Response to Review 1 (I. Fuller)

Response to general comments:

We welcome the comments of Professor Fuller and his wider discussion of the applicability of interventionist approaches for enhancing river function viewed against the backdrop of a growing appreciation of the need to make room for rivers and the concept of erodible river corridors. In the specific case of Glaisdale Beck, a large landslide actively coupled to the upland stream channel prompted the trial of a novel channel diversion and subsequent hard-engineering approaches to help address the perceived impact of excessive fine sediment load on the stream system. We do not advocate such approaches as standard practice for the management of upland rivers , and recommend more holistic approaches for the enhancement of aquatic habitats within these systems (P20 L10 - 14).

As Professor Fuller rightly highlights, despite the diversion demonstrably abating the flux of material from the progressive landslide complex, in the wider environmental management context of ensuring habitat conditions suitable for the endemic species, there is still considerable room for further improvement. This can only be achieved through an integrated, catchment based approach. In recent years, the wider application of this concept in the UK has highlighted the need to think at the large-scale, including the examination of distributed processes operating over a range of temporal scales (e.g. sediment source/pathway variability). In the case of Glaisdale Beck, addressing the issue of wider degradation is continuing, facilitated by the Environment Agency and other public partners (e.g. BIFFA, National Postcode Lottery) funded under the auspices of the Glaisdale Beck Restoration Project. This project will enable significant improvements across the wider catchment including over 2 km of fencing adjacent to the stream channel, tree planting, installation of livestock drinking bays, cattle pumps and crossing points to reduce agricultural impacts (NYMNPA, 2015). Additionally, in the headwaters over 300 ha of moorland have been surveyed with over 18km of grips and gullies being blocked to enhance stability and reduce sediment supply from the wider catchment (YPP, 2011).

Response to specific comments:

Comment 1. *I did wonder whether there may have been any change in flood regime during the monitoring period, since larger floods have the potential to destabilise upland channels as we well know (e.g. Warburton et al., 2002; Milan 2012). […] Some comment on flood regime during the monitoring period could be worthwhile, tabulating or graphing flood events over the period. From that, could you then comment on whether the adjusted managed diversion is in good shape to respond robustly to projected increased flood frequency and magnitude?*

Reply 1. Although our geomorphological surveys continued between 2007 and 2014, hydrometric monitoring of the catchment only occurred from 2007 - 09, restricting our ability to place the hydrology of the monitoring period within the wider context of the local long-term hydrological regime. We have therefore obtained long-term flow records from Lealholm monitoring station (NZ7627207611), located on the main Esk, approximately 3km upstream of the confluence with Glaisdale Beck (P8 L14 - 16). Using this data (1998 – 2014) we are able to place the observed events within the wider hydrological context (P 14 L 19 – 22 and Table 4).

Comment 2. *The role of lateral erosion in channel development in the British uplands has also been demonstrated in the River Coquet, where extremely high rates of change were measured by Fuller et al. (2003) in response to bend cutoff (p1181, L14).*

Reply 2. We have incorporated the lateral retreat rates presented by Fuller et al. (2003) within the introduction section to provide additional information about the role of lateral inputs within upland systems (P3 L 18). However, Glaisdale Beck differs from the River Coquet as it is much more confined hence the coupling of hillslope failure complexes direct to the channel.

Comment 3. *The location of the landslide complex contributing sediment to the pre-diverted channel could usefully be added to Figure 1.*

Reply 3. We have produced a modified version of Figure 1 which now provides more detailed information about the nature of the landslide.

Comment 4. *I wondered whether the geomorphic changes identified in Figure 8 and discussed on p1193 had been mapped? If so, such a map would provide a useful addition to the paper.*

Reply 4. We did not conduct detailed geomorphic mapping of the bank collapses presented in Figure 8. We relied on the collection of fixed-point photographic evidence to document the change between visits to the site (e.g. Figure 2).

Comment 5. *I must confess to finding it hard to discern evidence for knickpoint migration from Figure 10. Perhaps a trend line is needed to highlight this? Also, is the over-deepening evident downstream of the lower drop structure (A) genuine degradation, or a return to the pre-engineered channel bed following flushing of sediment accumulated in the channel immediately following re-alignment? The 2009 survey is two years after the 2007 engineering, so it is quite possible that the elevated bed level here reflects an initial infilling response from sediment eroded from the bed upstream. It might be helpful to identify which part of the long profile relates to the realigned channel.*

Reply 5. In response to the diversion a distinct knick-point step in the long profile whose morphology varied depending on the local substrate as shown in Figure 9. We have produced an asymptotic fit to this figure which displays the rate of knick-point migration over time. We agree that this further highlights the nature of the system response. Downstream of structure (A) in Figure 10 we do indeed observe a degree of erosion between the 2009 and 2014 surveys. This is most likely to be a result of the initial response (captured in the 2009 survey) resulting in downstream aggradation within pools and low-energy zones, with progressive events acting to winnow this material over time, re-exposing the pre-diversion surface (captured in the 2014 survey). For ease of interpretation we have modified Figure 10 to display the area within the plot which represents the realigned area of the channel.

Comment 6. *You comment on the arrest of the landslide within the old abandoned channel (p1196, L19) – is there any evidence / data on activity of this landslide you can refer to here? Is there the potential for landslide movement to resume, or even reach the new channel?*

Reply 6. The landslide itself was not subject to direct monitoring. However the activity of the mass-movement was informally evaluated as a result of routine site visits. Evidence of the relative stability is shown through repeat photographs of the area. Images collected in 2014 (Figure R1) clearly demonstrate several key features including:

i) revegetation of the erosional surface; and ii) progressive reduction in bank angle due to the lack of fluvial activity at the landslide toe and storage of hillslope material in the former channel. The storage of this material at the base of the slope is buttressing the landslide and arresting further progression. Based on observations during the active monitoring period, it is unlikely the landslide will re-activate given current site conditions.

Figure R1. Images of the landslide 07/04/2014 looking (a) NE towards the slip-face and (b) upstream in a SE direction.

References

North York Moors National Park Authority (NYMNPA) Catchment Trilogy – Part 1 https://northyorkmoorsnationalpark.wordpress.com/2015/12/07/a-catchment-trilogy-part-1/ Accessed 14 April 2016).

Yorkshire Peat Partnership (YPP) Yorkshire Peat Partnership, Research and Monitoring, Feb 2011 http://www.iucn-uk-peatlandprogramme.org/sites/www.iucn-uk-peatlandprogramme.org/files/Yorkshire%20Peat%20Partnership,%20Research%20and%20Monitoring,%20Feb%202011.pdf Accessed 14 April 2016.

Response to Review 2

We thank Reviewer #2 for their comments and we are grateful of the opportunity to address these.

Response to general comments:

The paper mixes methods and results throughout and sometimes to the surprise of this reviewer. Things appear on the abstract and results that were never mentioned in the methods section.

See replies to Specific Comment No.2 and 9.

The paper should be in the past tense.

