway and store of fine sediment. This Fluvial Audit comprises a catchment scale geomorphological assessment of the fine sediment system (Report A - this report), and provides management advice for reducing fine sediment delivery to Windermere (Report B - Action Plan). The study area, defined by the Environment Agency, includes 76km of the key tributaries feeding Windermere. The major rivers surveyed include the Brathay, Rothay, Trout Beck, Cunsey Beck and Great Langdale Beck.

Relatively little fine sediment sourcing was observed during the Fluvial Audit. A number of the steeper upland tributaries were naturally sourcing coarse sediment. It should be noted that the Audit, as defined by the study area, did not cover the headwaters of most rivers, which limited the number of sources recorded. Although many rivers were surveyed at moderate to high flow, little turbidity was observed, and this provides evidence that fine sediment delivery is currently low, as after a number of years with higher flows there is now little available for supply within the catchment. Some bank erosion occurred in the middle and lower reaches of rivers where the geology was softer and less resistant to erosion. Bank erosion was not a significant issue at the catchment scale; less than 2% of the bank length was actively eroding. In addition, less than 1% of the total bank length was affected by livestock poaching/ trampling. Of the sediment that was sourced, it is estimated that around 40% was composed of predominantly fine material (<2mm).

Although there were numerous coarse sediment deposits, only 3% of deposits were composed of predominantly fine material. This is a result of many of the rivers surveyed acting as efficient transfers for fine sediment. In the upper and middle sections, bedrock often formed the boundary conditions, leading to stable streams with moderate-steep gradients, promoting sediment transport but little erosion or deposition. Lower reaches were often realigned and walled or channelised, with little opportunity for erosion or deposition within the channel. Fine sediment would be efficiently transferred through these reaches. In addition, in some places floodplain connectivity had been limited due to the presence of embankments or walls, reducing the potential for out of bank events and thus reducing the likelihood that storage of fine sediments would occur on the floodplain.

The modification of many mid-lower reaches in the catchment means the rivers are an efficient system for transfer of fine sediment downstream, which results in the lakes forming the most significant sinks for fine sediment in the catchment. Future management to reduce the rate of fine sediment input to the lakes should therefore include actions which encourage more natural fine sediment storage within the river system, such as river restoration or re-connecting the rivers to the floodplains. It will also be important to promote good land management practices that will reduce the potential for future fine sediment supply at its source.

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1 Introduction

1.1 Background

This study, commissioned by the Environment Agency in September 2008, comprises a catchment scale geomorphological assessment focusing on the main sources and pathways of fine sediment from the wider catchment to Windermere. The outputs are presented in two reports. Report A (this report) records the detailed geomorphology study methodology and findings, and Report B is a 'management tool' style prioritised action plan for key sites.

Windermere has a water quality issue with regard to Phosphorus. One potential pathway to the lake is via the stream network and suspended sediment load. Fine sediment is likely to deliver increased rates of particulate phosphorus into the system, impacting on the nutrient status of the lake and affecting properties such as turbidity/light penetration and oxygen content. The catchment draining into Windermere functions as a potential source, pathway and store of fine sediment. The Environment Agency needed to elucidate the fine sediment system within the catchment, to prioritise actions to control fine sediment delivery within a wider lake restoration programme.

The study area, defined by the Environment Agency, is the Windermere catchment, with priority given to just under 80km of key tributaries feeding Windermere. The major rivers surveyed include the Brathay, Rothay, Trout Beck, Cunsey Beck and Great Langdale Beck. Other smaller watercourses were also surveyed.

1.2 Principles of Fine Sediment Supply and Geomorphology

Fine sediment being transferred to lakes in the Windermere catchment is a potential concern for the Environment Agency for catchment management. Accelerated fine sediment input can cause lakes to infill more rapidly than under natural conditions, and nutrient enrichment can occur through input of particulate phosphorus bound to the fine sediment. Phosphorus is largely transported by rivers as particulate phosphorus, which will be predominantly held in suspension (Owens and Walling, 2002). Owens and Walling (2002) suggest that in rural catchments, topsoil from upland moorland or pasture, and from channel bank material, are likely to be the main sources of particulate phosphorus during high flows. Inputs associated with urban and industrial land uses, such as Sewage Treatment Works, other effluents and dust, are likely to represent the dominant sources of particulate phosphorus under normal or low flow conditions. Floodplain deposition and fine-grained sediment stored in the river channels are suggested to be important sinks for particulate phosphorus.

The storage of particulate phosphorus throughout a river system is thus strongly dependant on river flow/hydrology, and also factors which influence geomorphological processes such as sediment erosion, deposition and remobilisation, and channel-floodplain connectivity. Naden *et al*. (2004) suggest that to consider the downstream impact of suspended solids it is important to assess the in-stream processes further upstream. Rather than simply looking at sediment budgets on an annual time scale, it is important to remember that during a single flood event, sediment waves and routing of water play a significant part within individual river reaches. It has been calculated that during a single flood event, over 50% of the annual suspended sediment load could be transported (and therefore deposited somewhere else). Therefore when surveying a catchment, it should be considered that this is snap shot in time and does not necessarily represent what will happen in a single year or over longer timescales. During a flood event, sediment from the upper part of the catchment can be eroded and moved downstream, while some may be deposited, depending on the carrying capacity of the flow. This deposited sediment may then be moved during a later flood event, resulting in the sediment budget of a reach approximately balancing. There are other controls on fine sediment patterns at a more local scale. Naden *et al.* (2004) also suggest that fine sediment collects in the lee of channel vegetation where velocity is slower. During the autumn months, this sediment is released when the plants begin to die back and flows tend to increase, causing additional pulses of fine sediment.

Current management approaches to fine sediments and diffuse pollution with respect to eutrophication in rural areas has focused on changes at the farm scale. This has included managing potential sources by reducing vulnerability to erosion and looking at the runoff of sediment into the rivers, by the creation of buffer strips and sedimentation ponds to limit fine sediment delivery to the channel. Another widely applied option is fencing of riparian areas, reducing stock trampling and allowing banks to stabilise and reduce nutrient inputs. However, care needs to be taken to ensure re-growth of vegetation does not overly restrict the flow within the channel. There are also wider catchment and land management protocols that could be established to generally reduce fine sediment runoff from land, and more site-specific actions for particular ‘problem’ areas within the river system, such as changing management practices or river restoration. To establish a need for, and to target, such approaches, an analysis of the sediment system is essential, and fluvial audits are a useful geomorphological assessment tool to form to develop a semi-quantitative understanding of the sediment budget. This is an important tool given the lack of detailed sediment monitoring in most UK catchments.

1.3 Aims and Objectives

The overall aim of the project is to assess the degree of fine sediment supply from rivers in the Windermere catchment. The survey will identify ‘problem areas’ and then provide management advice for reducing fine sediment delivery to Windermere. The objectives include:

Report A - Geomorphological Assessment and Catchment Erosion Risk
- To review historic catchment evolution and processes.
- To identify influential catchment processes, management practices and likely key sources of fine sediment supply to Windermere.

- To understand and evaluate the sediment budget (sources, transport, deposition) of the catchment and provide suitable mapping of outputs.
- To evaluate catchment erosion risk through the production of a GIS catchment erosion risk model.

Report B - Catchment Action Plan

- Summarise findings of the technical report in a non-technical manner.
- To provide a detailed catchment action plan, describing methods of land and river management that will help to reduce fine sediment delivery to Windermere.
- Prioritising key areas and detailing specific actions/recommendations, constraints/risks, timescales for improvement and opportunities for wider habitat improvement.

1.4 Method

The approach to the geomorphology study of the Windermere catchment follows a number of stages: desk study, field survey and subsequent data analysis, catchment erosion risk model, technical report and action plan report.

Report A (technical report) is divided into three parts, i) the desk study/catchment characterstics, ii) the field study and data analysis, iii) an erosion risk model (GIS) (Figure 1.1). The study uses Fluvial Audit, a technique described in the Guidebook of Applied Fluvial Geomorphology (Sear et al., 2003) and further refined by BBR (2004). Amendments were made to the original field survey sheets to reflect the data required to more specifically fulfil the aim and objectives of this study. The survey sheets used are included in Appendix A. Report B (Catchment Action Plan) is a non-technical document to inform the wider Windermere Catchment Restoration Programme. Report B is essentially a prioritised action plan which can be implemented but it also i) simply describes methods of land and river management that may help to reduce sediment supply to Windermere, ii) summarises the geomorphological conditions in the Windermere catchment and iii) identifies constraints/risks and opportunities for wider habitat improvement.

For Report A, the desk-based assessment involved an investigation of the physical catchment characteristics and the geomorphological evolution of watercourses within the study area, including modification due to past human interventions. Information relating to land use change was also incorporated. The field survey collected data by segmenting watercourses into ‘geomorphologically homogenous’ reaches, for which a range of associated geomorphological descriptors were recorded. The key tributaries which input directly into the lake were focused on, in total comprising just under 80km of watercourses. The data collected in the field were analysed using Excel and GIS to generate statistics that indicate the extent of erosion and deposition throughout the catchment as well as the generation of a broad sediment budget. The data has been documented in a series of summaries for sections of watercourses, presented in Appendix B.

This study also includes a GIS catchment erosion risk model (based on the approached developed by Orr *et al.*, 2004 on the Bassenthwaite Lake catchment). This has been used to 'fill in the gaps' examining the wider land use over the catchment as opposed to the main rivers investigated during the field survey. It involved processing GIS data for slope, vegetation cover types and stream order to produce a sediment supply risk map.

A combination of the findings from the sediment budget and fluvial audit, together with the catchment erosion risk mapping, have been used to identify possible options for river-related and wider catchment land management actions in Report B.

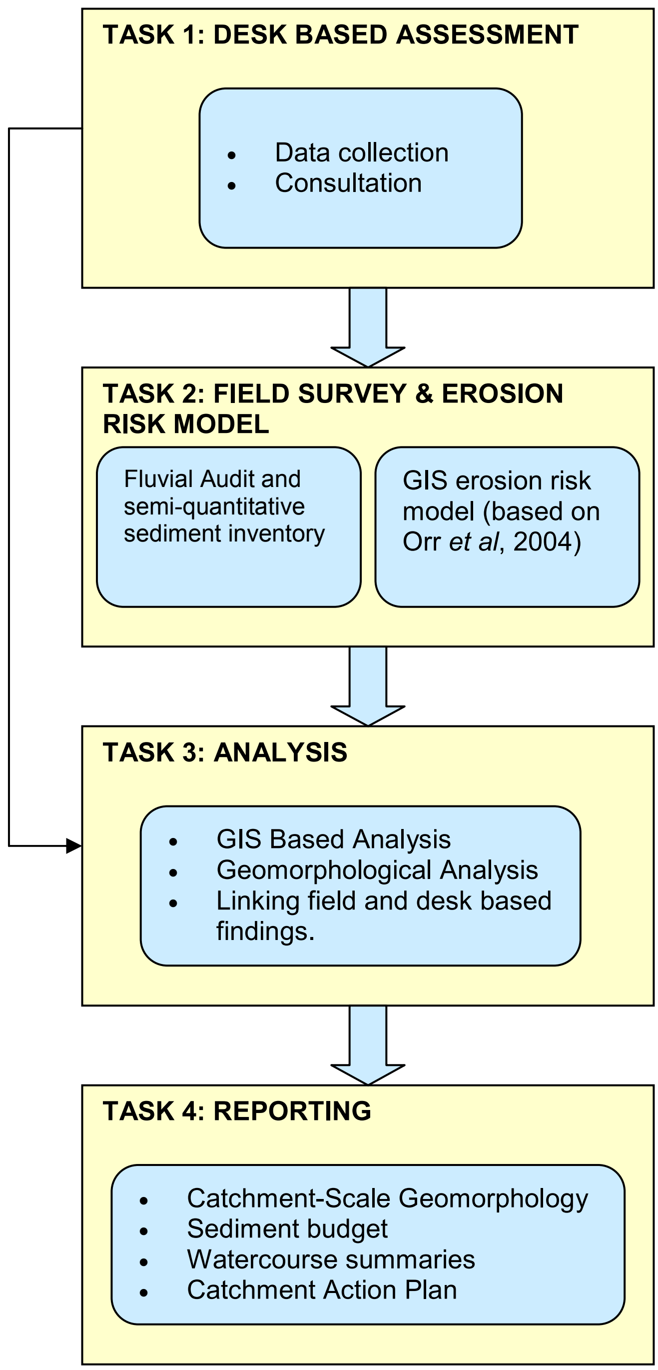

Figure 1.1: Outline of Fluvial Audit Method for Windermere Catchment

2 Catchment Overview

2.1 Introduction

This study focuses on the Windermere catchment, stretching from the hills above Grasmere in the north, to the southern tip of Windermere where it flows out into the River Leven near Newby Bridge. The total catchment covers an area of approximately 220 km^2 (Figure 2.1 - Appendix C). The catchment contains numerous lakes including Windermere which is the largest natural lake in England, and one of the most important tourist attractions in the Lake District. Other smaller lakes include Grasmere, Rydal Water, Elter Water, Esthwaite Water and various tarns. There is an intricate network of rivers which flow down the valleys into, and through, the lakes. The major rivers within the catchment include the River Brathay, Rothay, Great Langdale Beck, Trout Beck and Cunsey Beck. The catchment characteristics and geomorphological history (including hydrological and land use changes) are described in this catchment overview.

