The Status of Suspended Sediments in the High Peak Moorland Streams: Indices of Erosion.

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Abstract:

Peat erosion is the main source of suspended sediment in the output streams of peat catchments. This can have serious ecological and economical effects downstream. In theory the suspended sediment status of a catchment's outlet can be used as an index of the catchment's level of erosion. To test this, the suspended sediment statuses of four catchments in the South Pennines, whose differing levels of erosion were estimated using remote sensing and GIS, were monitored for stage and turbidity using field probes and data loggers. These were calibrated into discharge (cm^3/s) and suspended sediment concentration (mg/l) (SSC) using stage-discharge and turbidity-SSC relationships based on field samples. These were then used to produce sediment rating-curves to describe the sediment delivery regimes of each catchment and therefore study the spatial effects on sediment delivery. Past records of SSC and discharge for one catchment spanning over a year were also collected to investigate the temporal effects on sediment delivery and to ensure that any spatial effects witnessed were not due to differences in time. The sediment rating-curves varied considerably more in gradient between catchments than over time, suggesting that spatial differences are the dominant control on the suspended sediment status. These changes in gradient correlated extremely well with changes in the percentage of bare peat within the catchment ($r^2=0.9851$), suggesting that suspended sediment could well be used as an index of erosion – an extremely useful tool in peatland management. Though not as significant, temporal factors also showed their effects on sediment delivery and as a result should not be totally excluded from any suspended sediment based index.

Keywords: Field monitoring, GIS, peat erosion, sediment rating-curves, South Pennines, stage calibration, suspended sediment concentration (SSC), turbidity calibration.

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1. Introduction

Though peatlands such as the High Peak Moorland only cover a total land cover of around 8.6% in the British Isles, it is mainly in the uplands and as a result have a large bearing on the stream flow and erosion of most of the major rivers in Britain (Labadz et al. 1991). The suspended sediment in streams from the erosion of such peatlands is now recognised for its detrimental effect not only to the environment downstream, but also the economy – Walling (1988) estimated costs could be as much as $1 billion in the U.S.A. at 1988 values. In terms of weight, suspended sediment concentration (SSC) readings from peatland catchments are typical for a British upland catchment, but peat's low density means that volumetrically it is a problem, especially when concerned with such effects as reservoir infilling. The South Pennine database shows loss by infilling of 7.5% for the area since the original reservoir quoted capacity (Burt et al. 1997). Other effects include water discolouration, which is a particular problem to water companies due to the cost of the filtering processes needed to clean it, and the ability of suspended sediment to act as a transport medium for pollutants. The eroded sediment also leaves behind a very unsightly landscape that is difficult to walk across, limiting its recreational uses (Burt et al. 1997). The local ecosystem productivity may also be affected, not only by the loss of habitat, but also the clogging up of streams that affects the stream flora and fauna, especially invertebrate faunas (Crisp & Robson 1979).

This presence of suspended sediment in streams was once believed to be a direct result of the catchment size. Walling (1983) was the first to realise the error in this 'black box' theory due to the spatial and temporal lumping of the catchment's characteristics. The sediment supply and sediment transport within of a catchment are both extremely variable on a temporal and spatial scale (Labadz et al. 1995). Walling (1983) described how the sediment delivery of a catchment is affected by factors such as antecedent moisture conditions and season on a temporal scale and the diversity of topography, land use and soil conditions on a spatial scale, affecting the watershed delivery or conveyance function in much the same way as Manning's equation. The different assemblages of these factors characterise individual catchments and their sediment delivery regime. Upland peat catchments tend to place particular importance on meteorological and hydrological conditions as well as fluctuations in sediment supply (Labadz et al. 1995).

1.1 Sediment Transport

Sediment transport in peatland catchments varies very little on a spatial scale due to their extremely flashy characteristics. Much of the precipitation that lands on these catchments is returned almost immediately to the channel (Burt et al. 1997), some studies showing SSC peaks occurring as soon as 30 minutes after peak rainfall intensity (Burt & Gardiner 1984). The fact that there is little delayed flow in peatland hydrographs indicates the minor role that throughflow plays in comparison to overland flow, which because of the low gradients and high water tables is mostly in the form of saturation-excess overland flow (Burt et al. 1990, Holden & Burt 2003a). As a result, slopes and channels are very well coupled. This efficiency in flow is common on both undamaged and damaged peat with overland flow produced easily even under low intensity rainfall (Holden & Burt 2002), and therefore means that sediment supply is the most important spatial variable in the sediment delivery of peat catchments, though it may also vary temporally as well.

1.2 Sediment Supply

Sediment supply is unlikely to be of any significance in peatland catchments unless there are areas of bare, unvegetated peat because sheet erosion occurs on surfaces as vegetation breaks up and no longer protects the peat beneath it (Imeson 1974, Wishart & Warburton 2001, Charman 2002). This is the same explanation Burt and Gardiner (1984) suggested to explain the differences in SSC delivery in the two peatland catchments they were studying. They found the more eroded catchment was producing more SSC and as a result, SSC was much better related to discharge too. When unprotected by vegetation, the uppermost layer of peat loses it cohesiveness through frost action and desiccation (Bragg & Tallis 2001) and can therefore be easily removed by rain-wash (Tallis 1973, Crisp & Robson 1979, Francis 1990, Labadz et al. 1991, Burt et al. 1997). The limited sediment supply in well vegetated catchments often results in sediment exhaustion where SSC levels start to drop while discharge is still rising. This is known as positive hysteresis, and though is most prevalent in vegetated catchments where the sediment supply is extremely limited, it is also common in the majority of eroded catchments. Many believe that it shows the sediment needs to be 'prepared' by desiccation and frost action before it can be transported (Labadz et al. 1991, Burt et al. 1997, Holden & Burt 2002). This requirement for peat to be loosened by desiccation or frost action means that erosion is also temporally variable, with supply being highest in late summer after the period of most desiccation (Francis 1990, Charman 2002). Different studies have not agreed on what the dominant control on sediment supply is from the level of erosion in the catchment (Trimble 1981) to antecedent moisture conditions (Sichingabula 1998) to even catchment sizes (Labadz et al. 1991, Asselman 2000).