We have examined the text and changed all verb tenses to past tense in instances where we are not generalising to other systems, or providing perspectives (see marked-up version).

Wherever possible the paper should consider the implications for the wider journal audience and try not to sound too parochial as a report to the local agencies

Throughout the Discussion section we have placed the diversion of this upland channel within the context of river restoration as a whole and assess it as a principle in its own right. We also stress the potential for ineffective engineering and planning of restoration programmes to undermine their effectiveness. These general messages are already a key part of the paper and are also emphasised in both the introduction (e.g. P3 L2 – 3) and conclusion (e.g. P 20 L 9 – 18).

Response to specific comments:

Comment 1. *The abstracts reads as if two different timescales of data were available and so it reads like some data were ignored. A clearer experimental design statement is needed that outlines the stream monitoring was for 2 years within longer geomorphological surveying.*

Reply 1. See reply to Specific Comment No.7.

Comment 2. *ANCOVA is mentioned in the abstract but I did not spot it elsewhere*

Reply 2. We use ANCOVA to test for significant differences in the parameters of the pre- and post-modification rating curves. These results and details of the test are reported on Page 12 L20 - 28.

Comment 3. *Fine sediment is not defined*

Reply 3. We have defined fine sediment at its first occurrence in the manuscript (P3 L17).

Comment 4. *The term sensitive is used but why is this system more or less sensitive than any other? - How is upland defined?*

Reply 4. We don't necessarily mean that the catchment is more sensitive than any other. Rather we are merely commenting on the potential for these systems to be heavily impacted by relatively small disturbances (e.g. small landslides, point source contributions, etc.) which have the potential to increase pressure on the aquatic system due to a lack of buffering capacity which would be characteristic of a larger system. We define upland as regions with significant areas of land above the 300 m contour, together with their associated valleys (Atherden, 1992).

The majority of this catchment by area meets this definition. These points are clearly made in the paper (Section 2.1).

Comment 5. *I would like a clear statement of the paper's aims.*
Reply 5. Page 4 Line 24 - 31deal with the aims of the paper. However we have now modified this section to explicitly state the aims.

Comment 6. *P1186 – sentence about NIMROD seems out of place.*
Reply 6. I'm not sure which sentence you refer to. Reference to NIMROD on Page 8 states: i) that NIMROD is used for rainfall estimates; ii) the temporal and spatial resolution of data; iii) justification of its use over other rainfall sources. This is describing our methodology so is appropriately placed in the 'Materials and Methods' section of the paper.

Comment 7. *Needs an experimental design statement that gives the dates of monitoring and makes clear the time progress of the study, i.e. from stream monitoring to surveying.*
Reply 7. We now include statements that explicitly disclose the time frame over which the in-situ hydrological monitoring and geomorphological surveys took place (P7 L 26 – 28, P8 L17 – 18).

Comment 8. *Abstract mentions ANCOVA?*
Reply 8. See reply to Specific Comment No.2.

Comment 9. *It seems that each section of the results start with statement of methods, these are either repeats or are new. When they are repeats they should be deleted when new they should be removed but detailed in the methods. For example, remove the first sentence of section 4.3 as it is a repeat of methods. In section 4.3.1 there are references to methods and measures not previously actually mentioned in the methods section.*
Reply 9. We have removed any duplication and ensured that no new methods are introduced within any of the Results sections (see marked-up version).

References

Atherden, M. 1992. Upland Britain: A Natural History. Manchester University Press, Manchester, 224p.

Reduced fine sediment flux and channel change in response to the managed diversion of an upland river channel

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Abstract

This paper describes the implementation of a novel mitigation approach and subsequent adaptive management, designed to reduce the transfer of fine sediment (< 2mm) in Glaisdale Beck; a small, predominantly upland catchment in the UK. Hydro-meteorological and suspended sediment datasets are collected over a two year period spanning pre- and post-diversion periods in order to assess the impact of the channel reconfiguration scheme on the fluvial suspended sediment dynamics. Analysis of the river response demonstrates that the fluvial sediment system has become more restrictive with reduced fine sediment transfer. This is characterised by reductions in flow-weighted mean suspended sediment concentrations from 77.93 mg L^{-1} prior to mitigation, to 74.36 mg L^{-1} following the diversion. A Mann–Whitney U test found statistically significant differences ($p < 0.001$) between the pre- and post-monitoring median SSCs. Whilst application of one-way analysis of covariance (ANCOVA) on the coefficients of sediment rating curves developed before and after the diversion found statistically significant differences ($p < 0.001$), with both Log *a* and *b* coefficients becoming smaller following the diversion. Non-parametric analysis indicates a reduction in residuals through time ($p < 0.001$), with the developed LOWESS model over-predicting sediment concentrations as the channel stabilises. However, the channel is continuing to adjust to the reconfigured morphology, with evidence of a headward propagating knickpoint which has migrated 120 m~~120m~~ at an exponentially decreasing rate over the last 7 years since diversion. The study demonstrates that channel reconfiguration can be effective in mitigating fine sediment flux in ~~upland~~ headwater streams but the full value of this may take many years to achieve whilst the fluvial system, slowly readjusts.

1 Introduction

Changing catchment conditions and land use impact locally on river systems, through slope-channel coupling, but their cumulative impact is of global importance (Foley et al., 2005). RecentRecent government data reveals that 61% of monitored water bodies within the less favourable areas (LFAs) of England and Wales are currently at risk of failing the Water Framework Directive (WFD; 2000/60/EC) due to poor ecological status (Environment Agency, 2012), a key determinant of which is suspended sediment (Collins and Anthony, 2008). Such statistics have led to calls for suspended sediment to have a higher profile in diffuse pollution policy (e.g. Collins and McGonigle, 2008). This is assured given the pressure to ensure long-term improvements in water quality under the WFD and the government's own target of water-bodies in England being in excellent health by 2050 (DEFRA, 2011). However, to ensure improvements in condition and prevent the continual degradation of many upland catchments, river systems and their diverse ecosystems, a range of measures will need to be implemented to control fine sediment transfer (Newson and Large, 2006; DEFRA, 2011; Rickson, 2014).

Lateral erosion in particular plays an important role in channel migration, meander development and the delivery of fine sediment (< 2 mm) to upland channels (Lawler, 1993; Lawler et al., 2001; Fuller et al., 2003). Documented contributions of bankside sediment sources range from 1.5% to over 80% of total fine sediment flux (Bull, 1997; Stott, 1997), with high magnitude episodic events transferring significant volumes of bank-eroded material (e.g. Carling, 1986). However, on a global scale, the magnitude of sediment transfer typically observed in these upland catchments is relatively low (Evans and Warburton, 2005). Changes to runoff generation processes (Marshall et al., 2009; Holden et al., 2015), and the spatial distribution and magnitude of erosion (McHugh, 2007), can however result in the enhanced conveyance of bankside and hillslope eroded material into the fluvial networks draining these catchments (Owens et al., 2005). Drivers of these changes in the uplands of the UK include: farming and forestry operations (Burt et al., 1983; Tilman et al., 2002); moorland burning (Imeson, 1971; Arnold-Forster, 2002; Holden et al., 2015); peat degradation; metal mining (Macklin et al., 1997); artificial drainage (Ramchunder et al., 2009); and channelisation (Brown, 1997; Gilvear and Bradley, 1997), with few catchments remaining that can be described as being in reference condition (Sear et al., 2000; Sear et al., 2009). Enhanced sediment generation and delivery processes place additional pressure on aquatic habitats, increasing the risk of chemical and biological pollution, and habitat decline (Robinson, 1973).