Windermere is the largest town within the catchment; other settlements include Ambleside, Grasmere, Bowness-on-Windermere, Elterwater and Hawkshead. Overall the Windermere catchment is predominantly an upland rural catchment. The northern part of the catchment is characterised by upland fells and steep rough grassland, along with flatter improved grassland on the valley bottoms, providing land for farming and grazing. The western part of the catchment is characterised by a mixture of land use types, predominantly mixed woodland and improved grassland. To the east of Windermere the land use is more urban, consisting of the towns of Windermere and Ambleside. The area is less wooded than to the west and there are less rocky outcrops and larger hills than in the north. A number of disused quarries are evident, confirming past mineral-workings in the area.

The sub-catchments and individual watercourses surveyed in the Windermere catchment as part of the study are listed in Table 2.1 and displayed on Figure 2.2 (Appendix C). The information collected along these rivers forms part of the catchment wide geomorphological analysis. More information on the characteristics and geomorphological behaviour of each watercourse is provided in detailed watercourse summaries in Appendix B.

Table 2.1: Surveyed river lengths and sub-catchments of Windermere catchment

Sub-catchment	Watercourses	Total Surveyed Length (km)
Brathay	Great Langdale Beck; River Brathay; Oxendale Beck; Mickleden Beck; Redacre Gill; Greenburn Beck; Bleamoss Beck.	24.7
Rothay	Far Easedale Gill; Easedale Beck; Green Burn; River Rothay; Scandale Beck; Stock Ghyll; Rydal Beck.	17.16
Black Beck & Cunsey Beck	Black Beck; Cunsey Beck	4.85
Trout Beck	Trout Beck	7.59
West	Dan Beck; Wray Beck; Blelham Beck; Hoghouse	17.97

Sub-catchment	Watercourses	Total Surveyed Length (km)
Tributaries	Beck; Belle Grange Beck; Wilfin Beck; Tributary of Pull Beck; Pull Beck; Blake Beck; Gill Beck; Un-named A (Hollow Beck); Un-named B (High Dam); Un-named C (Stott Park Heights); Un-named D (Wilson Knott); Un-named E (near YMCA); Un-named F (near Cunsey Farm).	
East Tributaries	Hol Beck; Un-named G (Astley's Plantation); Un-named H (Gummer's How).	3.53
Total length surveyed		**75.8**

2.2 Geology and Soil

Figure 2.3 shows the basic solid geology within the catchment and Figure 2.4 illustrates the drift geology. These Figures are shown in Appendix C.

The southern reaches of the catchment (approximately to the south of Esthwaite Water) are underlain by Ludlow siltstone, mudstone and sandstone of the Windermere Supergroup, formed during the Silurian period. The solid geology is overlain with till, alluvium and lacustrine deposits. The area is crossed by a number of fault lines, the majority of which have a general north-south trend, one of which goes through the centre of Windermere. Further north, between Esthwaite Water and the northern extent of Windermere, the geology remains Silurian but changes to the Wenlock series, consisting of greater proportions of siltstone and sandstone.

North of Windermere the geology is dominated by the Borrowdale Volcanic series formed during the Ordovician period, consisting of lava and tuff. Drift geology includes scree, patches of made ground (probably mining spoils), and alluvium adjacent to some river channels. The Park Gill Thrust and Stockdale Thrust form a divide between the Windermere Supergroup in the south and Borrowdale Volcanic Group in the north. The possible implications for sediment delivery of this change in geology include a greater potential for erosion and more fine sediment available within the southern half of the catchment where the Windermere Supergroup is present, due to the predominantly sandstone and siltstone geology. The northern part of the catchment, consisting of the Borrowdale Volcanic group is relatively impermeable and less erodible. Therefore, the implication is that there may be less potential for a source of fine sediment in this area. One of the surveyed rivers, Hol Beck, follows the line of Stockdale Thrust. Other prominent faults in the area include the Brathay fault which runs north-south across the River Brathay.

2.3 Hydrology

There are four gauging stations in the Windermere catchment (data and station information acquired from the National River Flow Archive at www.ceh.ac.uk/data/nrfa/uk_gauging_station_network.html). The stations are located in the west of the catchment on Cunsey Beck at Eel House Bridge, and in the north of the catchment on the River Brathay at Jeffy Knotts and River Rothay at Millar Bridge House. The fourth station is on the River Leven at Newby Bridge, to the south of the study area (downstream of Windermere). The location of the gauging stations is shown on Figure 1 in Appendix C.

Cunsey Beck
Cunsey Beck gauging station is situated an artificially straightened reach and the gauge can be inaccurate at low flows due to seasonal weed growth in the channel.

River Brathay
The bed at the Brathay gauging station is known to have been dredged in July 1994, causing water levels to fall by approximately 0.2m. There are some hydrometric problems at the site as flows are affected by weed growth and heavily vegetated banks.

River Rothay
At Millar Bridge House gauging station on the River Rothay, high flows are not contained within channel. Instead, flow goes out of bank, down the road and across a field. A wooden low flow control was installed in 1991 but had deteriorated by 2002. A new timber control was constructed in July 2006.

River Leven
Level data on the River Leven has been recorded since 1939. The flows at this site are highly regulated by Windermere, and include compensation flows (occasional very low flows (e.g. autumn 1972) when the upstream fish pass was closed). The flows are also affected by major abstractions for public water supply from Windermere.

Summary data from these gauging stations is shown in Table 2.2 below and seasonal hydrographs are discussed in 2.3.1.

Table 2.2: Summary data for Windermere gauging stations

Gauging Station	Grid Reference	Catchment Area (km^2)	Altitude (m OD)	Mean flow (m^3/s)	Q95 95% exceedance (m^3/s)	Q10 10% exceedance (m^3/s)
Cunsey Beck	SD369940	18.7	63.4	0.92	0.031	2.254
River Brathay	NY360034	57.4	41.9	4.32	0.353	11.07
River Rothay	NY371042	64	40.8	4.2	0.344	10.1
River Leven	SD371863	241	38.4	12.39	1.104	29.04

2.3.1 Hydrographs and Seasonal flows

Maximum and minimum daily flows between 1976 and 2006 have been collated and are presented in hydrographs on the CEH National River Flow Archive website. Figure 2.5 shows the long term hydrograph for the River Brathay at Jeffy Knotts.

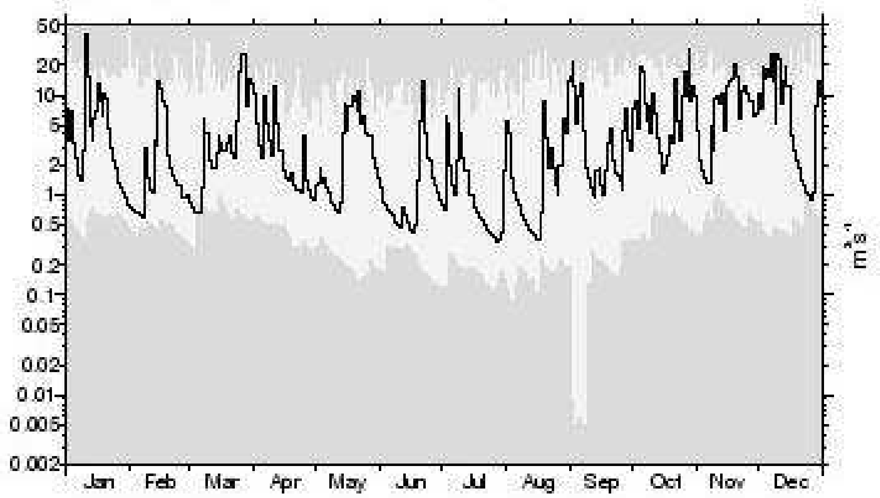

Figure 2.5: Hydrograph for River Brathay (1976-2005) from NRFA website

Cunsey Beck, the River Brathay and the River Rothay have fairly consistent flows throughout the year. In general there is little variation between peak and low flows during winter and summer flows. The months of June, July and August have slightly lower flows than the rest of the year. The River Brathay peak and low flows are very similar throughout the year. Between August and November there is less variation between the minimum and maximum flows compared to the rest of the year. These patterns show that the hydrological regime of the catchment is governed principally by rapid response to rainfall, with significant short-term variation in flows.

2.4 Environmental Designations

The whole of Windermere catchment lies within the Lake District National Park and is classed as an Environmentally Sensitive Area. Within the catchment there are discrete sites which are of national and/or international environmental importance and protected by law. There are 21 Sites of Special Scientific Interest (SSSI) summarised in Table 2.3 below. Three of these SSSIs are further recognised internationally (designated as Special Areas of Conservation (SAC). These are the Lake District High Fell, Yewbarrow and Esthwaite Water. In addition, Esthwaite Water is also protected as a Ramsar site (internationally important wetlands). Another three SSSIs are National Nature Reserves (North Fen, Blelham Bog and Rusland Moss). North Fen falls within Esthwaite SSSI boundary, Blelham Bog which lies within Blelham Tarn and Bog SSSI and Rusland Moss falls within Rusland Valley Mosses SSSI. North Fen National Nature Reserve is located at the northern end of Esthwaite Water and is famous for long term studies on plant community succession on lake margins (hydroseres).

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Table 2.3: Summary data for SSSIs

SSSI name	Type of habitat	Reason for designation	Condition
Baysbrown Wood	Woodland	Range of woodland which supports specialist moss and liverwort and contains rare species. Variable structure of wood supports rich bird life.	100% unfavourable no change
Blea Tarn	Lake	Key site for palaeo-environmental studies, sedimentation and deposits.	100% favourable
Blelham Tarn and Bog	Lake and fringing wetland	Variety of relatively undisturbed habitats which supports a wide range of invertebrates including a number of rare and uncommon species.	68% unfavourable no change 23% favourable 9% unfavourable recovering
Brathay Quarries	Quarries and rock outcrop	A site of historical, palaeontological and biostratigraphic significance.	55% favourable 45% unfavourable no change
Claife Tarns and Mires	Lakes and wetlands	Habitats are nationally rare and scarce in South Cumbria. Important for rich wetland flora and assemblage of dragonflies.	61% favourable 39% unfavourable no change
Dungeon Ghyll	Mountain stream	One of the most diverse Gills in South Cumbria displaying rich association of plant species from a variety of habitats.	68% unfavourable no change 32% favourable
Elter Water	Lake, wetland and woodland	One of least disturbed lakeshore transition habitats (wetlands) in South Cumbria. Undisturbed character of lake and its shores supports varied fauna and rich invertebrate fauna.	62% unfavourable declining 21% favourable 17% unfavourable no change
Esthwaite Water	Lake, fen and grassland	Moderately nutrient rich (mesotrophic) lake, the most productive of the larger lakes in the Lake District. It is one of the best examples of its kind in England and Wales. Site supports characteristic flora including nationally rare and local species and supports a range of breeding birds.	60% unfavourable declining 17% unfavourable recovering 14% favourable 9% unfavourable no change
High Lickbarrow Mires and Pastures	Wetland and grassland	One of the few remaining areas of farmland within South Cumbria which has escaped agricultural intensification and retains a wide and interesting range of plant species.	100% favourable
Langdale Pikes	Geology	Geological and geomorphological importance – stratigraphy and volcanic formation (volcano-tectonic faults).	100% favourable
Little Langdale Tarn	Lake and fringing habitats	Great diversity of undisturbed adjacent habitats including swamp, fen, marshy grassland, hay meadow and wet woodland. The varied habitats support a rich and varied fauna.	56% unfavourable recovering 28% favourable 16% unfavourable declining
Loughrigg Fell Flushes	Upland habitat including wetland	Important because of the occurrence of six different mire communities including marshy grassland.	61% favourable 39% unfavourable no change
Ludderburn and Candlestick Mires	Wetland	Important conditions for peat development, resulting in a very diverse range of bog or mire types. Areas of open water such as Podnet Tarn add to this site's habitat diversity.	88% favourable 12% unfavourable recovering
Ray and	Typical	High crags, gills and fell land. Geological	100% favourable

SSSI name	Type of habitat	Reason for designation	Condition
Crinkle Crags	upland habitats	importance. Site provides critical evidence on the character of volcanic activity during the early stages of the Borrowdale Volcanic Group.	
Rusland Valley Mosses	System of raised mires (wetland)	One of the few remaining examples of the formerly extensive system of estuarine raised mires around Morecambe Bay. Displays a rich fauna and supports over 170 species of butterfly and moth.	45% unfavourable no change 26% unfavourable recovering 19% favourable 10% unfavourable declining
Side Pike	Geology	Geological importance – rock outcrop of Borrowdale Volcanic Group. One of the very few instances in the British Isles in which evidence for sub-aerial volcanic processes can be readily examined.	100% favourable
Skelghyll Beck	Stream	Geological importance – important stratigraphic locality and well known for its extensive well preserved graptolite fossil fauna.	100% favourable
Trout Beck	Glacially eroded river valley system	Large variety of habitats including grasslands, fens, mires, upland vegetation and rush pastures. Site of geological interest. Borrowdale Volcanic Series bedrock is generally close to the surface with frequent outcrops along the valley bottom.	82% favourable 18% unfavourable no change
Wilson Place Meadows	Grassland	Series of herb-rich grasslands found along floodplain of River Brathay. Nationally important because no comparable managed hay meadows occur in this area.	91% favourable 9% unfavourable no change
Winster Wetlands	Wetlands	A system of mires providing a high diversity of plants and communities including nationally rare and highly localised plant communities.	58% favourable 42% unfavourable
Yewbarrow Woods	Woodland	Oak and birch woodland particularly notable for its extensive stands of yew *Taxus baccata* which are unusual in the typical soils of South Cumbria.	41% unfavourable no change 34% unfavourable recovering 25% favourable

2.5 Fisheries

Windermere has a varied coarse fish population which is suited to the water conditions, and includes pike, roach, eels and perch. Roach, carp and bream are thought to come down Trout Beck from Holehird Tarn, which was developed as a coarse fishery by North West Water more than 20 years ago. The trout fishery on Windermere appears to be in decline due to water quality changes and lack of incoming population from feeder tributaries (www.lakedistrictfishing.net).