As variations in sediment transport are negligible on a spatial scale in moorlands, if changes in the suspended sediment status of catchments are greater over a spatial scale than a temporal scale, then it can be used as an index of erosion. This is because though some believe catchment area is the dominant spatial control on SSC it is because of the remobilisation of deposited sediments in larger catchments. However there is very little storage of sediment in peatland channels (Burt et al. 1990), and so land cover (essentially the amount of bare peat) should theoretically dominate the sediment supply.

1.3 Sediment Rating-Curves

The sediment status of a catchment is best described through the use of a sediment raring-curve, which shows the average relation between discharge and SSC for a certain location (Asselman 2000). Previous studies have attempted to attach interpretations to different rating-curves (Sichingabula 1998, Asselman 2000) but any connections must be treated with caution as they are only speculative (Horowitz 2003). Linear rating-curves are used in this project whose change in gradient will represent different sediment delivery regimes. The flatter a rating-curve is, the less efficient the catchment is at delivering sediment, because as discharge rises, SSC does not. The opposite applies with very steep rating curves as SSC would increase significantly with a small increase in discharge. Of the two catchments studied by Burt & Gardiner (1984) the more eroded one had the steeper rating-curve, suggesting that the level of erosion does dominate the sediment supply. However Asselman (2000) suggests otherwise. His work on the Rhine showed that rating-curves became less steep the larger the catchment became even though the sediment delivery regime remained fairly constant across all the catchments. However Sichingabula (1998) suggests that the timing of events provides a partial explanation for the forms of rating-curves while spatial effects attenuate the characteristics of the events. Admittedly these studies were carried out over different catchment types with Burt & Gardiner's work being the only one carried out on a peat catchment. However it nonetheless still shows how every aspect can affect sediment delivery and it is not certain which causes the greatest variation in rating-curve gradient and hence which is the dominant control.

To create sediment rating-curves, discharge and SSC data is needed. Past work has highlighted the importance of storms in sediment delivery (Crisp & Robson 1979, Webb & Walling 1984) and as a result, the monitoring of high flow characteristics is imperative (Gordon et al. 1992). To establish accurate sediment load-discharge relationships, short, intense sampling programmes have been found to be the best (Moliere 2004) but logistically hard to carry out, especially if the recommended high flow readings are to be included. Therefore stage and turbidity are measured instead as surrogate variables for discharge and SSC respectively. They can be measured much more easily and at a low cost through the use of probes that can be left unattended in situ, while still producing reliable results (Kronvang et al. 1997).

Turbidity is a measure of the optical properties of water and is often used in sediment monitoring (Sun et al. 2001) with the assumption that water with a higher SSC will be less transparent. This is due to the increased scattering and absorption of any light transmitted through it by the increased number of suspended particles (Gordon et al. 1992). Though it can be affected by a number of different factors (Gippel 1989) including particle sizes, water colour and mineral content, it is still a reliable index. The preferred method of turbidity measurement as adopted by Standard Methods is using a nephelometric turbidimeter which measures the amount of light scattered at an angle rather than attenuance turbidimeters which measure the loss of intensity of a narrow parallel beam (Lewis 1996). Stage is the water level of the stream and is measured through the use of pressure transducers which measure the pressure of the depth of water above them.

The accuracy of stage and turbidity as surrogate measures depends largely on the accuracy of their calibration. For turbidity, this requires a relationship to be established between actual SSC measurements and their equivalent turbidity values. The relationship is then applied to the remaining turbidity readings to estimate SSC readings from them. However if the relationship is statistically insignificant then SSC calculations can be very misleading and distinctly alter the final sediment rating-curve (Horowitz 2003). The same applies to stage calibrations, but using a relationship established from actual discharge measurements and their equivalent stage. A large number of discharge readings are not needed, and in fact the use of more than three discharge readings will achieve little improvement in the calibrations long as they are at different levels of flow (Gordon et al. 1992).

1.4 Aims

The main aim of this project is to investigate the use of the suspended sediment status of a catchment's outlet as an index of the level of erosion in the catchment. The spatial and temporal effects on sediment delivery will be investigated to see which has the greatest influence on the local sediment delivery regimes. This will be done through the following objectives:

- Monitoring four catchments for SSC and discharge through the use of surrogate measurements.
- Creating sediment rating curves for each catchment with the collected data to study the spatial variation in sediment delivery.
- Creating a series of sediment rating-curves for one catchment over a period of time to highlight the temporal variations on sediment delivery.
- Establishing the level of erosion of each catchment through the use of GIS.
- Establishing which of the temporal or spatial variables has the greatest influence on sediment delivery, and therefore whether it can be used as an index of erosion.

2. Methodology

2.1 Site Selection

The High Peak Estate in the South Pennines is one of the largest areas of blanket peat in the British Isles (Labadz et al. 1991), and also one of the most eroded (Bower 1961). Though erosion is severe it is not homogenous across the whole area and therefore is ideal for investigating spatial effects as several catchments with different levels of erosion can be found in close proximity to one another. Four catchments were monitored, namely Hern Clough (Easting: 409854), Northing: 394750), Oyster Clough (E: 411758, N: 391460), Torside (E: 407641, N: 396880) and the Upper North Grain (E: 410378, N: 393520), whose locations can be seen in figure 1. The site choice was based upon two factors – the level of erosion and the ability to monitor them. The later was based on not only accessibility but in the case of Torside and the Upper North Grain on the fact that monitoring stations were already set up there and past SSC and discharge data existed for them both in case of any problems. All the sites were accessible with a 15-30 minute walk from the Snake Pass road (A57) that runs from Glossop to Sheffield, some being harder to reach than others. They also varied in levels of erosion which could be seen from aerial photographs of the area as well as walking around the catchments themselves. The same methods of data collection and calibration were used at each site, which are as follow in sections 2.2 and 2.3.