The implementation of positive measures to abate the transfer of fine sediment and pollutants whilst preserving the desired physical and biological functioning is, however, extremely challenging due to the legacy of extrinsic and intrinsic, historical and contemporary controls on dynamic river systems (Schumm, 1977; Elliott, 1997; Newson, 2002). This is partly why sensitive upland rivers of the UK have attracted less direct restoration than lowland counterparts (Environment Agency, 1998); and given the difficulties of access and working conditions have not received large-scale investment in geomorphological engineering.

To ensure a positive legacy of the continuing and future management of our upland catchments, it is imperative that rehabilitation efforts are based on sound scientific knowledge acquired through the progressive development of a solid evidence base consisting of the fluvial/catchment response to a range of interventions across multiple scales (Brierley et al., 2010). This will allow competent authorities to: a) predict the effectiveness of control measures (e.g. Wilkinson et al., 2013); b) predict the cost-effectiveness of resource allocation (e.g. Posthumus et al., 2013); and c) enable reliable and transparent decisions to be made about future catchment operations (Collins et al., 2012). Comprehensive monitoring is rarely undertaken with few quantitative assessments of whether restoration results in significant improvements in river function (Newson, 2002; Skinner and Bruce-Burgess, 2005; Newson and Large, 2006; Wohl et al., 2015).

The aim of ~~In the case of~~ this research conducted in the upland catchment of Glaisdale Beck; UK, is to assess the success of a novel mitigation approach and subsequent adaptive management, designed to reduce fine sediment transfer is assessed from a geomorphic and biotic view-point. This is achieved by monitoring the schemes impact on the river channels form, and the suspended sediment dynamics, whilst taking into account hydro-meteorological drivers. Due to the rarity of direct modifications to upland river systems this research offers insights into the functioning of a realigned upland river system and may act as a test-case, or trial for other upland catchments facing similar pressures and seeking appropriate solutions.

2 Regional Setting

2.1 Context and problem

Glaisdale Beck is located in the North Yorkshire region of England, UK with a catchment area of 15.6 km^2 (Figure 1). Originating on Glaisdale Moor at an altitude of 382 m~~382m~~, the upland river (as defined by Atherden (1992)) flows 7 km~~7km~~ before joining the River Esk. The climate is cool, temperate, with annual average rainfall of less than 1000 mm~~1000mm~~. The local geology is dominated by Jurassic rocks of the Whitby Mudstone Formation (mudstone and siltstone with calcareous nodule bands) overlain by unconsolidated boulder clay and undifferentiated drift in the valley bottoms (British Geological Survey, 1992). The dominant land-use is moorland, pasture and rough grazing with some woodland, particularly in the lower catchment (Figure 1). Each of these managed land-units creates specific pressures. The presence of artificial drains (or grips) on Glaisdale Moor alter the runoff regime, and the practise of managing the dry heath may result in bare soil exposure, increasing erosion risk. On lower-lying farm land, reported stocking densities of up to 1.51 livestock units per hectare creates diffuse pollution pressures within the catchment (Emery, 2010).

The Esk is a river of both ecological and economic importance at a national scale. It is the ~~only~~ principle river in Yorkshire ~~to support~~for Atlantic salmon and sea trout and is one of only two rivers on the east coast of England to have known populations of the freshwater pearl mussel, Margaritifera margaritifera (Geist, 2005). This species is one of the most critically endangered bi-valves in the world; listed on Annexes II and V of the EU Habitats and Species Directive and Appendix III of the Bern Convention (Machordom et al., 2003; Skinner et al., 2003). However, siltation and excessive suspended sediment concentrations (SSCs) have been attributed to causing their decline. This has led to local conservation and restoration efforts being driven by the National Park over the last 20 years (Arnold-Forster, 2002; Emery, 2010).

[Insert Figure 1]

Previous research has highlighted the Glaisdale sub-catchment as a key contributor to fine sediment fluxes in the Esk catchment (Bracken and Warburton, 2005). Through local surveys, a critical source area of fine sediment supply to the beck was identified (Warburton, 2007). This was a section of exposed, near-vertical, ~3 m~~3m~~ high channel banks ~100 m~~100m~~ in length consisting of unconsolidated sediments and overlain by shallow surface vegetation, which is regularly accessed by livestock (Figure 2). The availability of accessible material is also exacerbated by progressive movement of a large hillslope failure complex which supplies large quantities of easily eroded sediment directly to the river channel. Such failures are well documented in the North York Moors (Waltham and Forster, 1999). It was deemed that this combination of factors limited the potential for success of traditional channel margin stabilisation approaches.

[Insert Figure 2]

2.2 Reconfiguration

Following consultation and the presentation of available options (cf. Warburton, 2007), the competent agencies decided the most appropriate course of action was to divert the existing channel away from the toe of the large hillslope landslide, and re-establish the stream course further to the north (Figure 3). Emery et al., (2013) provide a thorough discussion of the process involved in reaching this consensus. In October 2007, engineering work to modify the course of Glaisdale Beck commenced. Prior to the realignment, the river had a meandering channel with a sinuosity ratio of 1.56 and a local gradient of 0.0061 m m^{-1}. By diverting the beck from its original pathway, the reach was shortened by 250 m~~250m~~, increasing the local slope to 0.050 m~~050m~~ m^{-1}. To accommodate for the increased slope, it was recommended that a boulder revetment should be installed along the outside of the new meander, along with drop structures constructed from large (> 0.5 m~~5m~~) boulders (Figure 3, Drop Structure A). These measures were recommended to prevent the beck reverting to its previous configuration and the occurrence of headward erosion and renewed bank erosion by undercutting (Hey, 1996).

Although a range of measures to control channel readjustment and fine sediment release were recommended, not all could be fully implemented due to local site conditions and the determined specification was not followed in detail. The most important deviation was the use of insufficient material to construct the drop structure located on the new cut-through section (Figure 3, Drop structure A). As a result of this structure becoming undermined, it needed to be later reinforced along with the addition of a drop structure upstream of the diversion (Figure 3, Drop structure B). This additional work was undertaken during February 2008. However, the materials and construction of the upstream drop-structure also deviated from the recommended specifications.