The River Brathay from Elter Water provides habitat for small trout and minnows. Few fish manage to negotiate Skelwith Falls as this is a natural barrier to fish migration. Downstream of Skelwith Bridge the river widens and slows, and there are deep pools which provide ideal habitat for a wide variety of species including brown trout, pike, perch, eels, roach, sea trout, salmon, lampreys and minnows. Charr from Windermere use the Brathay for spawning.

The Rothay is a typical spate river with a mainly small brown trout fishery. The river becomes a conduit for larger lake trout at times of high water and sea trout or salmon occasionally are caught.

2.6 Land Use

The pie chart below (Figure 2.5) illustrates the land use in the Windermere catchment. The majority of land cover is grassland, with a roughly even split between rough pasture and improved grassland. Much of the rough grassland is associated with sheep grazing, while improved grassland includes both sheep and cattle. There is no high grade (1 or 2) agricultural land within the Windermere catchment (from Defra Agricultural Land Classification data) and this is probably closely representative of the whole Lake District because there is a very low percentage of crops and fallow fields. The majority of land within the Windermere catchment is either grade 3 or 4 which is generally better suited to grazing.

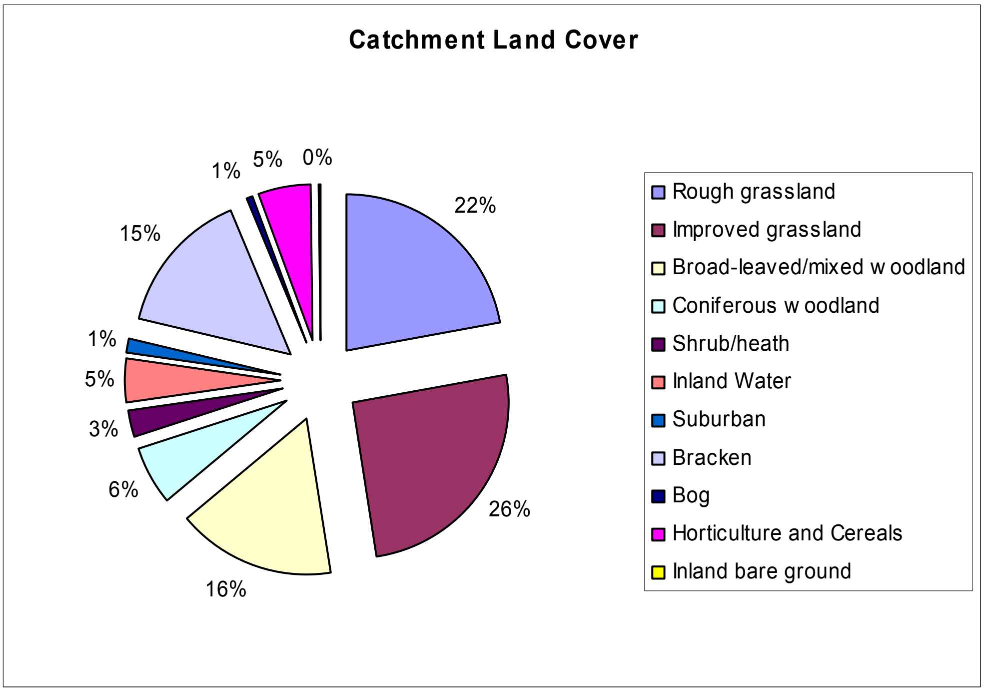

Figure 2.5: Land Cover in Windermere (data derived from LCM2000)

Around 20% of land cover is woodland. Broadleaf and mixed woodland is more common, some of this is semi-natural while other areas have been more recently replanted. Coniferous plantations are also present within the catchment.

The northern section of the catchment can be divided into two types of land use (Figure 2.6 – Appendix C); these are upland, rough grassland areas and flatter, improved grassland valley bottoms. The majority of the land is steep and rocky outcrops are commonplace. The land use is a mixture of scrub, bracken, heath and rough grassland. There are also a small number of broadleaf trees in some areas. The valley bottoms have much lower gradients than the valley sides and provide better land for farming and improved grassland, for grazing. Along the flat valley bottoms, there are clusters of trees, in direct contrast to sparser tree cover in the upland areas. In Grasmere and Langdale there are three lakes, namely Grasmere, Rydal Water and Elter Water. Ambleside is the second largest urban settlement and is located in the northern part of the catchment. Other settlements include Grasmere and Elterwater.

The western part of the catchment is characterised by a mixture of land use types, predominantly mixed woodland and to a lesser extent improved grassland. There are several areas of open water including Esthwaite Water and a few small settlements, including Hawkshead. Approximately 70% of land cover is woodland, which includes semi-natural woods and coniferous plantations. The wooded areas are made up of a mixture of broadleaf and coniferous trees. There are some rocky outcrops amongst the wooded areas.

Compared to the western section of the catchment there is a significantly smaller area of woodland on the eastern side of the Lake. A distinctive characteristic of the eastern side of the lake is the presence of the urban area of Windermere and Bowness, which is the largest urban settlement in the catchment.

2.7 Topography

Overall the Windermere catchment is predominantly an upland catchment (Figure 2.7 - Appendix C). However, on closer inspection the catchment can be divided into three parts – the northern, western and eastern parts. The northern part of the catchment is characterised by upland terrain and rough grassland. It is the steepest part of the catchment and is made up of a number of fells including Park Fell, Red Screes, Scandal Fell, Rydal Fell, Grasmere Common, Dale Fell, Langdale Fell, Furness Fells, Lingmoor Fell and Loughrigg Fell. Typical elevations at the fell peaks are 600-700m. Although there are steep areas in the western and eastern parts of the catchment there are fewer rocky outcrop areas and the fells are not as high, reaching around 250m.

In the northern part of the catchment there are four large flat bottom U-shaped valleys and three steep sided ‘V’-shape valleys. The ‘U’-shaped valleys are Little Langdale, Great Langdale, Grasmere and Trout Beck. It is these four previously glaciated valleys that most clearly delineate the northern part of Windermere catchment. Little Langdale and Great Langdale converge at Elter Water, to form one valley in which the River Brathay is located. Rydal Beck, Scandale Beck and Stock Ghyll lie at the base of steep V-shaped valleys, which are more closely coupled to the valley sides and therefore have a greater potential for direct sediment supply from the hill slopes.

2.8 Past and Present Channel Modifications and Maintenance Operations

In contrast to the rural and 'wild' nature of the Windermere catchment, many parts of the main river systems in the catchment, and the Lake District as a whole, are extensively modified.

There is extensive field evidence of historic channel modifications. These modifications, which are extensive throughout the catchment, consist of straightening, bank protection and embanking and major dredging works. Many of the modifications are historical, for example Great Langdale Beck had a series of channelisation works between 1954 and 1958. Sediment management is also carried out through the creation of gravel traps in the upland areas, for example the weirs on Mickleden and Oxendale Becks which trap large amounts of coarse sediment.

More detail on channel modifications is included in the watercourse summaries in Appendix B.

3 Catchment Scale Geomorphology

3.1 Introduction

As the sediment system in a river (or sediment regime) is a continuum of sediment supply, transfer and storage operating at a range of temporal and spatial scales, the analysis in this report will be conducted at the catchment or sub-catchment scale (Figure 2.2). The accompanying Action Plan report will focus on the recommendation and prioritisation of actions at the reach scale, based on a thorough understanding of the underlying catchment geomorphology.

3.1.1 Field Survey and data collection

The geomorphological assessment conducted in the walkover survey involved the completion of two forms. The first form was broadly an inventory of sediment pathways. This included the documentation of sediment sources and sinks; sediment transfer pathways such as field drains and tributaries; point sources associated with riparian land management, such as fords and coppicing; and in-channel structures (e.g. weirs and bridges). The data relating to sources and sinks was then analysed (section 3.4 and 3.5) to determine the overall sediment budget for the catchment.

Data for sediment sources recorded in the field included a description of the type of sourcing, i.e. whether it is natural bank erosion, livestock poaching or footpath erosion. The location was recorded using a GPS handset. By visual observation, estimates of length and height of erosion were recorded, usually to the nearest 0.25m. The width of sourcing was also estimated to allow a volumetric measurement to be made. However, it is difficult to determine the degree of bank retreat, so a standard of 0.1m was used, unless it was obvious that more sourcing had recently occurred. The length of bank erosion is the simplest indicator that can be used to indicate how widespread erosion is along a reach/river or sub-catchment. Volume was calculated by multiplying length x depth x width, so that sediment sources could be compared against the volume of sinks within the sediment budget (section 3.5). A visual observation was made of the mean grain size. Many of the sources had a range of sediment sizes visible in the bank, and where this was obvious, bi-modal sizes were recorded. It is possible that there could be a bias towards the coarser fractions, as these are more clearly visible when viewing the sediments. However, careful recording in the field should limit this.

Similarly to the sources data, the sinks were recorded using a description of the bar/deposit type, location, and notes about bar stability. Again, the length, width and depth of bars were visually recorded to the nearest 0.25m, as well as the mean grain size (or whether bi-modal) and vegetation cover.

The second form completed was a 'sweep up' of each reach to determine the main characteristics. This included valley overview (e.g. valley form, land use and floodplain information); channel geometry (e.g. channel planform, type of cross-section, dimensions, gradient and flow type); boundary conditions (e.g. bed and bank material, vegetation and any protection); reach conservation status and channel dynamics. This helped develop an understanding of river processes and influences on the sediment system, including interrelationships with the controls described in sections 3.2 and 3.3.

3.2 External Controls

External controls are influential factors outside of the natural geomorphological system. External controls influencing the sediment regime in the Windermere catchment (in addition to climate change and any downstream changes in base level) include:

- Catchment form
- Surface drainage network
- Flora and fauna
- Land use and land management practices
- Channel maintenance

3.2.1 Catchment Form

The overall form of the catchment is controlled by the underlying geology and topography. These physical characteristics have evolved over geological timescales and act as major controls over the internal fluvial system over shorter geomorphological timescales. Many of the geomorphological characteristics of the watercourses within the catchment, such as gradient and planform, are directly influenced by geology and topography.

The Windermere catchment divides roughly into two geological areas; the harder, more resistant rock north of Windermere and softer, less resistant rock below the northern point of the lake. North of the lake, the geology is dominated by volcanic rock overlain with patches of alluvium (adjacent to the rivers), scree and drift. In the southern reaches, below the northern point of Windermere and south of Esthwaite Water, the geology is dominated by siltstone, mudstone and sandstone overlain with till, alluvium and lacustrine deposits.

The topography of the Windermere catchment also roughly divides the area into two similar parts. North of Windermere is dominated by steep mountainous terrain and contains the highest and steepest points of the catchment. Overall the topography along the western and eastern boundaries of Windermere is not as steep or the elevation as high. However there are areas of very steep valley sides adjacent to the lake, which are often covered with woodland. This is in contrast to the generally more exposed and less wooded upland areas to the north of Windermere.

To erode the harder rock in the northern part of the catchment it is necessary to have higher energy or stream power. Higher stream powers are achieved where the gradient is high and slopes are steep. Bank erosion was observed in the steep upper tributaries of the main rivers (Mickleden and Oxendale Beck in Great Langdale, River Brathay and River Rothay) and Trout Beck. However, there were very few fine sediment deposits (only occasional overbank sandy floodplain deposits and localised silty margins) and almost all rivers flowed clear. There were numerous temporary/active (unvegetated) coarse sediment deposits. This follows an expectation that there will be less fine sediment in this area because the Borrowdale Volcanic group is relatively impermeable and less erodible geology.

In the south of the catchment there is a greater potential for erosion of fine sediment because of widespread till, alluvium and lacustrine deposits which overlie softer rocks (sandstone and siltstone). There are fewer bedrock outcrops in the south. Although the topography and relief of the southern catchment is flatter than the northern fells, many of the rivers have a moderate gradient which is sufficient to erode the surface/drift geology, exposing local bedrock. There were areas of erosion along the rivers in the southern part of the catchment especially where riparian zones and tree lining were absent along the banks. Erosion occurred only where the channel was not constrained by walls and where the rivers were actively able to migrate laterally.