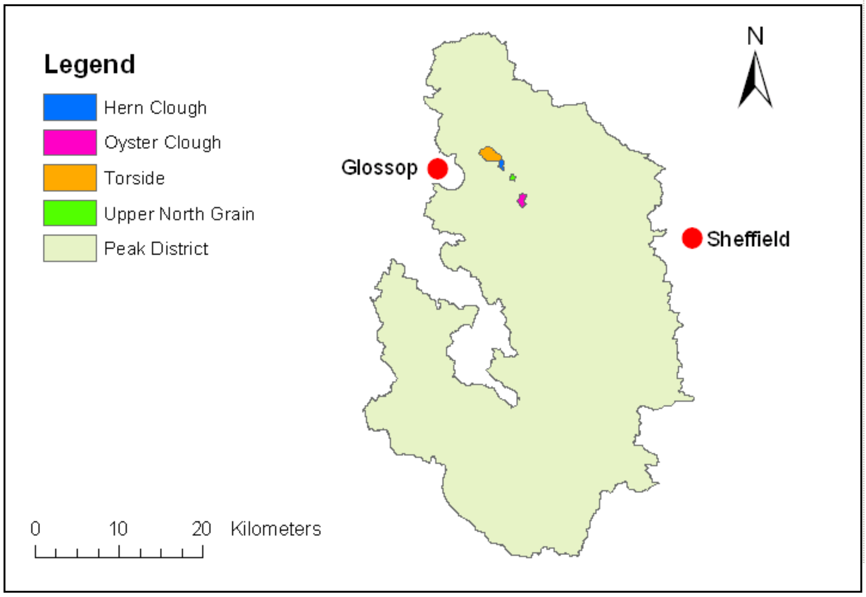


Figure 1: Location of the five monitored peat catchments.

2.2 Data Collection

Turbidity and stage readings were collected on a constant basis at five minute intervals by using probes connected to data loggers (Intelysis, Manchester), which were both controlled by the Sentry II programme. Turbidity was collected using Analite self-cleaning nephelometric probes where possible. If the probe used was not self cleaning then it was visited once a week and cleaned to ensure that possible algal growth on the probe did not interfere with the readings. Stage readings were collected using Intelysis pressure transducers which did not need cleaning. The sites were monitored for as long as was needed for a storm to be monitored so that the necessary high flow readings were collected, ranging from two weeks at some to a month at others.

2.3 Calibration

Actual measurements of SSC and discharge were collected for each site for calibration. SSC was measured by filtering samples collected at different stages. A rising-stage sampler (figure 2) was used to automatically collect the samples as stage rose, because the streams monitored were very flashy making it hard to get to in time for periods of high flow, especially when the site was remote and hard to access. The collected samples were filtered using vacuum pumps and Whatman GF/C 47mm filter papers. As this filter paper filters out any particles larger than 1.2μm it ensures that only suspended sediment is filtered. The resulting SSC (mg/l) was then matched with the turbidity readings taken at those stage levels by the probes. The ensuing relationship was then applied to the rest of the turbidity data to calculate SSC for the whole monitoring period.

The actual discharge readings consisted of taking flow readings at known stage heights. This combined with the cross sectional area of the channel could be used to calculate actual discharge readings. The methods used for the flow readings were as described by Gordon et al. (1992 pp160-161) using electromagnetic flow meters, but fewer than the recommended 20 sampling sites across the stream were used due to the size of the streams involved. They were however sampled at closer intervals than every 1m with the intention of sampling around 5-8 points across the stream, depending on the site. This was done twice at each site, once at a measured high stage and once at a measured low stage resulting in a two-point calibration. This was then applied to the stage readings recorded by the pressure transducer giving discharge readings for the monitoring period.The now calibrated readings of SSC (mg/l) and discharge (cm^3/s) were plotted together on a scatter graph with discharge on the x-axis and SSC on the y-axis, from which a sediment rating curve could be produced.

Secondary data was also collected for the Upper North Grain site including a set of 14 past storms ranging from March 2003 to November 2004. Already calibrated discharge and SSC readings for these storms were used to create a number of sediment rating-curves that spanned over different times of the year they occurred at in an attempt to show the temporal variation in sediment delivery.

Figure 2: A rising-stage sampler with one tube for inlet and one tube for air exhaust. The intake tubes were positioned so that there was a few centimetres difference between them with the intention of taking samples at regular intervals.

2.4 Quantifying Erosion

One of the main reasons the different catchments monitored were chosen was because of their varying levels of erosion. However, if this characteristic was to be used in analysing their sediment delivery, then it should be quantified. This was done through the using aerial photographs and digital terrain models (DTM) of the Longdendale region in the South Pennines and GIS (geographic information system) tools ArcMap and ArcCatalogue to establish a percentage of bare peat for each site. Though a number of different features characterise the severity of erosion (Bower 1961) a more accurate assessment of a catchment's level of erosion would be a project in itself and the percentage of bare peat alone provides a sound enough basis for the needs of this project. The aerial photos were obtained from GetMapping (www.getmapping.com) and were flown in 2000. The DTMs were in the form of lidar data flown in 2002 and were obtained from the National Trust. The latter were used to help isolate the catchments in question by creating contours and hill-shade images in ArcMap. These highlighted the gully networks and the contours helping to show where the water would flow which thus allowing the watershed to be more easily and accurately plotted. The aerial photos were then used to digitise the areas of bare peat within these catchments whose area were used with the catchment areas to calculate percentages of bare peat. False colour composites that could have highlighted areas of bare peat by taking advantage of the fact that their spectral response is more reflective in bands 5 (near-mid infrared light) and 7 (Mid-infrared light) of the Thematic Mapper sensor, were not used. The images were left as true colour composites, because the areas of bare peat were already clearly visible within their surroundings. Bare peat showed up as a reddish-brown, compared to the green of vegetation and the white of bare mineral soils as can be seen in figure 3. The bare peat was then digitised according to this and saved as a separate layer. The accuracy was checked by eye and the digitised areas of peat matched up very well with the aerial photos. The areas of the two layers, namely watershed and bare peat, were compared by their pixel counts available in their attribute tables. The number of pixels in each were used as indices for their areas and allowed a percentage area of bare peat to be calculated. The use of pixels could not be used to compare areas between catchments due to the different levels of zoom used when calculating their relative areas. To do this, their areas were calculated using the surface analysis tool available in ArcMap that calculates the areas of georeferenced polygons.