[Insert Figure 3]

Following the establishment of the newly engineered channel, it was assumed that in the medium and long-term, the disconnection of the immediately available and easily accessible sediment source from the watercourse would have demonstrable impacts on the suspended sediment load and SSCs, which would benefit the in-stream ecology and habitat quality of Glaisdale Beck. However, in the short-term following the diversion it was recognised that a temporary disequilibrium would be created, resulting in the active adjustment of the channel to the new conditions. Although previous studies have documented the immediate and instantaneous impact of such disturbances (e.g. Brookes, 1987; Sear and Archer, 1998); few provide a sustained assessment of the impacts of modification (e.g. Gilvear and Bradley, 1997).

3 Materials and Methods

~~2.3~~3.1 Physical Data Collection

An assessment of the fluvial sediment system of Glaisdale Beck was undertaken by monitoring the fine sediment dynamics immediately prior to and in response to the realignment work. ~~Geomorphological surveys were conducted on eight occasions with changes in the local morphology being quantified using a combination of a Leica 1200+ total station, Leica 1200 GNSS station and a Leica NA720 automatic level and staff.~~ An in-stream monitoring station was located 250 m~~250m~~ downstream of the diversion (Figure 3). This included a McVan Analite 395 turbidity probe and PDCR 1830 Campbell Scientific pressure transducer connected to a CR10X data-logger, alongside an ISCO 3700 automatic water sampler. Monitoring of

~~SSC~~turbidity and ~~flow~~ level began on 21st September 2007, providing 19 days of data prior to the engineering work, which took place on the 10th October 2007. ~~-~~Monitoring continued following the diversion for two years.

Turbidity and river level data was collected at 15-minute intervals with discharge estimated through the combination of river stage and velocity estimates (cf. Perks et al., 2014). The turbidity probe was deployed as a surrogate for SSC (cf. Gippel, 1995). To quantify the relationship, calibrations were conducted between the formazin calibrated turbidity (FTU) generated by the turbidity probe and SSCs determined using the gravimetric technique on samples collected by an ISCO automatic sampler and discrete manual sampling. In attempting to identify post-diversion changes in fine sediment dynamics it was deemed important to account for not only impacts of flow on the fine sediment response, but also how rainfall erosivity varied temporally. This ensured that systematic changes in storm/erosion intensity as a driver of the observed sediment dynamics could be ruled out, which would not necessarily have been picked up using the flow measurements alone. The rainfall estimates for the catchment are derived from the UK's NIMROD radar network. This provides rainfall estimates with spatial and temporal resolutions of 1km and 5-minutes respectively and was available for 95% of the entire monitoring period. The NIMROD radar network is one of the best operational sources of rainfall information, capable of producing rainfall estimates that are statistically similar to those derived from rain-gauges (Cranston and Black, 2006; Zhu et al., 2014). Additional 15-min river level data spanning 1998 - 2014 was acquired from the Environment Agency hydrometric monitoring station at Lealholm (NZ7627207611), located on the main Esk, approximately 3km upstream of the confluence with Glaisdale Beck. Complimentary to the collection of continuous data, g~~G~~eomorphological surveys were conducted on ~~eight~~nine occasions between October 2007 and April 2014, with changes in the local morphology being quantified using a combination of a Leica 1200+ total station, Leica 1200 GNSS station and a Leica NA720 automatic level and staff.

~~2.4~~3.2 Data Treatment

FTU - SSC pairings were plotted and a linear regression model was adopted to best describe the fit between the variables (Table 1). A condition set for the model was that the intercept had to pass through zero. Further to the development of the linear model, the uncertainty of the regression coefficients was evaluated using a bootstrap re-sampling method (*n* = 2000). The uncertainty of the regression coefficients along with the number of calibration samples (*n*) and summary statistics is shown in Table 1. This calibration is within the acceptable range of uncertainty for the given operating range, as set out by Gray et al. (2002).

[Insert Table 1]

Sediment rating curves were constructed following the log-transformation of discharge normalised by mean discharge, $\hat{Q}$ (cf. Warrick, 2015) and SSC from which the regression coefficients a and b were obtained by ordinary least squares linear regression:

$$\text{Log}SSC = \log a + b \cdot \log\hat{Q} \qquad (1)$$

By transforming the data so that the trend is linear in log-space, the regression slope can be back-transformed into original units, producing an exponential fit (Helsel and Hirsch, 1992). The Duan (1983)~~. The Duan (1983)~~ smearing factor was subsequently applied to correct for bias introduced during the transformation process. This correction factor (CF) is widely used and unlike alternative approaches does not assume normality in the residuals. Following back-transformation, the rating curve is modified using Equation 2.

$$SSC = a\hat{Q}b \text{ (CF)} \qquad (2)$$

Non-parametric analysis was also undertaken to describe the relation between $\hat{Q}$ and SSC. The locally weighted scatter smoothing (LOWESS) technique was chosen as it provides an objective approach that infers the form of the relationship from the observations directly with no prior assumption (Cleveland, 1979;Hicks et al., 2000). In conducting this analysis, a 'stiffness factor' ~~is~~ was~~(Cleveland, 1979; Hicks *et al.*, 2000). In conducting this analysis, a 'stiffness factor' is~~ required to determine the proportion of the population to include in the weighted local regression. A range of factors were evaluated from 1% to 50% at 0.12% intervals. The span that minimised the sum of square errors for predictions generated by a leave-one-out cross validation was selected.

Following acquisition of the NIMROD rainfall data for the UK, a representative rainfall rate for the Glaisdale Beck catchment was calculated by first averaging the rainfall estimates (mm hr^{-1}) from across the catchment grid at each 5-minute time-step. Utilising this data, the unit rainfall energy e (MJ ha^{-1} mm^{-1}) for each rainfall event r is calculated from the empirical function proposed by ~~Brown and Foster (1987):~~Brown and Foster (1987):

$$e_r = 0.29[1 - 0.72\exp(-0.05 i_r)] \quad (3)$$

where i is the rainfall intensity during the time interval (mm h^{-1}). The event rainfall erosivity index $Ei30$ (MJ mm ha^{-1} h^{-1}) is subsequently calculated as follows (Angulo-Martínez *et al.*, 2009; Sheridan *et al.*, 2011; Meusburger *et al.*, 2012):

$$Ei30 = \left(\sum_{r=1}^{0} e_r \, v_r\right) I_{30} \quad (4)$$

where v is the rainfall depth (mm) and I_{30} is the maximum rainfall intensity during a period of 30-minutes during the event (mm h^{-1}). Finally, the median rainfall erosivity index is calculated for each season, taking account of all observed storm events.

~~3~~4 Results

~~3.1~~4.1 Pre-Diversion

~~Monitoring of SSC and flow began on 21st September 2007, providing 19 days of data prior to the engineering work, which took place on the 10th October 2007.~~ During ~~this~~ the short pre-diversion monitoring period, $\hat{Q}$ and SSC were highly correlated (Kendall's Tau = 0.66; p < 0.001). The flow-weighted mean concentration was 77.93 mg~~93mg~~ L^{-1} with a SSC_{50} of 35.19 mg L^{-1}, range spanning 15.37 – 671.21 mg L^{-1} and median absolute deviation of 12.15 mg L^{-1}. This available data indicates that prior to diversion, the river conditions were unfavourable for the freshwater pearl mussel populations due to the exceedance of a 10 mg L^{-1} critical threshold (Stutter et al., 2008), and may also be sub-optimal for Salmonid and Cyprinid fish populations due to SSCs at low flow exceeding 25 mg L^{-1} (Collins and Anthony, 2008; Bilotta *et al.*, 2010).