3.2.2 Surface Drainage Network

The pathways via which surface water drains from the catchment influence the supply, transport and storage of sediments. Tributaries converging with the main rivers appeared to contribute little sediment, as limited suspended sediments and tributary/confluence bars were observed. It is assumed that over recent timescales, fine and coarse sediments have been supplied in roughly equal amounts as, where visible, bank materials were predominantly bimodal. Fine sediment input to the main rivers and tributaries is largely ‘supply limited’, which means the amount of sediment transported is limited by the sediment available for erosion. Due to recent wet summers and previous high flow events, it appeared that a large proportion of the fine sediment had already been washed out from the banks, leaving coarser material behind. The clear flowing water of the tributaries and main rivers observed during site visits (moderate to high flow events) supports this hypothesis. It is therefore difficult to quantify exact volumes of fine or coarse sediment supply without regular and long term monitoring.

3.2.3 Vegetation

Vegetation has an impact on the supply and storage of sediment within the Windermere catchment. A large proportion of the land is either grazed grassland or woodland. Woods line some watercourses and there are managed plantations (either coniferous or mixed plantations) and semi-natural woodlands (broadleaf or mixed). Tree roots help improve the strength of river banks, reducing the potential for erosion. However, if the banks are undercut, the surcharge could cause trees to fall into the channel and the bank to collapse. Wind-throw is an additional problem associated with trees with a dense canopy on thinner soils. In plantations, trees are typically planted in rows, which encourages erosion of topsoil as the water is funnelled between them. In addition, a dense canopy cover inhibits undergrowth from developing, and as a result, top soil is vulnerable to erosion because more bare ground is exposed.

In-channel vegetation was limited in watercourses in the Windermere catchment. This was a result of coarse sediment beds, which makes stable rooting difficult, steep gradients and the frequency of high flow events. In-channel vegetation was generally limited to mosses, exposed tree roots and large woody debris. In areas where the width:depth ratio increased, typically where the gradient reduced and velocities slowed, emergent reeds have developed along channel margins and more submerged vegetation was evident. Conditions are more favourable for vegetation in these areas because a greater volume of fine sediment is deposited where velocities slow in wider and flatter reaches, for example along the River Brathay. Typically, reeds and submerged vegetation are found upstream of lakes and online ponds, for example along Black Beck upstream of Esthwaite Water.

In wooded reaches, fallen trees and large woody debris contribute to a higher amount of in-channel vegetation, for example along Hollow Beck. Woody debris can create dams which act as a temporary sediment store. While the obstruction is in place sediment will become deposited behind it, but when the structure fails, sediment will be flushed through the system. Tree falls create a point source of sediment when sediment is brought into the channel via the tree roots. The bank face will also become exposed to erosion, particularly if the tree diverts flow towards it.

Where riparian zones were observed, they often consisted of a single line of trees with little ground vegetation other than grass. There was rarely a distinct riparian buffer zone of any longer grasses or shrubs. In areas of rough pasture and improved grassland, where some form of riparian zone was present, (even a single line of trees), there was usually less erosion than where it was absent.

Vegetation had less impact on the supply and storage of sediment within reaches that are heavily modified, such as the River Rothay through Grasmere, Stock Ghyll through Ambleside, and Great Langdale Beck.

3.2.4 Land Use and Management

Nearly 50% of the Windermere catchment area is grassland (see LCM2000 land use map, Figure 2.6 in Appendix C). Grazed land was a mixture of rough pasture and improved grassland. No arable/tilled fields were observed adjacent to the watercourses.

Poaching was a problem where animals/livestock had access to the water edge/bank tops. Uncontrolled stock access can cause trampling of bank vegetation along watercourses (particularly if stock density is high). This could also occur at specific animal crossing locations. If the bank vegetation becomes trampled and bare, fine sediment is exposed and becomes available for erosion and entrainment. One of the principal farm management measures that can influence the level of fine sediment input into watercourses is livestock fencing, which limits poaching/trampling and controls stock access to specific points along the watercourse.

A clear example of where fencing was being used to reduce fine sediment sourced from poaching was on the un-named watercourse at Low Cunsey Farm (watercourse code UNF). Recent fencing had been placed along this watercourse where it flowed through the farm. There was already evidence that plants had begun to recolonise along the banks.

Stone walls, which demarcate field boundaries, were commonplace within the catchment and prevent livestock from accessing the rivers. In addition, some rivers had embankments constructed along the bank tops which restrict livestock access. Great Langdale Beck and Redacre Gill had continuous embankments along some reaches. Stone walls and embankments can limit fine sediment carried in surface runoff from entering watercourses, but have the disadvantage of reducing floodplain connectivity and thus reduce the potential for fine sediment to be deposited onto the floodplain during high flow events.

Through urban/suburban reaches, land use has a greater effect on the hydrological regime as paved surfaces give rise to faster runoff, particularly during intense rainfall events. The overall impact on the Windermere catchment is minimal as urban areas cover a very small proportion of the whole catchment (1.2%). However, channelised reaches in rural locations within the catchment were efficient conduits for the transfer of water and fine sediment.

3.3 Internal Controls

Internal controls are factors that affect geomorphological behaviour from within the fluvial system. These controls are interdependent, therefore changes in one factor may have knock-on effects on other controlling factors.

3.3.1 Gradient

The Windermere catchment includes watercourses with a variety of different gradients. As a result of the catchment's upland nature, the gradient primarily ranges from moderate to high.

The sources of the main rivers (River Rothay, River Brathay and Great Langdale and Trout Beck) are located in upland terrain. The rivers had steep gradients as they flowed down from the fells which surround the area north of Windermere. The gradients lessened through glacial valleys in the middle to lower reaches, and bed gradients further reduced in online ponds and prior to discharging into lakes.

As the gradient of a river decreases, stream power decreases and thus the watercourse has less power to transport sediment. This increases the likelihood of deposition occurring. Within an upland system such as the Windermere catchment, the largest sediment is deposited first (Redacre Gill is an example). With large areas of boulder and cobble sized sediment found in the middle to upper reaches of the catchment. Finer sediment would be efficiently transferred through these reaches (and onto the surrounding floodplain) and was only deposited in the river when the gradient lessened to such an extent that fine sediment dropped out of suspension. This occurred when rivers met online ponds or lakes (for example the River Brathay just upstream of Windermere).

3.3.2 Mode of Adjustment

This refers to the river 'processes' that are taking place within the catchment. The natural mode of adjustment is largely dependent on underlying geology, topography and the gradient of the channel. The majority of watercourses within the Windermere catchment are currently stable (not actively adjusting). There were several reaches along different watercourses which were aggrading, incising, laterally adjusting or widening, but only a small proportion of the total number of reaches surveyed. Figure 3.11 in Appendix C illustrates reach processes across the catchment.

The width of rivers is maintained either naturally (adjusted to the hydrological and sediment regime) or through modification to the bank or channel. In Windermere, the watercourses are currently not actively adjusting as many are cut into bedrock, have tree-lined banks or are artificially stabilised with bank protection (usually walling). Where rivers have been channelised the bank protection was usually in relatively good condition and was rarely failing. Extensive bars or berms were generally absent along the margins of modified channels, indicating that sediment is efficiently transported through these reaches.

There were few significant areas of erosion or deposition. Depositional features were mostly coarse gravels and cobbles forming bars. These deposits were often unvegetated, suggesting they are actively being deposited or transferred around the channel. Instead of supplying sediment (by erosion) or storing it (by depositing), the majority of watercourses were efficient systems of transporting sediment, particularly fine material.

3.3.3 Cross Section Morphology

Despite the upland and rural nature of the catchment, many of the reaches within the Windermere catchment have been modified to some degree. Some modifications have taken place in villages and towns, where river cross-sections were often rectangular/trapezoidal due to reprofiling, straightening and walling. Examples include the River Rothay through Grasmere, and Stock Ghyll through Ambleside. Even in more rural locations, the main rivers were often modified, including realignment, walling and embankments. Artificial cross-sections have often been formed to improve flow conveyance or to increase the productivity of land adjacent to rivers. An example is Great Langdale Beck. The shorter, smaller watercourses typically had more natural-cross sections.

The River Brathay's natural cross-section (width:depth ratio) fluctuated through a number of online pools, such as Skelwith Pool, downstream of Elter Water, where the width:depth ratio increased dramatically. Typically, where a watercourse fed into a lake, their width:depth ratio increased as water was ponded by the lower gradient. Examples include the River Rothay, which feeds Grasmere and Rydal Water; Greenburn Beck, which flows into Little Langdale Tarn, the River Brathay into Elter Water; Great Langdale Beck, which flows into Elter Water; Black Beck which feeds into Esthwaite Water and Cunsey Beck, which feeds into Out Dubs Tarn; and the largest of all is the River Brathay, which discharges into Windermere.

The cross-section morphology is linked to external controls such as catchment form, particularly geology and vegetation cover, because these controls constrain the channel dimensions both vertically and laterally.

3.3.4 Bed and Bank Conditions

Details of the bed and bank materials of specific watercourses are given in the Watercourse Summaries (Appendix B). The majority of river banks were natural and had bi-modal material, comprising a mixture of fine (silt and sand) and coarse sediments (gravel and cobble). Boulders and bedrock formed extensive boundary conditions in many of the smaller streams. There were also many reaches with artificial banks. These were typically formed from laid cobbles or stone walls. Great Langdale Beck, in particular, had an extensive amount of stone walling lining the river banks.

In some places embankments had been constructed to form part of the bank face. An example was on Redacre Gill where tipped cobbles formed an embankment along the bank face. Stone walls, which mark field boundaries rather than being built specifically to protect the bank, also formed all or part of the bank face along smaller watercourses, for example along Bleamoss Beck.

Bed material was typically formed of coarse sediment, predominantly cobbles and gravels, and some boulders and bedrock. There was little fine sediment present on the bed of most watercourses, because the moderate to high gradients result in fast flows which efficiently transport fine sediment downstream. The ultimate receptor for this fine sediment is Windermere, or other lakes further upstream in the catchment. Immediately upstream of most lakes, and in online ponds, there was an increase in the amount of fine sediment on the bed and/or channel margins, due to a reduction of flow velocity caused by wider channels at the river–lake transition area.

3.3.5 Floodplain Connectivity

Rivers in the Windermere catchment were generally well connected to their floodplains (see Figure 3.8 in Appendix C). Approximately half of river reaches had good floodplain connectivity. A fifth of reaches were disconnected from their floodplains. Around a fifth of reaches did not have a distinct floodplain because of valley shape and local topography.

After the high flows that had occurred recently in the catchment, trashlines were present along many reaches, indicating that land adjacent to rivers becomes inundated during very high flows.

Good floodplain connectivity was indicated where there were wetlands adjacent to watercourses, which included the River Brathay, River Rothay, Blelham Beck, Black Beck, Cunsey Beck, Blake Beck, and Pull Beck. The final reach of Blelham Beck, before it discharges into Windermere, flowed through wet woodland.

3.3.6 River Continuity

There was fairly good river continuity in the Windermere catchment. 28 weirs of various sizes and 19 culverts (typically shorter than 10m) were recorded. The River Rothay, Great Langdale Beck and Trout Beck had weirs present (four were recorded on the River Rothay, two on Great Langdale Beck and one on Trout Beck). Weirs on the smaller watercourses were generally less than a metre high. Weirs act as point sinks for sediment where the flow slows behind them, and they segment the river and inhibit sediment transfer to varying degrees, as sediment transported as bedload would become trapped behind the structures. Culverts, although not prevalent within the Windermere catchment, also influence sediment transfer. Culverts often reduce the overall capacity of the channel at a certain location and can either be prone to sedimentation, or can create a 'chute' for sediment. Some culverts observed in the catchment were partially blocked by leaf litter.

Large woody debris dams were observed in the catchment and often caused significant deposition of sediment upstream of the obstruction. The steep, wooded reaches along the western shore of Windermere, for example Belle Grange Beck and Hollow Beck, had significant amounts of woody debris.

3.3.7 Flow Regime

Detailed consideration of the flow regime was beyond the scope of this study. However, morphological forms provide some indication of catchment flow conditions. The coarse sediment bed and moderate to high gradient of most watercourses in the Windermere catchment resulted in predominantly higher energy flow types, typically broken and unbroken standing waves. Bedrock outcrops created chutes, cascades and waterfalls.

Most rivers had varied or highly varied flows. Some examples include the River Brathay, where the planform and character alternated between wide flat reaches and narrow, confined and steep reaches. Consequently, flow types along this river varied considerably between low energy flow types (smooth or ponded, such as at Skelwith Pool) and high energy flow types (broken waves and free fall flow at Skelwith Force). Great Langdale Beck had varied flow throughout its whole length, but unbroken and broken standing waves were dominant throughout individual reaches.