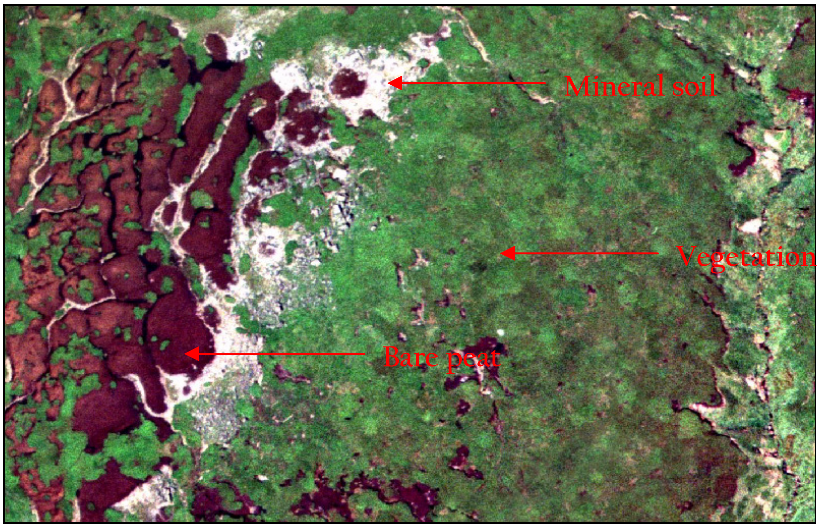


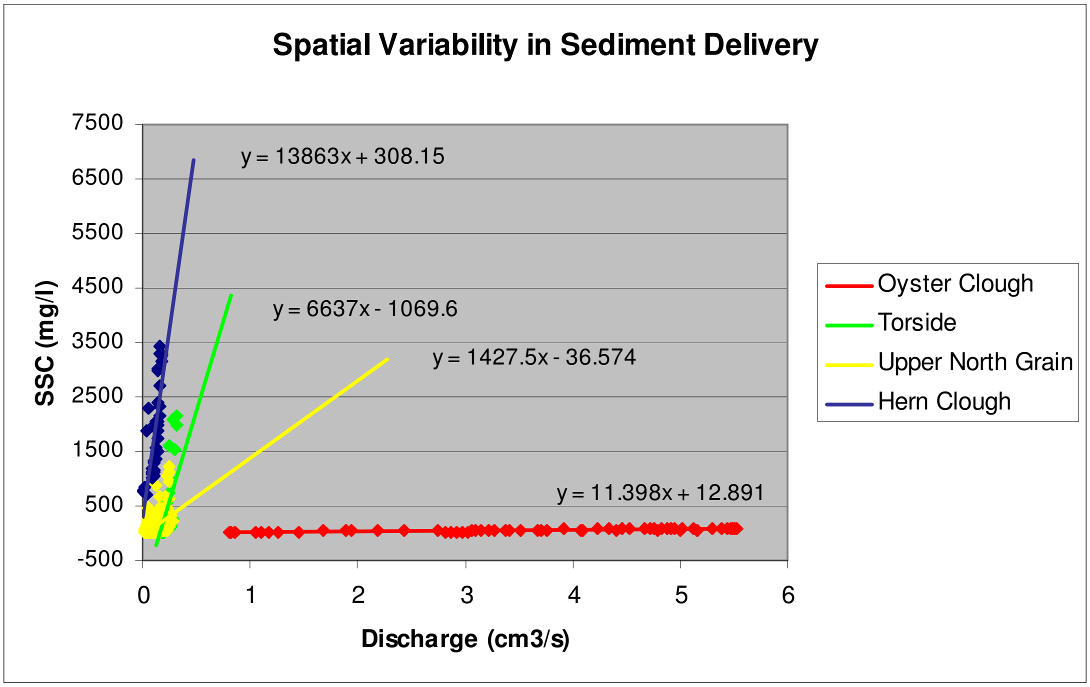
Figure 3: A true colour composite showing the clear differences in spectral response between bare peat, vegetation and mineral soils.

3. Results

3.1 Spatial Variability

The final rating-curves for each site can be seen in figure 4 and their individual rating curves can be seen in Appendix 4, but the data collected varied in use from site to site (Appendix 1). All the stage calibrations established from the flow readings were based upon 2-point relationships and simple flow readings and therefore encountered few problems (Appendix 2). However, the number of points used for the turbidity calibrations varied as the number of samples the rising-stage sampler collected depended on the size of the storm it sampled and what stage the resulting flow reached. Therefore taking into account the results of the monitoring period and the calibrations for each catchment, the periods of data were edited for each catchment before they were used to plot rating-curves.

Figure 4: Rating curves for each of the catchments based on either monitored and calibrated data or past records. The individual rating curves for each catchment can be seen in Appendix 3.



3.1.1 Hern Clough

The Hern Clough turbidity-SSC relationship established from the filtered samples was very steep but had very strong with an r^2 value of 0.9024 (Appendix 2).

This suggested that this steep relationship was true to the catchment and would create a seemingly reliable calibration for SSC. However, the calibrated results from the monitored stage readings were seemed wrong for data that was during periods of low flow. This was because the samples taken by the rising-stage sampler were from a major storm and therefore the resulting calibration, though worked well for the storm period, exaggerated results for other periods of low flow (Appendix 1). Though the monitoring period for Hern Clough stretched from 19/06/2005 till 01/07/2005 only one storm of suitable size was monitored and in fact occurred on the first day (Appendix 1). Therefore since the calibrated data for the storm was the only data that was not overestimated and that had high flow readings, it was the sole period of data that was used for the catchment sediment rating-curve. The curve's gradient was very steep as can be seen in figure 4 with a value of 13,863 according to the curve's equation.

3.1.2 Oyster Clough

The turbidity-SSC relationship calculated from four Oyster Clough SSC samples was very flat compared to the Hern Clough calibration and had a fairly strong relationship with an r^2 value of 0.7935 (Appendix 2). Before calibrating the data, it could be seen that the raw data was quite 'noisy' and therefore was smoothed using a 7-point average. When the calibrations were applied to the smoothed data, there was only one storm period that seemed to be of any use and occurs on the 05/07/2005 (Appendix 1). There was a second smaller period of rainfall that occurred towards the end of the monitoring period, but the discharge and SSC readings for it seemed unrelated to one another due to a second higher turbidity peak occurring on the descending discharge limb. This seems to be due to a possible major bank collapse in the catchment and therefore an anomalous result and misleading in terms of the sediment delivery of the catchment. As a result it was excluded from the rating-curve (figure 4) and only the first storm was used. Though this also has a second peak in turbidity, it is not as dominant and therefore does not affect the rating curve as much (as seen by the fact that the r^2 for the curve is the best of all the sites at 0.7948). In fact its effect can be seen in the figure of eight shape of the scattered points (Appendix 3), as it is responsible for the lower loop of the eight which, as can be seen in Appendix 3, is quite a minor feature. The final rating curve has a very gentle gradient as is shown by the curve's equation with a value of 11.398 (figure 4).