3.24.2 Disturbance

During channel diversion, no measures were put in place to minimise downstream transfer of fine sediment. Consequentially, the maximum observed instantaneous SSCs reached 2468 mg L^{-1}, nearly 3600% greater than the upstream concentration (Figure 44). Although this declined rapidly, concentrations were still 510% greater two hours after the breakthrough, with downstream concentrations of 359 mg L^{-1}. Such disturbances have been observed elsewhere; with sediment loads immediately downstream of in-stream works measuring between 40 and 150% more than those immediately upstream (Brookes, 1987; Sear and Archer, 1998). The observed duration and concentrations may have short-term impacts on the primary productivity and the free-living ecology of the river such as reduced natural penetration of light; increases in the rate of drift and reduced abundance of invertebrates (Rosenberg and Wiens, 1978; Doeg and Milledge, 1991); and modified Salmonid feeding and foraging behaviour (Robertson et al., 2007). However, a longer term concern is was the potential for this material to clog Salmonid redds, reducing oxygen availability (Carling, 1984). Positively, annual survey data indicated no decline in the numbers of Salmonids the following year (Environment Agency, 2011).

[Insert Figure 44]

3.34.3 Impact

Monitoring of SSC and flow continued following the diversion for two years. During the two year's of flow and SSC monitoring following the diversion, During this period $\widehat{Q}$ and SSC were highly correlated (Kendall's Tau = 0.36; $p = 0$). The flow-weighted mean concentration falls by 5% to 74.36 mg L^{-1}. SSC_{50} is 18.98 mg L^{-1}, which is significantly different to the pre-diversion median SSCs with a reduction following the diversion (Mann–Whitney U test; $p < 0.001$). The monotonic trend in $\widehat{Q}$ is positive (Kendall's Tau = 0.05; $p < 0.001$), whilst the SSC trend is negative (Kendall's Tau -0.05; $p < 0.001$). Following diversion, median concentration falls below the 25 mg L^{-1} threshold of the (now repealed) EU Freshwater Fish Directive (2006/44/EC); however it still exceeds the 10 mg L^{-1} level recommended for the protection of freshwater pearl mussel habitats (Stutter et al., 2008).(Stutter *et al.*, 2008). These thresholds are exceeded 33.75 and 94.11% of the time respectively.

3.3.14.3.1 Parametric Time-series Analysis

Regression of Log C on Log $\widehat{Q}$ provides a linear model, which when back-transformed predicts SSC from discharge for the pre- and post-diversion monitoring periods (Table 2), resulting in the development of empirical models which meet the acceptance threshold for analysis utilised by Syvitiski *et al*., (2000). However, above a $\widehat{Q}$ threshold value (Tv) of 4.6 m^3 s^{-1} the suspended sediment response is poorly replicated by a power-law model; with the SSC response to increasing discharge becoming becomes dampened. This results in curvature in the $\widehat{Q}$-SSC relationship in log space which is inadequately characterised by the model (Figure 55). This reduced sensitivity is demonstrated when the dataset it partitioned at Tv and the creation of two discrete models: one for low flows and one for high flows. The resulting *b* coefficient shifts from 1.13 (when $\widehat{Q} < Tv$) to 0.23 (when $\widehat{Q} > Tv$) (Table 2). The form, explained variance and error associated with the partitioned model (when $\widehat{Q} < Tv$) is similar to the original model incorporating all observed discharges (Table 2). However, the partitioned model (when $\widehat{Q} > Tv$) has poor explained variance and large errors associated with it (R^2 = 0.07; RMSE = 174.54). This is indicative of a complex and highly variable SSC response at moderate and high discharges in Glaisdale Beck. This is related to the supply-limited nature of the fluvial sediment system which is related to either a reduction in the availability of fine sediment sources e.g. through the exhaustion of readily available material temporarily stored on the river bed (Gao and Josefson, 2012) and/or; a reduction in rainfall effectiveness as the storm progresses (Wood, 1977). These dynamics cannot be adequately characterised using a simple power-law.

[Insert Table 2]

[Insert Figure 55]

The observed rating curve coefficients are within the normal range of what would be expected for temperate rivers (Reid and Frostick, 1987;Syvitski et al., 2000),(Reid and Frostick, 1987; Syvitski *et al*., 2000), however following diversion, the Log *a* coefficient decreases from 1.76 to 1.42, whilst the *b* exponent also decreases from 1.57 to 1.14. These coefficients have been shown to respond to patterns of sediment production, availability and transport capacity, with reductions being associated with a move to a more restrictive sediment transport system

(Asselman, 2000; Warrick and Rubin, 2007; Yang *et al.*, 2007). To test whether these changes are statistically significant and to confirm the impacts of modification, a one-way analysis of covariance test (ANCOVA) was conducted on the log-model coefficients. For this to be a valid comparison, only discharge data within the range observed pre-diversion was utilised (i.e. normalised discharge < 2.37 $m^3 s^{-1}$). Results indicate highly significant differences between the pre- and post-diversion monitoring period for both Log *a* and *b* coefficients (Table 3). This confirms that modification of Glaisdale Beck has resulted in a suspended sediment regime which responds significantly differently to changes in flow, likely as a consequence of the changes to local shear stress and sediment availability following the diversion. Encouragingly from a river remediation point-of-view, a $\widehat{Q}$ of 2.37 $m^3 s^{-1}$ prior to modification would have yielded a typical SSC value of 221.77mg L^{-1}, whereas the modified system would typically result in a SSC of 70.33 mg L^{-1}; equivalent to a 68% reduction. These findings suggest differences in flow effectiveness, with flows following diversion failing to have the same erosive impact (Hicks et al., 2000;Wolman and Miller, 1960).~~(Wolman and Miller, 1960; Hicks *et al.*, 2000).~~

[Insert Table 3]

~~3.3.2~~4.3.2 Non-parametric Time-series Analysis

As a consequence of the aforementioned curvature between $\widehat{Q}$ and SSCs, LOWESS analysis ~~is~~ was undertaken to quantify the form of the relationship and to assess how this ~~has~~ changed as a result of channel diversion. A stiffness factor of 0.134 was assigned to the model as this minimised the sum of the squared errors. The form of the LOWESS fit is largely comparable to that of the power law up to a $\widehat{Q}$ of ~7 $m^3 s^{-1}$ where curvature in the suspended sediment response becomes pronounced as a result of relatively lower SSCs (Figure ~~6~~6). A second inflection is identified at 20 $m^3 s^{-1}$ as a result of increasing SSCs at the higher discharge range. This non-parametric model performs better than the original power law (Table 2), with an RMSE of 39.29. The median of the residuals is -3.62 mg L^{-1} with the residuals exhibiting a slight negative monotonic trend over time (Kendall's Tau = -0.04; $p = 0$), indicating a reduction in the observed SSCs relative to the model predictions. The correlation between $\widehat{Q}$ and model residuals is also negative (Kendall's Tau = -0.213; $p = 0$). This is a reflection of the heteroscedasticity in the residuals, with a wide range of SSCs observed at low flows whilst during higher magnitude events the suspended sediment response is better constrained.