Flow conditions varied during the field surveys. This is largely a result of the flashy responsive nature of watercourses in the Windermere catchment (mainly caused by impermeable geology, steepness of the catchment and rainfall patterns). At most times the river bed was visible in all but the deepest reaches, but there were times of heavy prolonged rain which caused water levels to rise significantly (fieldwork was abandoned on one occasion). Surveys were also undertaken after periods of dry weather where water levels fell significantly leaving some watercourses almost dry (as observed at Mickleden Burn on a subsequent visit).

3.4 Sediment Regime

This section considers the three main elements of the sediment regime: sediment supply (source), sediment transport (transfer/pathway) and sediment storage (sink/receptor) (Figure 3.1). These three components are interdependent and interact with the flow regime to control channel morphology over a range of temporal and spatial scales.

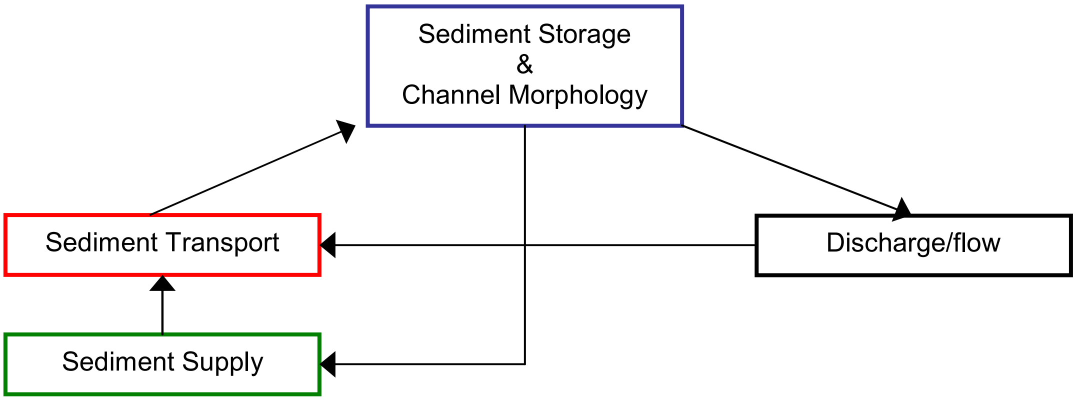

Figure 3.1: Interdependence of the sediment and flow regime

The purpose of this section is to provide a broad scale overview of the sediment regime and determine how it functions at a catchment scale. Information regarding the geomorphological behaviour of specific watercourses can be found in the watercourse summary sheets within Appendix A.

3.4.1 Sediment Supply

Sediment supply to a river channel can be described as a point or a diffuse source. Point sources include those that occur at a single location such as inputs from field drains and tributaries, poaching by livestock, footpath erosion, collapsed walls and tree-fall. Diffuse sources are those that occur over a wider area, for example erosion over a length of channel bank or hillslope supply. All locations and respective volumes of sources are displayed on Figure 3.2 (a-h) (Appendix B). Figure 3.3 displays the proportion of material (m^3) that each sediment source type was contributing from the field survey on a catchment-wide basis. The total volume of sediment sourced was just over 400 m^3, with bank erosion contributing over 56% of the volume of material entering the Windermere system (refer to section on Diffuse Sources below) and poaching contributing to approximately 26% (refer to section on Point Sources).

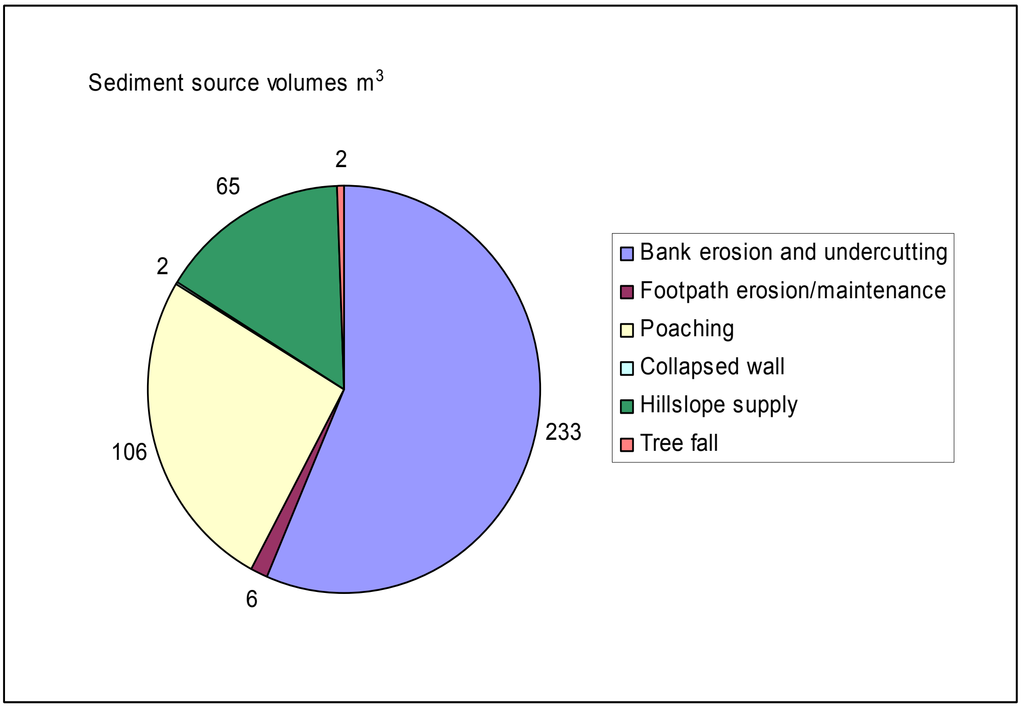

Figure 3.3 Relative contribution of each sediment source (m^3)

Point Sources

Livestock poaching generally released fine sediment into the river, and was present in localised areas, contributing approximately 106 m^3 of sediment to the system (26% of all sources). Poaching occurred in the Rothay sub-catchment, and to a lesser extent in the Brathay, Black Beck and Cunsey Beck sub-catchments and some of the smaller tributaries. It was difficult to assess how much fine material could enter rivers from field drains and tributaries as at the time of survey most had a clear flow, even during and after heavy rainfall. However, tributaries are likely to convey fine and coarse sediment from the headwaters to the main rivers. There was one tributary entering Great Langdale Beck and an un-named watercourse near Cunsey Farm which appeared turbid. Minor localised footpath erosion was evident in some locations along the River Rothay, Great Langdale Beck, Black Beck and an un-named watercourse downstream of High Dam. Some collapsed walls were evident along the River Rothay and Blelham Beck but this was only a minor source supplying a relatively low volume (<2 m^3) of coarse sediment. Some fallen trees along Hollow Beck also provided a small amount of coarse sediment to the river.

Diffuse Sources

Bank erosion contributed a relatively large proportion of sediment (56% of all sources) to the system (Figure 3.3). Although much of the river network was either walled or constrained by bedrock, there were many sections where there were no constraints and the channel was able to migrate laterally. Bank erosion was more prevalent in the Trout Beck and Brathay sub-catchments (particularly in the lower reaches of the River Brathay) in terms of volume of material sourced per km length of watercourse (Figure 3.4). Along Trout Beck, the lower reaches of the river were more vulnerable particularly where there was a lack of trees, or between trees where there were exposed roots. The volumes given are crude figures as it is difficult to accurately determine recent bank retreat. In terms of the number of areas of bank erosion, Trout Beck, the River Rothay, Wray Beck and Bleamoss Beck had many areas of erosion, but covered relatively short lengths and supplied low volumes. Other diffuse sources included hillslope supply, mainly evident in the middle reaches. Here, there was some potential for fine sediment supply in steep wooded valleys, where there was little undergrowth and more bare ground, but this could not be fully quantified. In the upper reaches covered by the Fluvial Audit there was little evidence of hillslope sourcing, however the reaches at the top of the catchment were not included in the scope. There was some potential for fine sediment sourcing through surface runoff, for example along Dan Beck where there was evidence of sediment laden runoff from the fields into the river. Overall this did not appear to be a major issue in the catchment, as after heavy rainfall the rivers remained clear and generally contained very little suspended sediment.

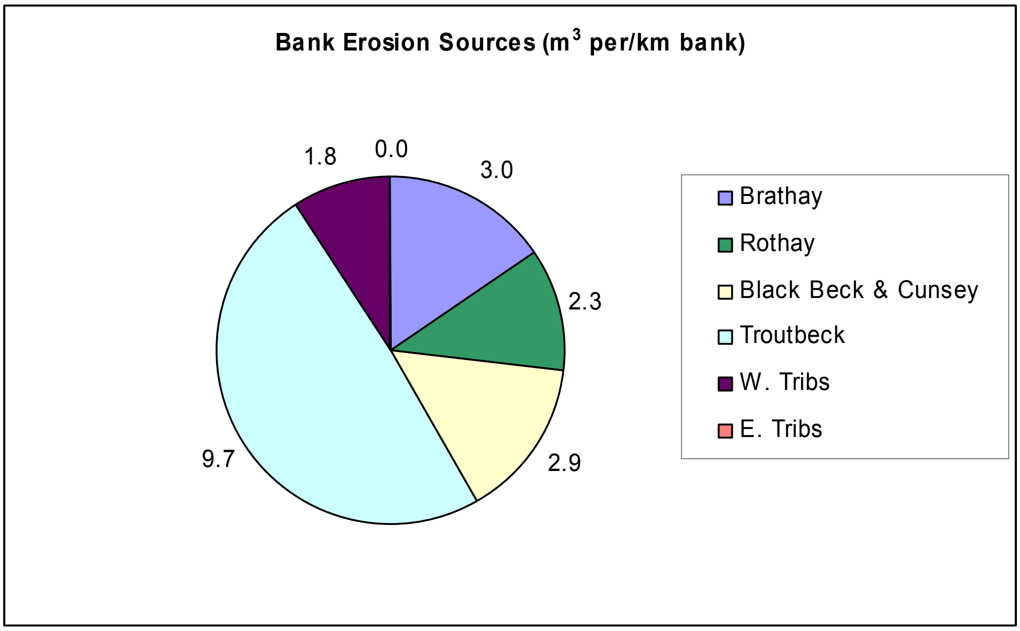

Figure 3.4 Amount of material sourced through natural bank erosion per km bank

Sediment Size

In the Rothay, Black Beck and Cunsey Beck, and small tributary sub-catchments, the sediment sourced was predominantly fine (< 2mm) with some coarse and bimodal sources. In comparison to these catchments the Brathay sub-catchment was predominantly bi-modal, but still supplied a large proportion of fines. Trout Beck sub-catchment was predominantly sourcing coarse sediment. 38% of the sediment sourced from the bank was fine (< 2mm). 34% of sediments from bank erosion were coarse material, and 29% was defined as bi-modal. 44% of the sediment sourced from poaching was fine (<2mm).

Relative Importance of Sediment Sourcing

Erosion is a natural process along river systems and is important in determining the form and function of river channels. It also has an essential role in floodplain development and for the creation of habitat diversity. Where rivers were modified, with natural processes compromised, or were constrained by bedrock, the extent of erosion along a bank length was lower. The rate of erosion is difficult to calculate at a single field visit, as sediment could either be sourced over a period of time, or during one single high flow event. The rate of erosion depends on various factors including bank material and composition, bank vegetation and surrounding land use, soil moisture and weathering. Without regular monitoring it is difficult to produce an accurate sediment budget (Section 3.5). However, this semi-quantitative analysis does provide some value by helping to prioritise management (refer to the Action Plan). Bank erosion was sourcing the greatest volume of sediment in the Windermere catchment, but it was not, overall, a significant feature (Table 3.1). The length of bank erosion, collapsing walls and poaching were not key issues when the volume of sediment supplied into the system was compared to the length of bank affected. This is illustrated in Table 3.1 which shows the length of bank affected by each type of source, compared to the total length of bank surveyed in each sub-catchment.

Table 3.1 Length of banks affected by sourcing

Sub-catchment	Source	Length of Bank Affected (m)	Percentage of Bank Affected (m)
Brathay (Potential banks 49416.m)	Bank erosion	671.5	1.4%
	Poaching	28	0.1%
	Footpath erosion	5	<0.1%
Rothay (Potential banks 34314 m)	Bank erosion	319	0.9%
	Poaching	225	0.7%
	Footpath erosion	7	<0.1%
	Wall collapse	3	<0.1%
	Valley side	17	0.1%
Black Beck & Cunsey (Potential banks 9701 m)	Bank erosion	187	1.9%
	Poaching	9	0.1%
	Footpath erosion	2	<0.1%
Troutbeck (Potential banks 15186 m)	Bank erosion	182	1.2%
	Valley side	24	0.2%
West Tributaries (Potential banks 35931 m)	Bank erosion	319.5	0.9%
	Poaching	52	0.1%
	Footpath erosion	1.5	<0.1%
	Wall collapse	5	<0.1%
	Valley side	12	<0.1%
	Fallen trees	5.5	<0.1%
East Tributaries (Potential banks 7056 m)	Valley side	5	0.1%

The surveyed bank length totalled 151.6 km (left + right bank). The total length of bank affected in each sub-catchment, for each of the source types listed, was less than 2%. Even for Trout Beck sub-catchment, where the proportion of bank erosion is relatively high, the percentage of bank affected only totalled 1.2%. The percentage of bank length affected in the Black Beck and Cunsey Beck sub-catchment was greater with 1.9% but the total volume was low as these are short rivers.