3.1.3 Torside

The original monitored data set for Torside was abandoned due to the equipment used providing extremely faulty readings. Therefore to compensate for this lack of data, past data records available from the University of Manchester were used to create a rating-curve for the catchment. A collection of 7 storms from late summer 2004 till winter 2004 were used. The resulting sediment rating-curve can be seen in figure 4 which shows it to have a steep gradient with a value of 6637.

3.1.4 Upper North Grain

The Upper North Grain site is a permanent site that is maintained by the University of Manchester. Though the probes were kept clean to prevent algal growth on the probe affecting the readings, algal growth still managed to affect the monitored turbidity readings as can be seen by the records (Appendix 1) rendering them unreliable. The readings show a constant slow rise in turbidity which is in fact continued algal growth. However, cleaning the probe did not help in this case because it was not algal growth on the actual probe that was causing this false reading, but rather algal growth in the water itself – on the 12/08/2005 when the probes were routinely being cleaned, the channel was noticeably murky with algae after a period of warm weather. However, the channel was clear again after a storm. The drop in turbidity readings in the rising limbs of storm discharge (Appendix 1) suggests that the initial high flow from a storm is responsible for sweeping away the algal growths. As a result the data is extremely misleading and therefore excluded from the rating-curve. It was replaced by past records for the site obtained from Manchester University. These included discharge and SSC readings for 14 storms initially intended for the investigation of temporal variation in sediment delivery (Appendix 4). They were however brought together to also create a general rating-curve to characterise the catchment's sediment delivery (Figure 4). The final rating was fairly steep with a gradient of 1427.5.

3.2 Temporal Variability

Past records of SSC and discharge measurements for the Upper North Grain were used to create 14 rating-curves for individual storms dating from March 2003 to November 2004 in order to cover all the meteorological characteristics of the seasonal cycles. These were all plotted on the same graph for ease of viewing and comparison (figure 5) but individual rating curves for each storm can be seen in Appendix 4. The rating-curve equations for each of the storms can be seen in table 1 which also shows their gradients and r^2 values.

Figure 5: A collection of the rating curves based on 14 storms over the period of March 2003 to November 2004, for the Upper North Grain.

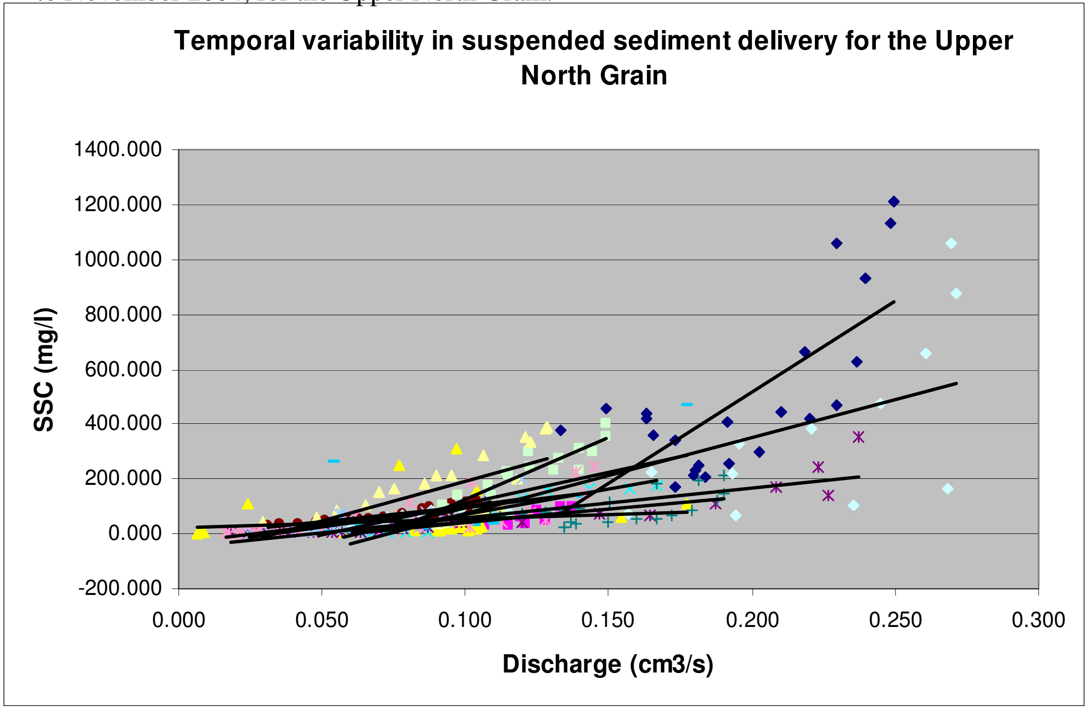


Table 1: Summary of the rating-curves used in temporal analysis (figure 5), including the rating curve equation, r^2 values and the curve gradients.