[Insert Figure ~~6~~6]

The maximum positive LOWESS residuals are identified as occurring during the construction of the channel diversion (+1054 mg L^{-1}) and as a result of SS spikes occurring immediately prior to, and independent of storm events during November 08 and 09 (+849.5 and +1038 mg L^{-1} respectively; Figure ~~6b~~6b). The maximum negative residuals occur during storm events in January and December 08, resulting in deviations between observed and predicted concentrations of -263.5 and -292.1 mg L^{-1} respectively. Upon the calculation of the median LOWESS residuals for each monitored storm, and by season, striking patterns are observed (Figure ~~7~~ 7 a-b). For each storm occurring prior to diversion, highly positive median residuals are produced as a result of the LOWESS model underestimating concentrations. During this unit of analysis (storm and base flow component), the median of the residuals is 13.86 mg L^{-1}; the highest observed during the entire monitoring period. During the following three seasons (autumn 08 – spring 09), the median of the residuals are negative with a range spanning -2.64 to -4.63 mg L^{-1}. Negative residuals are also produced for the same seasons during the second year of monitoring, although their magnitude is greater (with the exception of spring). The seasonal pattern of the residuals is quasi-cyclic with largest post-diversion residuals occurring during the summer months, followed by the spring months. However, there are no observable relationships between the erosivity index of the rainfall and the residuals produced by the LOWESS model, therefore this observed pattern is not believed to be influenced by seasonality in the storm intensity and erosion potential (Figure ~~7~~ 7 c-d). Whilst the role of land management activities, natural variability of sediment supply across the wider catchment, and additional stressors, or mediating factors cannot be excluded, it is significant in the context of this research that the trend in the residuals is negative, with the suspended sediment response becoming increasingly dampened throughout the monitoring period.

[Insert Figure ~~7~~7]

~~3.3.3~~4.3.3 Long-term Geomorphic Impact

Although direct monitoring of the hydrology and sediment dynamics at Glaisdale beck was concluded in 2009, two years after the channel diversion, the longer term development of the site ~~has been~~was observed through site visits up until 2014. Over this period in the Esk catchment, the median river level was slightly less than the long term (1998 – 2014) median level. However, the probability of moderate and high magnitude flow events was equal, or greater than prior to the diversion (Table 4).

[Insert Table 4]

As a result of these erosive events during this period, continued erosion in the form of a headward migrating knickpoint (visible as a step in the clay of the river bed substrate) has resulted in a progressive wave of channel instability that has migrated upstream. This is the morphological response to over-steepening of the channel gradient in the vicinity of the original channel diversion. Due to a lack of appropriately engineered grade control (drop) structures in the engineered reach this has resulted in channel bed lowering, bank undercutting and lateral bank failures upstream. Figure ~~8~~ 8 shows a series of three time lapse images taken from approximately 50 m~~50m~~ upstream of the head of the channel diversion reach over a seven-year period from 2007 to 2014. During this time extensive bank erosion and channel widening have occurred. At this particular site, erosion was evident only two weeks after the initial diversion with the knickpoint migrating through the reach, lowering the bed elevation. In response, the banks started to slump, tension cracks approximately 1.2 m~~2m~~ back from the bank appeared on the bank top and the bank dropped approximately 0.4 m~~4m~~ with a slight rotational movement, which over time became more pronounced (Figure ~~8A~~8A). As time progressed, further slumping led to destruction of the rotated soil block allowing the river to flow behind the disintegrating bank material and erode directly the freshly exposed soil (Figure ~~8B~~8B). Eventually the soil block became completely detached from the bank but was held together by a root ball of a tree growing in the centre of the failed block (Figure ~~8C~~8C). This became established in the centre of the channel diverting flow around both sides of the obstruction, eventually triggering a second phase of bank collapse (Figure ~~8C~~8C). However, due to increased channel width the final phase of bank collapse resulted in a soil wedge at the base of the bank which appears to have protected the toe of the bank preventing further lateral expansion. The extent of erosion shown in these images represents the ‘worst-case’ example of erosion with the total channel width increasing by nearly 300% by 2014.

[Insert Figure 88]

[Insert Figure 99]

The temporal sequence of images in Figure 8 8 A to C are also labelled on Figure 9 9 to cross reference the local erosion observed at a point in relation to the progression of the eroding knickpoint upstream. Over the seven year observation period the point of observed bank undercutting and bed instability, shown by a small step in the river bed long profile, has migrated 187 m187m upstream at an average annual rate of approximately 30 m30m per year. Over time this rate has slowed dramatically from an initial rate, in the first two months since diversion, of nearly 1.4 m4m per day to an eventual rate of less than 1 mm1mm per day; a decrease in rate of approximately 1400% (Figure 99). This reduction in the rate of knickpoint migration follows an exponential trend with the rate slowing dramatically towards the present (2014). The most recent observations suggest the headward migration of the channel knickpoint has now almost ceased and there is little evidence of further bank instability much beyond 200 m200m upstream of the point of the original channel diversion. The increase in slope caused by the diversion has largely been accommodated by adjustments to the channel bed slope and cross-section morphology. It is estimated that the channel diversion increased the local reach slope from approximately 0.0061 (following the old meandering course) to 0.05 in the freshly engineered diversion reach (Table 45). Following seven years of channel readjustment the contemporary 2014 channel slope has now returned to the pre-diversion state, which explains why further upstream knickpoint migration and erosion have largely ceased.

[Insert Table 45]

The thalweg profile along the reconfigured channel reach was surveyed in detail on two occasions in March 2009 and April 2014 spanning a period of 5 years. A comparison of the two channel long profiles (Figure ~~10~~10) supports the observations of the sequence of bank collapse (Figure ~~8~~8), and headward progression of the eroding knickpoint (Figure ~~9~~9). The period between March 2009 and April 2014 (500 to 2400 days since diversion) spans the period of adjustment following major channel degradation which occurred in the first 500 days following the engineering works (Figure ~~9~~9). Nevertheless the channel was still degrading over this period and some significant local variations in channel sedimentation were observed (Figure ~~10~~10). In Figure ~~10~~10, A and B represent locations of the two drop structures (weirs) and the dashed rectangle is the zone of rapid channel change associated with bank collapse shown in Figure ~~8~~8. Above the upper weir, apart from a deep scour pool below a piece of large woody debris (c. 10 m) upstream of the grade control structure, the channel has aggraded slightly over time. Downstream of the lower weir, although the level of the main bars has remained relatively consistent between 2009 and 2014, the degraded pools remain over deepened with bed levels lower by almost 0.5 m~~5m~~ in places. Between these two sub-reaches is the dynamic reach affected by the large scale bank collapses (Figure ~~8~~8); here local adjustments in bed level dominate with erosion and deposition varying by up to +/- 0.5 m although the overall pattern is next degradation of the reach. The dynamic response of these three sub-reaches to the channel reconfiguration characterises nicely the ongoing adjustment of the stream. Above the upper weir the channel is largely stable with net aggradation; in the areas of bank collapses local adjustments continue; and below the lower weir the channel still shows signs of bed lowering.