3.4.2 Sediment Sinks

Volume of Sediment Stored

Over 1400m^3 of sediment in the Windermere catchment was stored as discrete bars (point bars, side bars, tributary bars, mid-channel bars or bars formed at an in-channel structure or fallen tree) (Table 3.2, Figure 3.5, Figure 3.6). In the Rothay and Brathay sub-catchments there was evidence of out of bank/floodplain deposits. With the exception of the Brathay, there was a relatively low volume of sediment stored within river channels. The Brathay sub-catchment had a large volume of sediment stored in multiple mid-channel islands (>50% vegetated) consisting of vegetated boulders and cobbles in an over-widened section of the river with some bedrock outcrops. Mickleden Beck, Oxendale Beck and Redacre Gill within the Brathay sub-catchment also had evidence of relatively permanent coarse gravel, cobble and boulder deposits in the upland sections. Due to the large volume of sediment and many indistinct features, it was not possible to quantify the extent of this deposition. The Trout Beck and Brathay sub-catchments had a large volume of sediment stored in temporary bars which were less than 50% vegetated.

Table 3.2 Volume of sediment stored in the channel as bars per km of river surveyed

Sub-catchment	Stability of deposit	Volume of Sediment Stored (m^3)	Length of Surveyed Watercourse (km)	Volume of Sediment Stored per km of Surveyed Watercourse (m^3km^{-1})
Brathay	Discrete bars <50% veg	510.9	24.7	20.7
	Bars >50% veg inc. mature islands & berms	3727.3	24.7	150.9
	Out of bank deposits	15.1	24.7	0.6
Rothay	Discrete bars <50% veg	196.1	17.2	11.4
	Bars >50% veg inc. mature islands & berms	54.9	17.2	3.2
	Out of bank deposits	14.2	17.2	0.8
Black Beck & Cunsey	Discrete bars <50% veg	40.2	4.9	8.3
	Bars >50% veg inc. mature islands & berms	38	4.9	7.8
Troutbeck	Discrete bars <50% veg	484.9	7.6	63.9
	Bars >50% veg inc. mature islands & berms	297	7.6	39.1
West Tributaries	Discrete bars <50% veg	172.7	18.0	9.6
	Bars >50% veg inc. mature islands & berms	31.1	18.0	1.7
East Tributaries	Discrete bars <50% veg	2.6	3.5	0.7

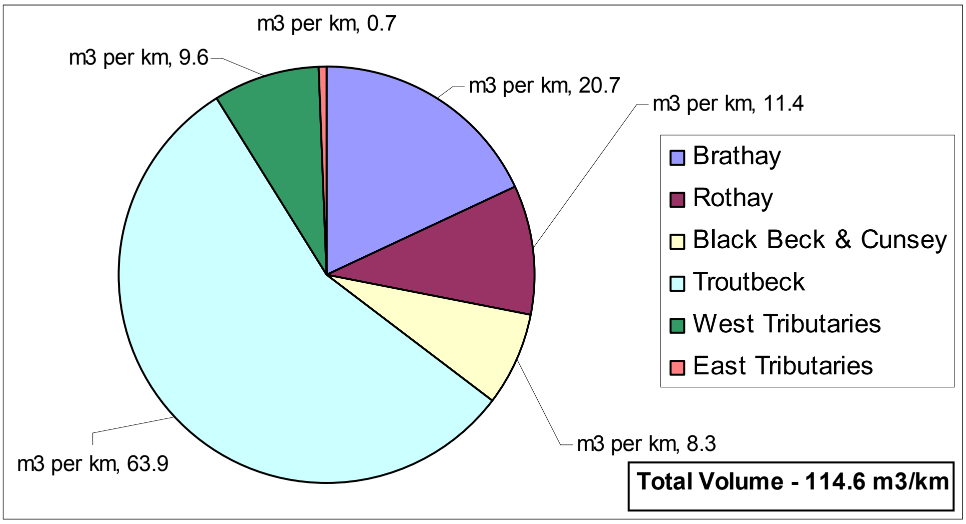

Figure 3.5 Volume of sediment stored in the channel as <50% vegetated bars per km of river surveyed

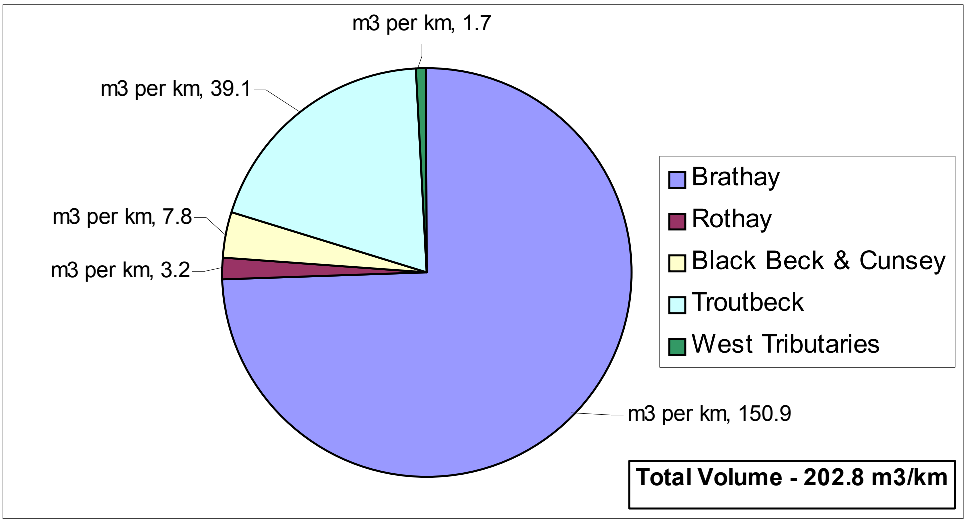

Figure 3.6 Volume of sediment stored in the channel as >50% vegetated bars per km of river surveyed

Bar Stability

The catchment as a whole is particularly flashy in nature with periodic entrainment and transport of sediment. The predominant storage in the Windermere catchment appeared to be of a temporary nature (vegetated <50%) particularly in the Brathay and Trout Beck sub-catchments. The Brathay sub-catchment also had a large volume of more permanent deposits. For example, there were larger, permanent mid-channel islands, related to bedrock outcrops at the surface. Due to the lower gradient and energy and wider channel, sediment has been able to deposit more readily in these areas. There was some evidence of out of bank deposits which could have occurred as result of high flows/floods shortly before the surveys. Figure 3.7 (a-h) (Appendix C) highlights that the majority of sinks were located in the upper to middle reaches of the rivers, where gradient reduces below the steeper upper sections, or where sediment was being actively managed (for example in the upper reaches of the Brathay sub-catchment).

Bar Formation

Side bars were the dominant type of deposit within the Windermere catchment. Table 3.3 highlights the number of each bar type in each sub-catchment. Side bars were most prominent in the Black Beck and Cunsey Beck, West Tributaries and Rothay sub-catchments. Point bars were predominantly found along some tributaries of the Rothay, along Black Beck and Cunsey Beck and in the upper reaches of the Brathay catchment. This was mainly due to these channels displaying a more sinuous meandering planform, where sediment has been deposited on the inside of bends. Mid-channel bars were less common throughout the catchment, most evident along Trout Beck and some of the western tributaries. Mature islands were found in the Brathay sub-catchment where the gradient reduced. A limited number of bars were found at tributary confluences where the gradient and flow reduced causing sediment to deposit. Similarly some bars had formed where rivers flow into lakes, due to the reduced energy conditions at the upstream limit of the lake.

Table 3.3 Type and grain size of channel deposits

Sub-catchment	Bar type	Total No. of bars	No. of bars/km^{-1}	Average Grain Size (%) Fine ≤2 mm	Coarse ≤30 mm	≤60 mm	>60 mm	Bimodal	Not visible
Brathay	Side bar	15	0.61	7	67	20		7	
	Point bar	16	0.65	6	25	38	19	13	
	Mid channel bar	9	0.36	11		33	44		11
	Mature islands	8	0.32						100
	Tributary bar	2	0.08						100
	Berms	3	0.12				33	67	
Rothay	Side bar	34	1.98	3	56	21	3	18	
	Point bar	13	0.76		31	69			
	Mid channel bar	11	0.64		18	18	55		9
	Tributary bar	1	0.06		100				
Black Beck & Cunsey	Side bar	13	2.68	8	54	38			
	Point bar	9	1.86		44	22	11	22	
	Mid channel bar	1	0.21			100			
	Mature islands	1	0.21					100	
	Tributary bar	1	0.21		100				
Troutbeck	Side bar	7	0.92		29	43	29		
	Point bar	2	0.26		50	50			
	Mid channel bar	7	0.92		29		57		14
	Berm	1	0.13			100			
West Tributaries	Side bar	46	2.56	2	37	48	13		
	Point bar	10	0.56		30	60	10		
	Mid channel bar	16	0.89	6	31	44	13		6
	Tributary bar	1	0.06				100		
	Lake/Outlet deposit	2	0.11		50	50			
	Berm	1	0.06			100			
East Tributaries	Side bar	1	0.28		100				
	Deposit behind boulder	1	0.28		100				

Grain Size

Most of the material stored within the channel was coarse sediment (>2 mm). Table 3.3 summarises the grain size data for each bar type. Mid-channel bars comprised the coarsest material, side bars finer material. Overall, the bars predominantly consisted of coarse sediment over 2 mm in size. Side bars were mainly ≤30 mm, point bars between 2 mm – 60 mm and mid-channel bars generally over 60 mm in grain size. Very few deposits were predominantly fine in nature. However, some of the recorded bars were bi-modal with finer material interspersed within the coarser substrate. In general, more of the finer material would have been transported downstream rather than stored in bars, as it is held in suspension at all but stagnant flow. In general, the temporary sediment sinks comprised predominantly coarse material, and the more permanent features often consisted of a mixture of coarse and fine material which has aided vegetation colonisation.

Floodplain Storage

Floodplain storage was an important feature within the Windermere catchment. The floodplain is a natural storage area for flood flows and fine sediment. When inundated, the velocity of water flowing over the floodplain falls, leading to sediment becoming naturally deposited. In areas where there was good floodplain connectivity there was greater opportunity for out of bank sediment deposition to occur, which is likely to form a permanent sink. At various locations, ponds, standing water or wetland areas were observed on the floodplain. Examples included Greenburn Beck, Wilfin Beck, the River Brathay as it enters Elterwater and the Brathay/Rothay confluence. Figure 3.8 (a-c)

(Appendix C) shows that good floodplain connectivity was found in the lower reaches of the sub-catchments.

Relative Importance of Sediment Storage
Figure 3.9 (a-h) (Appendix C) clearly illustrates that there was significantly more sediment stored in the channel than currently being supplied to the rivers. This is because sediment is often stored over longer time frames because of the episodic nature of erosion and transport processes. However, most reaches showed only a limited amount of sediment input or storage and were classed as predominantly transfer zones. For example, Green Burn upstream of the Rothay, and smaller tributaries on the east and west banks of Windermere (UND – Wilson Knott and UNG – Astley's plantation) had no recorded sources or sinks, due to their steep, bedrock nature and walling further downstream. However, a downstream culverted section may conceal an area of deposition (Appendix B Watercourse Summaries). Sediment was generally sourced in the upper to middle reaches of the sub-catchments and was also temporarily stored in these locations, prior to being transported downstream. It was generally stored in the middle and lower reaches in more permanent deposits due to the reduction in gradient allowing more deposition than erosion to occur.

3.4.3 Sediment Transport

The processes of sediment supply and sediment storage are linked by sediment transport. It is therefore possible to deduce trends in sediment transport through comparison of the distribution of sediment sources and sediment stores, and through observations in the field. Many of the individual reaches had more than one function (and in some cases all three), but a dominant function was identified in the majority of reaches. Overall the rivers within the Windermere catchment were transfer zones. Figure 3.10 (a-c) (Appendix C) highlights that the transfer zones occurred predominantly along the upper and middle sections of the sub-catchments. Many of the smaller tributaries were characterised as transfer zones for the full length of the river. The channels in these sections were either partially stabilised by bedrock, particularly in the upper reaches, had a steep gradient promoting sediment transport, or were realigned and walled, leading to few/no erosion or deposition opportunities.

The sediment sources and sinks maps (Figure 3.9 (a-h) – Appendix C) indicate that the majority of hillslope sediment was not generally supplied in the higher reaches covered by the audit, but more in the middle reaches. Sediment was predominantly supplied by bank erosion in the upper to middle reaches of the sub-catchments where there was less modification, and less bedrock, allowing lateral migration and other sediment-releasing processes to occur. However, the spatial extent of the survey (as defined by the Environment Agency) did not cover many of the headwater systems so this needs to be taken into account when interpreting this information.