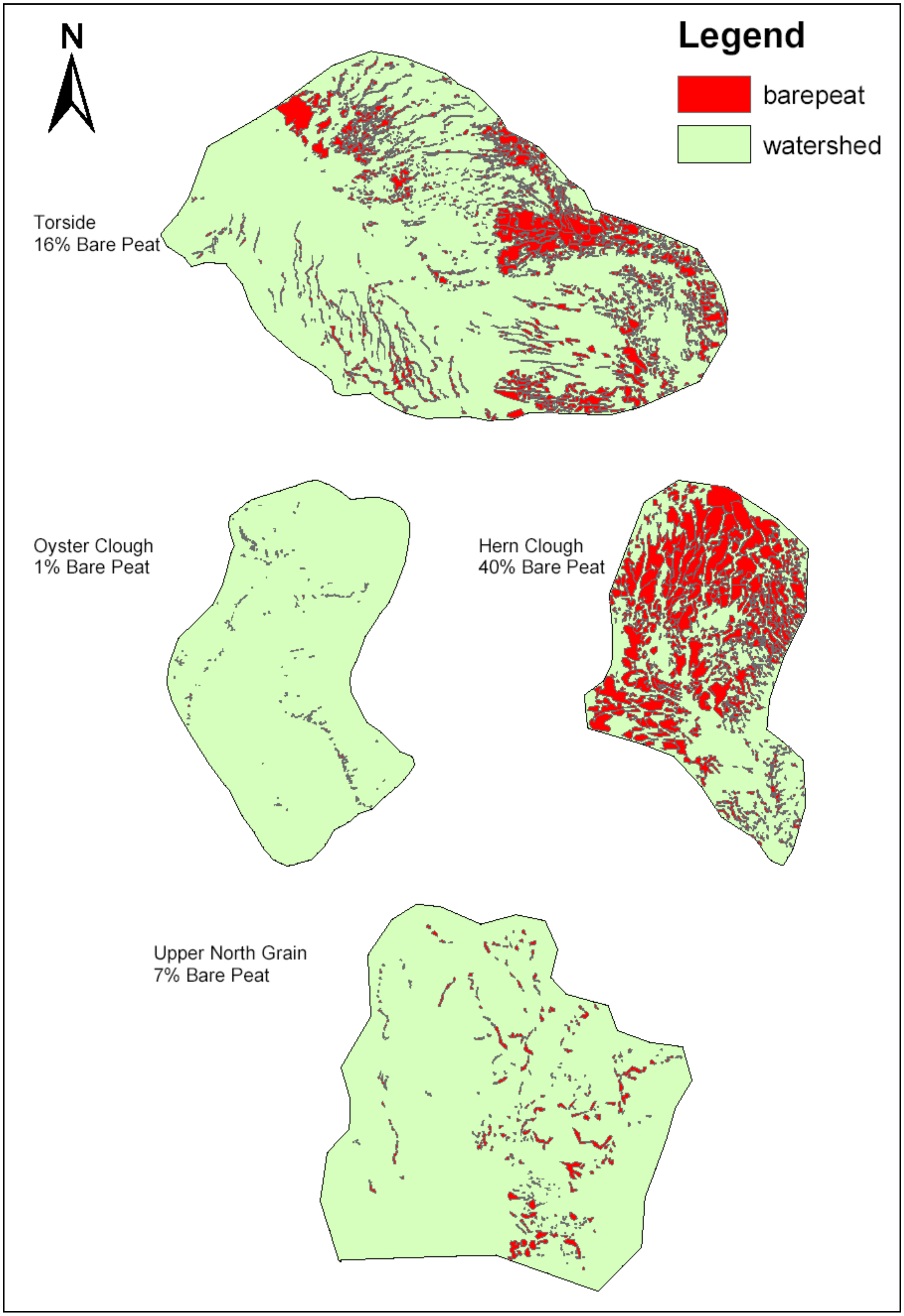
Storm	Rating-curve equation	R^2	Gradient
1	y = 6661.2x - 811.8	0.5203	6661.2
2	y = 939.56x - 52.481	0.666	939.56
3	y = 1861.3x - 116.97	0.9351	1861.3
4	y = 1087.3x - 48.6	0.7811	1087.3
5	y = 1096.2x - 9.2866	0.8557	1096.2
6	y = 929.47x - 46.812	0.4997	929.47
7	y = 2505.8x - 157.73	0.7555	2505.8
8	y = 2285.3x - 115.39	0.459	2285.3
9	y = 2755.2x - 200.75	0.5342	2755.2
10	y = 4482.7x - 319.5	0.8713	4482.7
11	y = 2855.3x - 94.851	0.4208	2855.3
12	y = 1486.4x - 47.688	0.6517	1486.4
13	y = 1278.5x - 33.072	0.601	1278.5
14	y = 360.8x + 35.261	0.0804	360.8

It can be seen that there seems to a general trend for the catchment with the exception of a few of storms. Two of the storms with the steepest rating-curve gradients are storm 1 (gradient of 6661.2) and 10 (gradient of 4482.7) which occur in March and June respectively and the lowest the being storm 14 with a gradient of 360.8 occurring in November. The remainder of the storms all have rating-curve gradient somewhere in the range of 900 to 2900.

3.3 Catchment Erosion

The results of the GIS analysis of catchment land use can be seen in figure 6. All the catchments vary in the percentage of bare peat they have. The images alone show us that Hern Clough is clearly the most eroded and has 40% of its land cover as bare peat, with Torside with the next highest levels of bare peat at 16%. They are followed by Upper North Grain and Oyster Clough with 7% and 1% bare peat respectively.

Figure 6: Results of the GIS applied catchment analysis show the range of erosion levels that the sites cover. The catchments are not depicted to scale.



4. Discussion

4.1 Spatial Variation in Sediment Delivery

The results clearly show that spatial variation does occur in the sediment delivery of peat catchments. Figure 4 plainly shows that the four different catchments have rating-curves with extremely different gradients, clues to this happening seen in the already differing SSC-turbidity calibration curves of Hern Clough and Oyster Clough. Oyster Clough has the lowest rating-curve gradient with a value of 11.398. This is to be expected as it has the lowest percentage of bare peat. However, in comparison with the other rating-curves it is almost completely level suggesting that very little suspended sediment is produced and delivered. This is despite the fact that it experiences the highest discharge of all the catchments. The level of bare peat within the catchment is also very low and close to non-existent at 1%. It therefore suggests that bare peat is essential for any suspended sediment to be present, as suggested by much previous work (Imeson 1974, Wishart & Warburton 2001, Charman 2002). Upper North Grain is the catchment with the next highest gradient with a value of 1427.5. With a percentage of bare peat at 7% it is to be expected that it would have a steeper gradient than a catchment such as Oyster Clough that has near to no areas of bare peat and the trend continues with Torside and Hern Clough. Torside has the next highest level of bare peat with 16% and also has the next highest rating-curve gradient at 6,637. This is followed by Hern Clough which has the largest percentage of bare peat at 40% of its total land cover and the steepest rating-curve gradient at 13,863. It is therefore clear to see that the higher the percentage of bare peat a catchment has, the higher the suspended sediment concentration in the catchment outlet. There also seems to be an ensuing pattern in the relationship where an increase in percentage of bare peat results in a similar sized increase in rating-curve gradient. This is confirmed by plotting them together on a scatter graph. As can be seen in figure 7, when the percentage bare peat of the catchment is plotted against the gradient of the sediment rating-curve an almost perfect linear relationship exists between them shown by its r^2 value of 0.9851. This is an astonishingly good relationship and supports the work of Burt & Gardiner (1984) in that it shows that catchments with more areas of bare peat will produce more suspended sediment for the catchment's transport mechanisms to wash away during periods of high flow. Though catchment size may still have some effect on sediment delivery, these results disprove the belief that catchment size is the dominant control on sediment delivery in peatland catchments, though it may still apply to non-peat of catchments (Asselman 2000). This is seen by the fact that Torside, by far the largest of the monitored sites, has a lot lower suspended sediment concentration than Hern Clough, one of the smaller catchments. It seemingly also only has a steeper rating-curve than the other sites because it has a larger area of bare peat. The unimportance of catchment size on sediment delivery can be seen when the two are plotted against each other as done in figure 8. The relationship between the two is almost non-existent as shown by the r^2 value of 0.0086.