[Insert Figure ~~10~~10]

~~4~~5 Discussion

~~4.1~~5.1 Channel Evolution and Stability

The changes observed in Glaisdale beck following channel reconfiguration were predicted beforehand (Warburton, 2007). It was anticipated that channel bed instability would result from the steepening of the newly aligned river channel and without appropriate engineering measures the channel would erode in a headward direction. However, lack of experience and appreciation of techniques for creating stable grade control structures, by the contractor and a dearth of suitable materials on-site resulted in the control measures becoming undermined. In the immediate vicinity of the channel diversion, rip rap successfully confined the stream to the desired location restricting the risk of lateral instability and channel migration. However, vertical down cutting, initially focused upstream of the grade control (drop) structures was triggered by local scouring which was exacerbated by steepening of the stream profile and the associated headward propagating knickpoint. The diversion of the channel resulted in a steepening of the local slope to a gradient close to 5% (Table ~~4~~5), which shifted the channel into the range of slopes typical of step-pool streams (Chin et al., 2009). Under these conditions a new channel morphology needs to be considered and step-pools need to be considered as a suitable channel engineering structure. In this case study, a single large step was engineered to create the new channel morphology and ultimately this was unsuccessful and failed. Chin et al. (2009) list a set of important considerations relating to the design, construction and maintenance of step pool structures that should be followed when restoring high gradient channels. With the benefit of hindsight a staircase of multiple steps, constructed of large rock (imported to the site), spaced appropriately in the diversion reach would have been more effective in mitigating headward degradation (Chin et al., 2009). Overall however, the scheme effectively slowed the downslope movement of the large landslide complex which was destabilising valuable farmland and contributing significant quantities of fine sediment to beck. By disconnecting the river channel from the distal end of the landslide, and preventing over-steepening of the toe, the landslide crept into the old abandoned channel where movement was arrested.

~~4.2~~5.2 Channel Realignment as River Restoration

Connectivity between potential sediment source areas and drainage networks in the uplands of the UK results in the mobilisation and transfer of fine sediment from a range of point and diffuse sources across a catchment (e.g. Foster and Lees, 1999; Johnson et al., 2008). In order to identify areas of enhanced fine sediment transfer within the Esk catchment, research followed spatially nested-hierarchical principles (Brierley et al., 2010). This knowledge of sediment transfer processes enabled better understanding of the diversity and pattern of river character and behaviour across the catchment system. Areas within the catchment with atypical sediment dynamics compared with similar sub-catchments were identified. More focussed geomorphological surveys then identified key critical areas within the sub-catchment units. This process led to the identification of a specific reach along Glaisdale Beck as a key contributor to fine sediment loadings in the Esk catchment, prompting action from local authorities (Bracken and Warburton, 2005; Warburton, 2007). The authorities, primarily concerned by the potential loss of salmonid spawning and freshwater pearl mussel habitats following large quantities of fine sediment being mobilised by a progressive landslide and associated localised bank erosion, responded by consulting with local stakeholders over the available options before finally choosing to divert the river from the easily accessible sediment source. Inherent in this approach was the assumption that the risk to in-stream habitat was greater by doing nothing than by attempting to divert the channel away from the primary fine sediment pollution source. Due to the sensitivity of the site, it was agreed that in order to alleviate the problem effectively efforts should be directed towards a hard-engineering approach, which should minimise the potential risk of failure. In the case of the channel realignment option, the channel was designed to be laterally stable with grade control measures in place (Warburton, 2007). This approach had the inherent potential to remove natural variability and heterogeneity in channel morphology, flow dynamics and available river habitats along the affected reach, whilst contradicting the popular movement from hard to soft engineering solutions (Hey, 1996; Richards, 2001; Raven et al., 2010; Newson, 2012). However, the clear identification of a manageable critical point source of fine sediment provided an opportunity to significantly reduce degradation of the system and to enhance the overall ecological integrity of the river beyond that of the reach scale (Palmer et al., 2005). Nevertheless as Wohl et al. (2015) suggests, reconfiguring channels is fraught with difficulty and often is only partially successful due to the local focus on the reach-scale. This case study, through long-term monitoring, has demonstrated this limitation but more importantly shown how the engineered reach, through longer-term natural adjustment, eventually reconnects with the larger river network to deliver large scale benefits.

~~5~~6 Conclusions

Glaisdale Beck was highlighted as experiencing elevated levels of fine sediment flux, with a significant source of this material being attributed to a large hillslope failure complex which was directly coupled to the channel. This reach was subject to a specific set of pressures which would result in traditional geotechnical stabilisation techniques being inappropriate and ultimately unsuccessful. This offered the opportunity to trial the diversion of an upland channel, with the aim of reducing fine sediment flux, affording us the opportunity to gain a comprehensive understanding of the impacts of upland channel diversion on the fluvial sediment system. From the analysis of over two years discharge and SSC data prior to, and following the diversion of Glaisdale Beck, it is clear that the sediment transfer regime has become more restrictive as evidenced by:

- Reductions in median SSC from 35.19 to 18.98 mg L^{-1}.
- 5% reduction in flow-weighted mean SSC.
- Negative trend in SSCs (Kendall's Tau; $p < 0.001$).
- Development of sediment rating curves with statistically different coefficients following diversion. Both the Log *a* and *b* coefficients were smaller following the diversion.
- Decline in LOWESS residuals over time indicating an overestimation of SSCs as the channel stabilises over time.

This monitoring campaign has indicated that prior to the diversion; Glaisdale Beck was experiencing enhanced fine sediment flux, with conditions unlikely to be favourable for Salmonids or ~~the endemic~~ pearl mussel populations. Following channel diversion, a prolonged period of disturbance lasting approximately 7 years was observed. During this time, the channel and sediment regime are highly dynamic, with order of magnitude changes in fine sediment response occurring over short temporal scales. This is a result of disequilibrium in the fluvial sediment system following diversion with readjustment to the new channel configuration resulting in variations in the supply of fine-grained material. Despite this transient behaviour, there is evidence of non-stationarity in the fine sediment flux signal and it is anticipated that providing allogenic controls do not force further threshold changes, suspended sediment transfer will remain at lower levels than that of pre-diversion conditions, with a fine sediment transfer regime becoming established that is commensurate with the newly imposed conditions.