The major sink zones included the upland areas of the Brathay sub-catchment, particularly the upper reaches of Mickleden Beck and Oxendale Beck, where coarse sediment had been actively managed in gravel traps through the use of weirs, which reduced the local bed gradient and promoted deposition. The level of deposition behind weirs has not been quantified. In addition, in Redacre Gill there were temporary sink zones where coarse sediment had been deposited due to the large volumes of sediment supplied to the system in a recent major flood event. Downstream of these features there was a sudden change in gradient which also increased the level of more permanent deposition. In the lower reaches of the River Brathay, close to Windermere, there were sink zones due to the reduction in gradient and the effect of ponded flow. In the Black Beck and Cunsey Beck sub-catchment there were temporary sink zones in the upland areas, particularly in reach BLK003, where the gradient reduced before the river flowed into Esthwaite Water. Similarly, this occurred in reaches CUN002 and CUN005 of Cunsey Beck where the gradient of the river bed reduced. In the Rothay catchment, Scandale Beck, (reaches SCA002 and 003) and Stock Ghyll, (reach STO002), were temporary sediment sinks due to historic channel confinement or more recent modification and independent sediment management.

3.5 Sediment Budget

It is difficult to determine an accurate sediment budget without regular and long term monitoring. Within a larger catchment with many rivers of various sizes, like Windermere, there is more uncertainty in the estimation of quantities of sediment sources and sediment sinks. The sediment budget presented in this section is based on data collected during the survey, so provides information for only a snap-shot of time and in only the mid-lower parts of the catchment covered by the Fluvial Audit. As mentioned in Section 3.4.1, bank erosion rates are difficult to determine, as are the residence times of the material stored within the bars in the channel. The values presented in Figure 3.11 are therefore crude, but still useful to evaluate the sediment regime if the limitations are taken into consideration.

The sediment budget of the Windermere catchment shows 5.5 m^3 per km^{-1} of sediment supplied to the Windermere catchment, of which bank erosion contributes 3.1 m^3 per km^{-1}. This sediment is either transferred downstream, stored as in-channel bars, or deposited in the lakes. Storage in the Windermere catchment totals 73.7 m^3 per km^{-1}, of which over two-thirds is stored as permanent/semi-permanent in-channel bars or berms. The active bars (sediment accumulations with less than 50% vegetation cover) make up approximately 18.6 m^3 per km^{-1} of the total being stored in river channels. The current sediment budget (storage deficit of -13.07 m^3 per km^{-1}) indicates that more sediment is being temporarily stored than is being sourced. However not all sediment sources in the catchment will have been recorded. Possible reasons for the lower sourcing figures include;

- data was only collected for 76 km of the rivers within the catchment, not for the whole catchment, (particularly the upland headwater systems which would be significant contributors of sediment were not included);
- surface runoff from fields and field drains was not possible to quantify within the scope of the study, although observations were made;
- erosion of the channel bed was not possible to quantify within the scope of the study.

Figure 3.12 summarises the breakdown of where sources and sinks were found within the catchment. It highlights that the Trout Beck catchment was reasonably active with the highest volume of sourcing and temporary sinks per kilometre. The Brathay catchment also had a large number of sinks however these were predominantly permanent features.

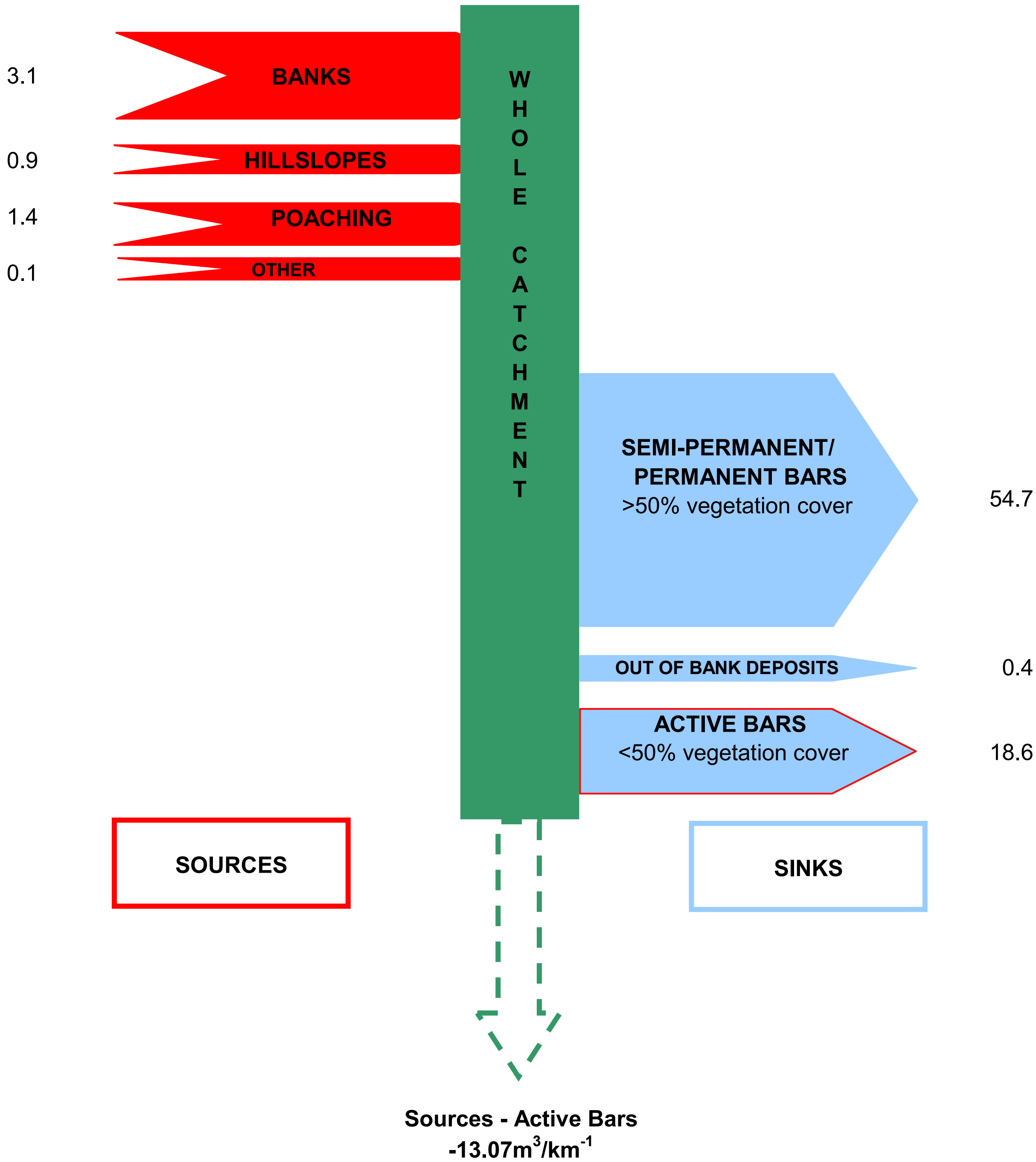

Figure 3.11 Sediment budget for Windermere catchment
(Other sources include footpath erosion/maintenance, collapsed walls and sediment supply from tree fall).

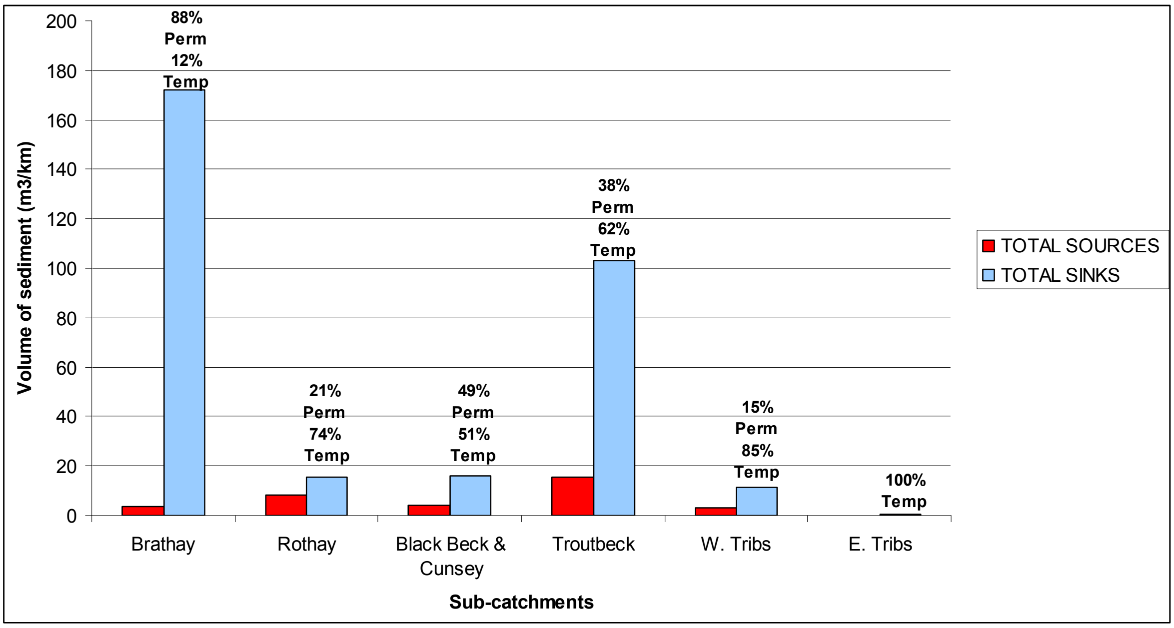

Figure 3.12 Comparison of sources and sinks by sub-catchment (Including % of permanent and temporary sinks)

3.6 Summary

3.6.1 Sediment Sources

- Sediment source regions were in the upper catchment, where the gradient was steep, and also in the middle reaches where there was potential for greater lateral migration. The lower reaches of the River Brathay also showed evidence of poaching and bank erosion before entering Windermere.
- Approximately 400 m^3 of sediment has been sourced to the Windermere catchment (from direct, visible sources), of which approximately 56% was derived from bank erosion processes.
- Bank erosion was more prevalent in the Trout Beck and Brathay sub-catchments in terms of volume. In addition, the River Rothay and Wray Beck had a larger number of areas of erosion, while Black Beck and Cunsey Beck had the longest lengths of bank affected. Overall bank erosion was not a significant issue on a catchment wide scale. Less than 2% of the bank length was eroding in each sub-catchment.
- Only 38% of the material sourced from bank erosion was fine (<2 mm), 34% is coarse (>2 mm) and 29% bimodal.
- Similarly, poaching was not a significant issue at the catchment scale, as less than 0.7% of the bank length had evidence of poaching. The Rothay sub-catchment was identified as having the highest level of poaching.

3.6.2 Sediment Sinks

- The middle to lower catchment was dominated by sediment storage (sinks) and transfers. The gradient was lower in these reaches and the channels were wider, promoting sedimentation. In the upper catchment sediment was often stored as temporary sinks before being transported downstream.

- Over 1400 m^3 of sediment in the Windermere catchment was stored as temporary bars, over 4148 m^3 was stored as semi-permanent/permanent bars or berms and there was evidence of sediment being deposited out of bank (i.e. during flood events).
- The Trout Beck sub-catchment stored the most sediment in discrete temporary bars (per km length of surveyed watercourse) partly due to over-widened reaches. The Brathay sub-catchment stored the most sediment as permanent bars, islands and berms (>50% vegetated).
- Most of the material stored in bars comprised coarse material. Mid channel bars had the coarsest material (but were also one of the rarest features), while the side bars had the finest material. 14% of all the bars had material over cobble size (60 mm) and only 3% of bars consisted of fine material (<2 mm).
- The majority of the storage in the catchment appeared to be of a semi-permanent/permanent nature in the form of vegetated bars and mature islands.

3.6.3 Fine Sediment

- 38% of sediment sourced from the banks was fine (<2 mm).
- 44% of sediment sourced from poaching was fine (<2 mm).
- Of the total sourced material, 37% of the material was classified as fine and 31% bi-modal.
- Only 3% of deposits were predominantly fine, largely consisting of side bars.
- A further 6% of bars were considered bi-modal which would consist of both fine and coarser material.
- Most of the rivers, tributaries and field drains/ditches appeared to have a clear flow, even during, and after, heavy rainfall.
- One tributary entering Great Langdale Beck and the un-named watercourse near Cunsey Farm appeared to have a turbid flow. Many rivers were also transporting leaf litter as the field surveys took place in autumn.

4 Catchment Erosion Risk

4.1 Introduction

The Sediment Source Risk Map is intended to provide a simple indicator of potential pathways for sediment supply into the Windermere system from the wider catchment. Identifying the wider erosion risks throughout the catchment can help in the development of wider catchment action plans including land management opportunities such as afforestation. This process does not specifically differentiate between fine and coarse sediment supply.

Only selected rivers within the Windermere catchment were surveyed during the Fluvial Audit, as requested by the Environment Agency. This included the more downstream reaches of the larger rivers in the north of the catchment, along with smaller streams in the east and west that discharge directly to Windermere. The risk rating is a good method for analysing the whole catchment to identify key areas outside the extent of field survey which could present a greater risk for sediment sourcing.