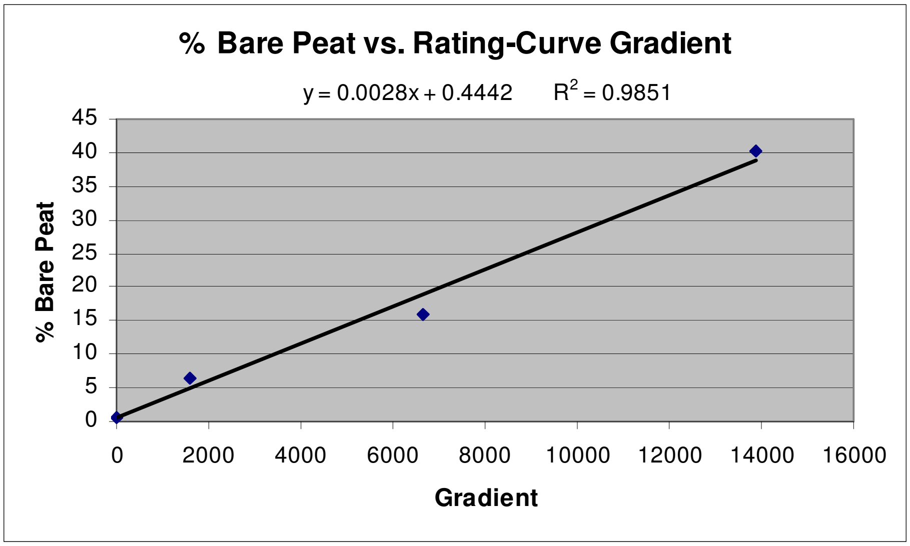


Figure 7: A Scatter graph showing the relationship between percentage bare peat for each catchment and the gradient of its sediment rating-curve.

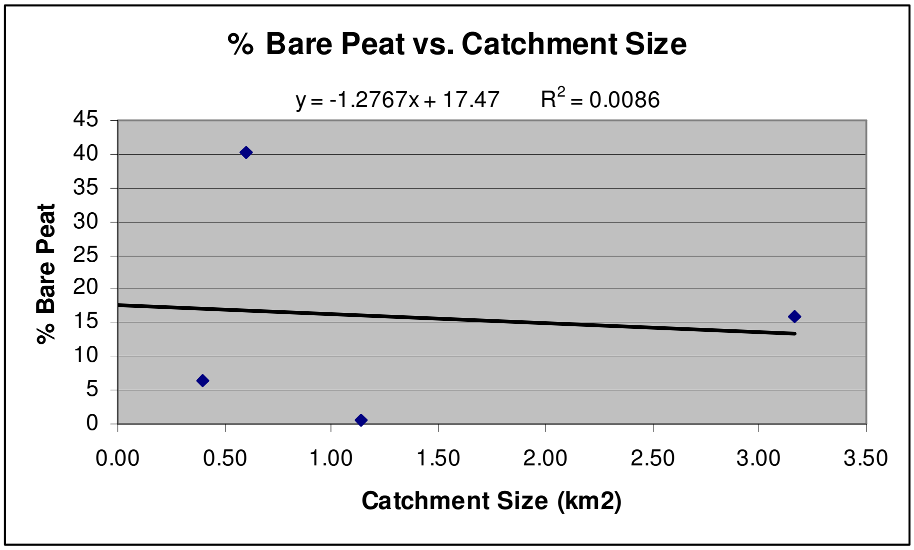


Figure 8: A Scatter graph showing the relationship between percentage bare peat for each catchment and the size of the catchment area.

Because the rating curves were based on single storms, it is possible that these results could be a coincidence and purely based on the size of the storm that they monitored. It is also possible that the different points in time at which their monitored data came from could also interfere with the sediment supply. It has already been mentioned that summer time desiccation is main reason behind an annual peak in sediment supply (Francis 1990, Charman 2002), and it is possible that because Oyster Clough was monitored at a later date than Hern Clough, desiccation had already started to decrease making sediment supply more vulnerable to exhaustion. This temporal argument can also be applied to Torside and Upper North Grain, which were based on a series of storms that covered a range of time, unlike Hern Clough which was based on a single storm that occurred in late summer when sediment supply was theoretically at its greatest. Their rating-curves would therefore be an average of a series of events attenuating any seasonal peaks in suspended sediment, which could be what Hern Clough's rating-curve represents. Therefore the temporal effects on sediment delivery must be investigated. If the temporal variation in sediment delivery, shown by the rating curves from the Upper North Grain that are based on periods of data from throughout the year, is greater than the spatial variation, then the conclusion that erosion is the dominant control on SSC in this study would be very sceptical.

4.2 Temporal Variation in Sediment Delivery

The results show in figure 5 that there are also variations in sediment delivery on a temporal scale. However, they are not of the same magnitude as those on a spatial scale. Even when including the three storms that are at the extreme ends of the range of gradients, the range of 360.8 to 6,661.2 is nothing compared to the range of 11.398 to 13,863 for the spatial variations in gradient. This is highlighted by the standard deviation of each set of gradients. For the set of rating-curve gradients that came from different catchments (figure 4) their standard deviation was 6236.721. This is much larger than the standard deviation of 1674.776 for the set of Upper North Grain storms that were taken at different times through the year (figure 5). While this shows that the level of peat erosion is the dominant factor in determining the suspended sediment status of the catchment outlet streams, it still shows that temporal factors can have an effect on the SSC. This is mostly due to the fact that the amount of sediment that is 'prepared' for transport (Labadz et al. 1991, Burt et al. 1997, Holden & Burt 2002) varies through the seasons due to the dependence of frost action and desiccation on climate. Due to the popular belief that summer time desiccation is the most important weathering agent of peat, it is also interesting to see that the largest storm at Upper North Grain occurred in March, suggesting that frost action during the winter in fact produces more loose sediment.

4.3 Implications and Applicability

The extremely good linear relationship between the percentage area of a catchment that is bare peat and the gradient of its sediment rating-curve (figure 7), show that the use of the latter as an index for peat erosion is very promising. However, though peat erosion is the dominant control on SSC, the temporal effects can still not be ignored as they clearly have some effect. As a result if sediment rating-curves are to be used as an index of the level of erosion in a catchment, they should be based on a collection of storms from throughout the year to ensure an accurate representation. This would be especially important when comparing catchments that are similar in levels of erosion as the ranges of sediment rating-curve gradients that they exhibit may overlap and small variations that could be brought about by temporal factors could make the comparison between the two misleading. For example, in this project, the largest storm monitored in the Upper North Grain had a rating-curve gradient of 6661.2 – steeper than the rating curve used to represent Torside, a catchment with twice as much bare peat in relation to the catchment size. Therefore if this was used as the sole period of data to characterise the Upper North Grain's sediment delivery, then it would falsely show it to be more eroded than Torside. This would be particularly important for management, as the level of erosion for a catchment would be monitored from year to year where changes in erosion are small. However, if the changes in rating-curve gradient are greater within the year than between years, then even if a catchment has improved it terms of erosion, it may still look like it has deteriorated if an event after a long period of desiccation is used to produce the catchment's rating-curve. Though it has been established that long periods of data do not necessarily improve a rating-curve's accuracy (Gordon et al. 1992), it would be advisable to use several storm events from throughout the year to represent the catchment's sediment delivery regime.

The wide scale application of such an index of erosion would also need to address a number of issues. The index would obviously not be applicable to non-peat catchments, and in fact past work has shown that in non-peat catchments, catchment size is the dominant control of sediment rating-curve gradients (Asselman2000). However, up to what point is a catchment considered to be a peat catchment? It may be that it could only be applied to catchments that are completely covered in peat. There is also the issue of catchments experiencing extreme erosion, where peat has been eroded as far down as the mineral soil beneath it. In such a case, because there is no peat left, the sediment rating-curve for the catchment would have a very gentle gradient and as an index would show that there is little erosion, when in fact quite the opposite would be true.

4.4 Limitations

This project encountered several limitations that the author would have like to have avoided, but unfortunately could not be accounted for. The first is that initially, more catchments were intended to be used in assessing the spatial effects on sediment delivery. Two catchments, namely Blackden Brook (E 410220, N 3931449) and Nether Grain Clough (E 412413, N 388586) were monitored but had to be excluded from the final analysis because of faulty readings from the probes used. A lack of time meant that they could not be returned to, to re-monitor them and therefore only four catchments were used in the investigation. The same occurred at Torside and Upper North Grain, but luckily past records existed that could compensate for the faulty monitored data. The inclusion of Blackden Brook and Nether Grain Clough would have helped add weight to the results if they had proved to follow the trend witnessed in the project, especially since they had similar levels of erosion as Oyster Clough at 1% and 2.2% respectively of their catchments consisting of bare peat. It would have been interesting to see if they produced similarly sloped rating curves as Oyster Clough or whether their different catchment sizes would have had an effect.

Another possible limitation stems from the use of GIS in estimating the percentage of bare peat in each catchment. A number of errors can arise through the environmental application of GIS, especially when digitising (Congalton & Green 1995), but for this project, many of the errors would have been on too precise a scale to make any real difference. However, what may have introduced some noticeable errors was the use of aerial imagery that dated back to 2000. Detailed aerial photographs are expensive to obtain, as they require flights to be made over the area in question, and these were the most recent images available for the area. As a result, the estimates of erosion for each catchment were based on their conditions five years ago, while the monitoring of their suspended sediment statuses was recent. Over that five year period, the catchments' characteristics may have changed greatly, making it possible that the estimates of their levels of erosion are unrepresentative of their present state.

A number of errors may also have been introduced through carrying out any field measurements such as factors other than SSC affecting turbidity or the rising-stage sampler not taking a fully representative sample of the stream, or even human error in taking flow readings. However for environmental studies, an extremely high degree of precision is not needed in stream monitoring (Gordon et al. 1992) and therefore the possible inclusion of such errors would not have had much impact on the outcome of the results.

5. Conclusion and Recommendation for Future Work

The main aim of this project was to see if the suspended sediment status of a stream could be used as an index for the level of erosion in its water shed. The four catchments that were monitored produced very different sediment rating-curves and the ability to use the suspended sediment status of a catchment's outlet stream as an index for erosion seems highly plausible. It has been shown that the spatial differences that occur between peatland catchments in the South Pennines cause larger variations in the levels of SSC present in the outlet stream than temporal differences do. This shows us that the spatial differences could not be attributed to temporal factors. Catchment size and the amount of bare peat present in a catchment are the main spatial differences but there was an extremely strong correlation between the amount of bare peat in a catchment and its sediment rating-curve gradient. Quite the opposite can be said for the catchment size resulting in the amount of bare peat being the dominant control over SSC. The strength of the relationship shows the great potential for developing the suspended sediment status of a stream as an index for peat erosion – something that would be extremely useful in moorland management. However, despite temporal effects not having as much of an effect on SSC levels as the amount of bare peat in the catchment, they nonetheless still do have an effect. If an index was to be developed, its effects could not be ignored, especially when comparing two catchments that have similar levels of erosion, or monitoring a single catchment form year to year. This is because the variations in caused by temporal effects may be larger than the differences being studied, be it between catchments or between years. The index could therefore be very misleading, and would need to use storm events from throughout the year to average out the extreme seasonal peaks that occur, to avoid this.

This project establishes the distinct possibility of using the suspended sediment status of a catchment's outlet stream as an index for the level of erosion within the catchment. It therefore acts as a pilot study in that it provides the basis for a great deal of possible future work in terms of refining the index. Future studies could include testing the index by using a larger number of catchments and a larger number of storm events per catchment to produce arguably more reliable sediment-rating curves for each of them. Even testing the index against a number of catchments with similar levels of erosion would be a good test, showing the possible effects of different types of erosion - type 2 erosion has much straighter gullies on steeper ground that follow topographically induced flow paths (Bower 1961) and therefore should have more efficient sediment delivery than the dendritic gullies of type 1 erosion that occur on flatter surfaces (Bower 1961).

Testing the index over different types of peat catchment would also be particularly interesting, seeing at what point it can no longer be used with any degree of certainty. All these different projects that would refine the index and improve its accuracy would all be required before it could be put to most use in a management context.

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