The Sediment Source Risk Map is created using three variables that control broad patterns of erosion. These are land cover types (which infer a degree of vegetation cover), slope angle and Stream Order. This is in contrast to erosion risk assessed using physical processes observed during watercourse surveys. The potential sources of sediment from the field surveys are identified in section 3.2.

4.2 Methodology

4.2.1 Risk Map

The development of the sediment supply map is based on the methodology presented in Orr et al. (2004) for a similar study of Bassenthwaite Lake catchment. The risk assessment is based on physical processes and is based on two (50m x 50m) grid based variables (slope angle and land/vegetation cover) and in addition, includes the weighting on the grid according to Stream Order (Strahler, 1965) (see Table 4.1). The mapping of bare ground used by Orr *et al*. (2004) (and designed by McHugh *et al*., 2002) was not used in this study as it would involve considerable time to generate and was not a priority for the Environment Agency at this stage. However, bare ground is considered within various subsets of the LCM 2000 dataset that was used for land cover assessment.

The land cover raster dataset was reclassified using the LCM 2000 classes published by the Centre for Ecology and Hydrology (CEH) to account for potential sediment supply risk. All waterbodies and lakes were separated from the raster dataset as these were not included in any risk category.

The slope data were derived from the NextMap Digital Elevation Model (DEM) using ESRI Spatial Analyst extension in ArcMap 8.3. The slope angles derived from the DEM were reclassified based on their risk ratings (Table 4.1).

The risk surface was derived by adding the land cover and slope variables together using the Raster Calculator in Spatial Analyst. This gives a new raster dataset showing a combined risk surface for the Windermere catchment (Figure 4.1 – Appendix C).

Table 4.1 - Risk Rating Table

Sediment Supply Risk	**HIGH**		**MEDIUM**		**LOW**
	5	**4**	**3**	**2**	**1**
Slope	49-60°	37-48°	25-36°	13-24°	0-12°
Vegetation (LCM 2000)	• All sediment and rock classes	• Arable and horticulture • Peat Bog • Urban • Littoral rock	• Coniferous woodland • All grass • Bracken • Montane habitats • Suburban	• Set aside grass • Open shrub heath	• Broadleaved / mixed woodland • Dense dwarf shrub heath • Fen, marsh and swamp
Stream Order*	1	2	3	4	5

** Those sub-catchments that were defined without a stream identified were given a rating of 0*

4.2.2 Sub-catchments and stream order

It is more useful to visualise the resulting erosion risk grid in sub-catchment areas by generalising/averaging the data across a defined area. The sub-catchment watersheds for the Windermere catchment area were derived from the DEM using the ArcHydroTools extension in ArcMap following the methodology outlined by Chen *et al*. (2007). Firstly, the raw DEM was reconditioned allowing the surface drainage pattern present in the catchment to be easily recognised by imposing a river networks onto the model to provide more efficient watershed delineation. The grid was processed to remove any elevation anomalies (e.g. where water may become trapped and unable to flow in any direction). This process of filling the 'sinks' modifies the elevation to eliminate these problems. Subsequently the flow patterns and stream definitions were calculated. The *Catchment Grid Delineation* function creates a grid in which each cell carries a value indicating to which catchment the cell belongs. The value relates to the stream segmentation that drains the area, defined earlier in the process. The results of this process allow sub-catchment polygons to be defined for the entire catchment. Using *Zonal Statistics* tool from Hawths Analysis Tools (a freely available extension for ArcGIS) the grid-based risk surface was generalised (based on an average value) for each sub-catchment.

Finally, the sub-catchment risk map (Figure 4.2 - Appendix C) was then combined with the stream order risk value as calculated from the polyline river network. The polyline shapefile was converted (based on the risk value in Table 4.1) to a raster dataset and the average risk rating added to the existing sub-catchment risk map to derive the risk model for each sub-catchment. The raster conversion allows for the extent of the river in each sub-catchment to be accounted for.

The methodology followed is summarised in Figure 4.3.

4.3 Results

4.3.1 Results of catchment-wide model

The majority of the Windermere catchment has a moderate-high or high potential for supply of sediment into the river system. There are sub-catchments with a medium erosion risk rating scattered to the north and west of Windermere and a small cluster of low erosion risk sub-catchments on the eastern shore of Windermere.

The sub-catchments with the greatest erosion risk are predominantly to the north of Windermere in the upland terrain. These sub-catchments have steep slopes and less substantial vegetation cover and therefore create the greatest risk.

The sub-catchments with a medium-high erosion risk make up the bulk of the Windermere catchment. These have a combination of moderate to high slopes and a moderate to high land cover risk rating (a high land cover rating is allocated because the soil and sediment in these areas are thought to be vulnerable to erosion based on the type of land cover). They may also have a high slope but low land cover risk (e.g. mature/wooded vegetation) or a low slope but high land cover risk (little vegetation cover, mainly sediment and rock).

Although the erosion risk map suggests a high potential for sediment supply, the field survey results do not directly correlate with the findings in most areas. The fluvial audit did not reveal areas of very significant erosion or large volumes of sediment supply. The majority of reaches surveyed were stable without significant erosion or deposition. The most upland reaches in the north of the catchment, with the potential for high sediment supply, were not included in the field survey. It is likely that these sub-catchments do have a high risk of erosion and sediment supply. This supply is likely to be from coarse sediment from valley side/scree sources. During the field survey a record of the connectivity between the river channel and valley side sediment sourcing was made, but this very rarely revealed a combination of high connectivity with significant sourcing areas.

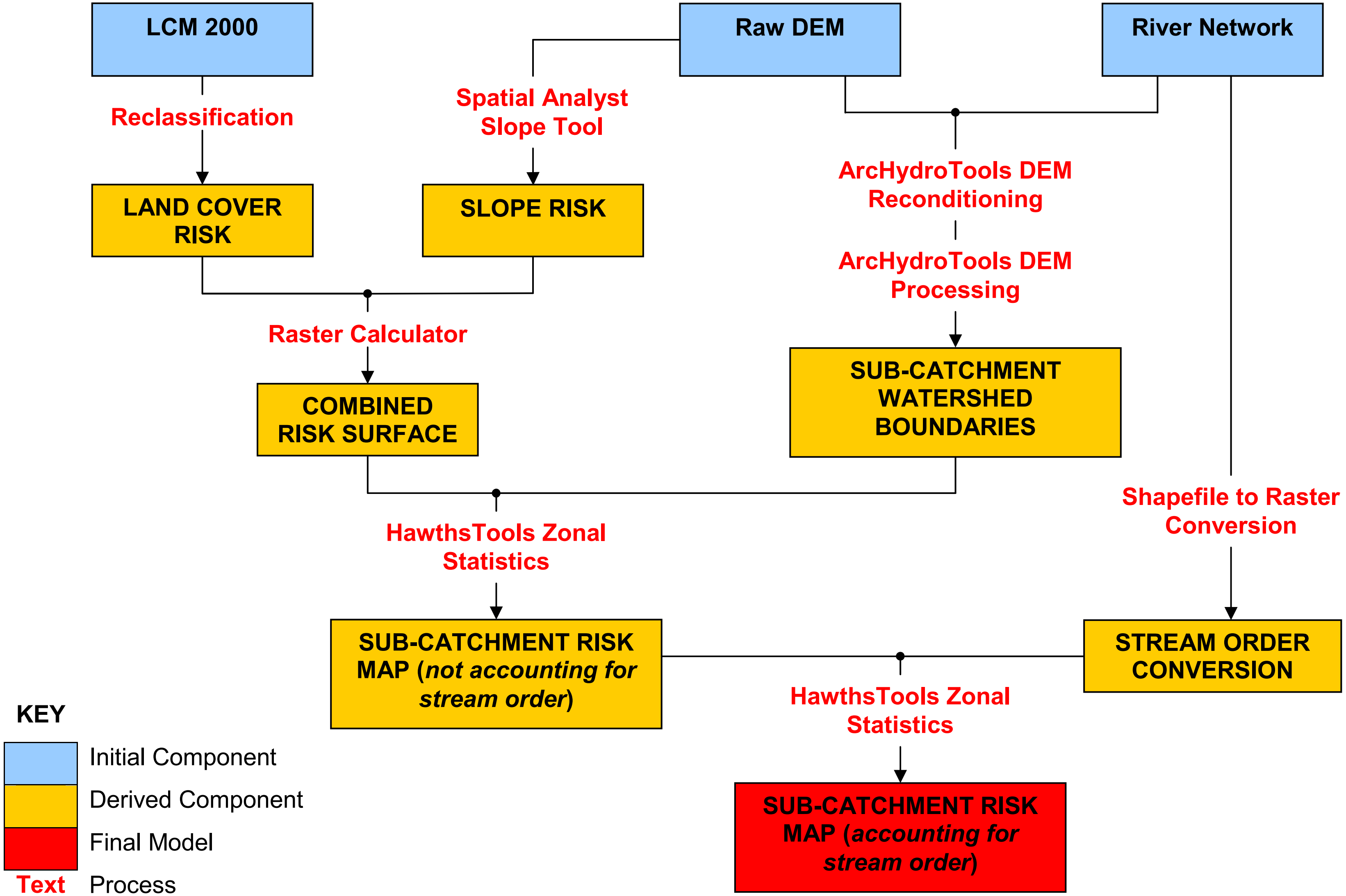

Figure 4.3: GIS processes involved in creation of Catchment Risk Map

4.3.2 Limitations

There are a number of very general assumptions made in the generation of the Sediment Source Risk Map which limit the detail of the map.

Although there have been site-specific studies of the transfer of slope-derived materials to watercourses, it is generally not well reported or understood at the catchment scale. Consequently there are limits to a simplistic model's ability to indicate how much of any material sourced from catchment slopes makes its way to rivers and eventually to lakes, nor the timescales for these processes. This is also altered by modifications and management practices to 'trap' gravel in the upper reaches (such as at Mickleden Beck in Great Langdale). It is also clear from the field data that only a small proportion of the high risk areas are actually eroding or can be considered as significant sources of sediment due to connectivity between valley sides and river channels.

Erosion of the channel margin is assumed to be a direct source of transportable material. Bank erosion and poaching sources were identified in the field survey rather than being included in the erosion model as they are too small scale and 'location-specific'. A further caveat is that the risk map does not represent the sediment being supplied through sub-surface drainage and trampling of drains and minor tributaries (Orr et al 2004). It is also assumed that the lowest order streams (those highest in the catchment) are at greater risk from erosion and therefore potentially contribute the larger volume of fine and coarse sediment. However this is not necessarily the case; although they have a high potential energy, the lowest order streams rarely have floodplains to be eroded and are usually controlled more by bedrock and solid geology (more resistant materials). Consequently, erosion adjacent to these streams will produce/supply predominantly coarse sediment. Higher order rivers have more extensive floodplains and more drift geology (less resistant material), which have developed through sediment deposition over time. Therefore the higher order streams may actually contribute more fine sediment to the rivers because they have the potential to migrate across the valley floor and release the fine sediment stored in the land adjacent to the river.

5 Conclusion

5.1 Summary and Conclusion

The character and behaviour of watercourses in the Windermere catchment was strongly influenced by the topography and geology. Fine sediment sourcing was limited in the upper regions of the catchment due to the hard geology. Some evidence of sourcing was observed in the Brathay catchment where the drift geology differs slightly, and a number of the steeper upland tributaries were promoting natural coarse sediment sourcing. The highest volumes of bank erosion occurred in the middle and lower reaches of rivers where the geology was softer and less resistant to erosion. The Trout Beck and River Brathay sub-catchments were areas where higher levels of bank erosion and poaching occurred. Although bank erosion contributed the majority of the sediment to the system, it was not a significant volume in relative terms; less than 2% of the bank length was actively eroding in each sub-catchment. Poaching also did not represent a significant issue at the catchment scale, with less than 1% of the total bank length affected. Other sources, such as footpath erosion/maintenance, collapsed walls and tree fall, do not currently present a problem other than in very localised areas. Of the sediment that was sourced, it is estimated that 38% of the sediment sourced from the banks and 44% sourced from poaching was composed of predominantly fine material (<2mm).

Many of the rivers surveyed were acting as transfers for sediment. In the upper and middle sections, bedrock often formed the boundary conditions, leading to stable streams with moderate-steep gradients, promoting sediment transport but little erosion or deposition. Lower reaches were often realigned and walled/channelised, with little opportunity for erosion or deposition. Fine sediment would be efficiently transferred through these reaches. Generally the rivers within the catchment were stable, and only a few reaches showed evidence of active geomorphological processes of lateral adjustment, incising, narrowing, aggrading and widening, which influence patterns of sediment erosion and deposition.

The sediment budget of the catchment suggests that there is (currently) thirteen times more sediment stored in the channel than being sourced to the system. However, this number should be treated with caution as many of the upper headwater systems were not in the scope of the survey and hence this figure could be skewed. Generally, coarse sediment sourced in the upper/middle catchment was temporarily stored in active deposits, before being transported downstream where it was more permanently stored in mature islands and more permanent bars that have become vegetated over time. Only 3% of the deposits were predominantly fine material, largely forming temporary side bars. The majority of fine sediment would have been carried in suspension and flushed through the system during earlier rainfall events, to be deposited within the numerous lakes within the catchment.

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(Environmental Designations)

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