Although knickpoint migration has now nearly ceased, the channel is continuing to adjust to the threshold change, with evidence of continuing local instability. It is therefore recommended that this approach to reducing the fine sediment flux of upland rivers should not be adopted as standard practice. However, ~~and~~ where significant modifications to upland channels are made, comprehensive in-stream monitoring and geomorphological assessments should be regularly conducted to evaluate the response of the river to the new conditions. This research has also highlighted the importance of ensuring appropriate controls on sediment release during in-stream works and effective installation and maintenance of grade control (drop) structures. If these measures had been rigorously applied the overall goal of reducing fine sediment flux through the fluvial system could have been achieved in a more timely fashion.

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Tables

Table 1. Summary statistics of the turbidity probe field calibrations. The relationship is significant at the 99.9% level.

	Calibration	SSC Range (mg L^{-1})	R^2	Uncertainty (95%)
Glaisdale Beck (*n* = 58)	y = 1.1298*x*	1.65 – 1266.20	0.92	22.96%

Table 2. Summary of the developed empirical models for the prediction of suspended sediment concentrations from normalised discharge. Tv is the normalised discharge threshold value for model partition, set at 4.6 m s^{-1}. * Represents use of the Duan (1983) correction factor

Period	Condition	*n*	Log Model	R^2	Final Model	R^2	RMSE
Before	All	1776	$1.7575 + 1.5669x$	0.59	$57.22x^{1.57}1.1448^{*}$	0.45	52.72
After	All	56653	$1.4199 + 1.1360x$	0.47	$26.30x^{1.14}1.19^{*}$	0.35	48.63
After	$\widehat{Q} < Tv$	56106	$1.4188 + 1.1292x$	0.40	$26.23x^{1.13}1.1919^{*}$	0.38	36.03
After	$\widehat{Q} > Tv$	547	$2.3303 + 0.2332x$	0.08	$213.94x^{0.23}1.0961^{*}$	0.07	174.54

Table 3. Results of t-tests on model parameters for the relationship between Log normalised Q and Log SSC, before and after channel diversion.

	Log *a* (T and *p* values)		*b* (T and *p* values)	
Before vs. After	22.72	*0.00*	13.21	*0.00*

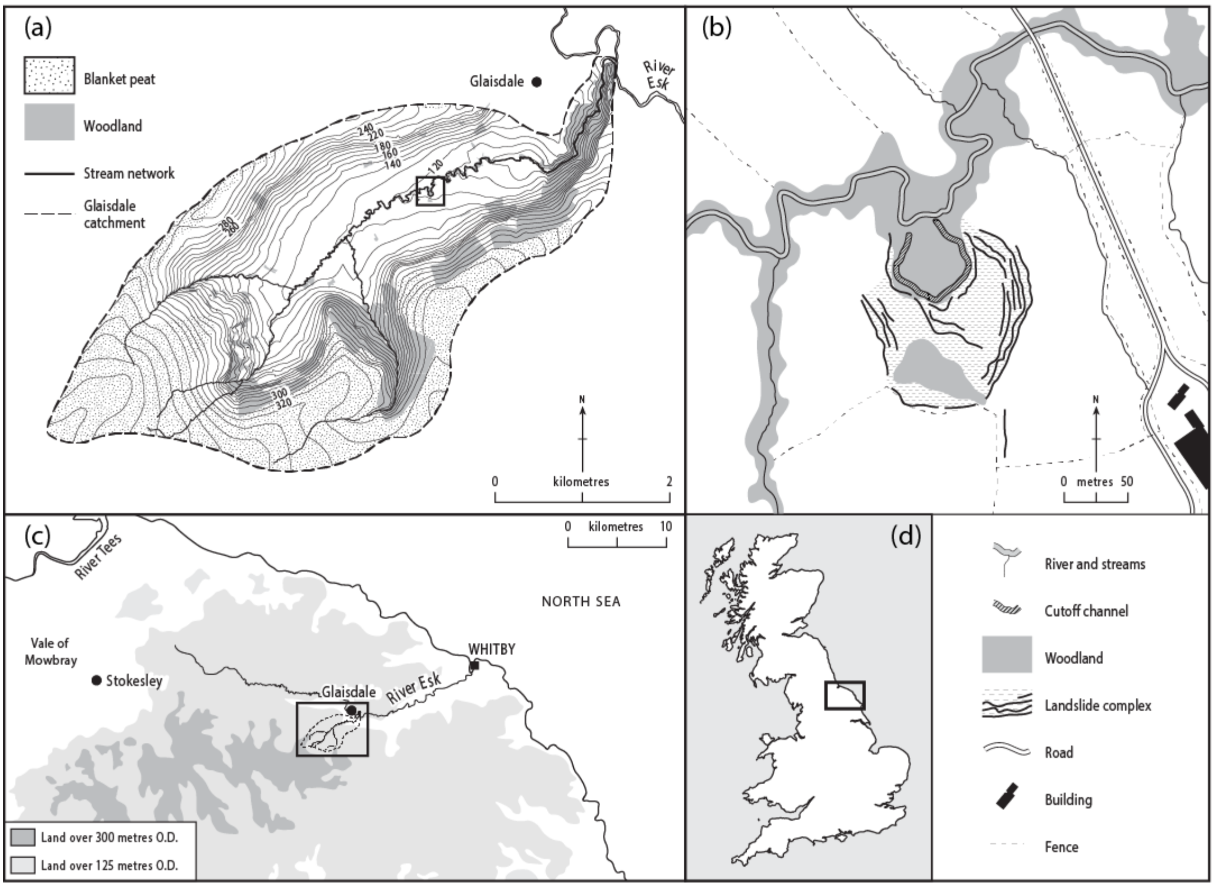
Table 4. Summary statistics calculated from river level data collected at Lealholm monitoring station (NZ7627207611) based on observations at 15-min intervals. Statistics provided include the mean, median and maximum river levels and the probability that the river level exceeds the long term (1998 – 2014) median (M), median*5 (M5), and median*10 (M10) threshold values. This is calculated for both pre-diversion conditions (02/12/1998 – 10/10/2007) and post diversion conditions (10/10/2007 – 08/04/2014).

Condition	Mean (m)	Median (m)	Maximum (m)	Exceedance Probability		
				M	M5	M10
Pre-Diversion	0.24	0.19	3.66	0.53	0.012	0.0025
Post-Diversion	0.22	0.16	3.13	0.44	0.014	0.0025

Table 45. Changes in reach averaged slopes before and after channel diversion

Reach / Condition	Date	Average channel slope (m m^{-1})
Meandering channel pre-diversion	< 2007	0.0061
Diverted – engineered channel	2007	0.05
Adjusted channel	2014	0.0065

Figures


(a)
Blanket peat
Woodland
Stream network
Glaisdale catchment
Glaisdale
River Esk
240
220
180
160
140
120
280
260
300
320
N
0 kilometres 2
(b)
N
0 metres 50
(c)
River Tees
0 kilometres 10
NORTH SEA
WHITBY
Vale of Mowbray
Stokesley
Glaisdale
River Esk
Land over 300 metres O.D.
Land over 125 metres O.D.
(d)
River and streams
Cutoff channel
Woodland
Landslide complex
Road
Building
Fence

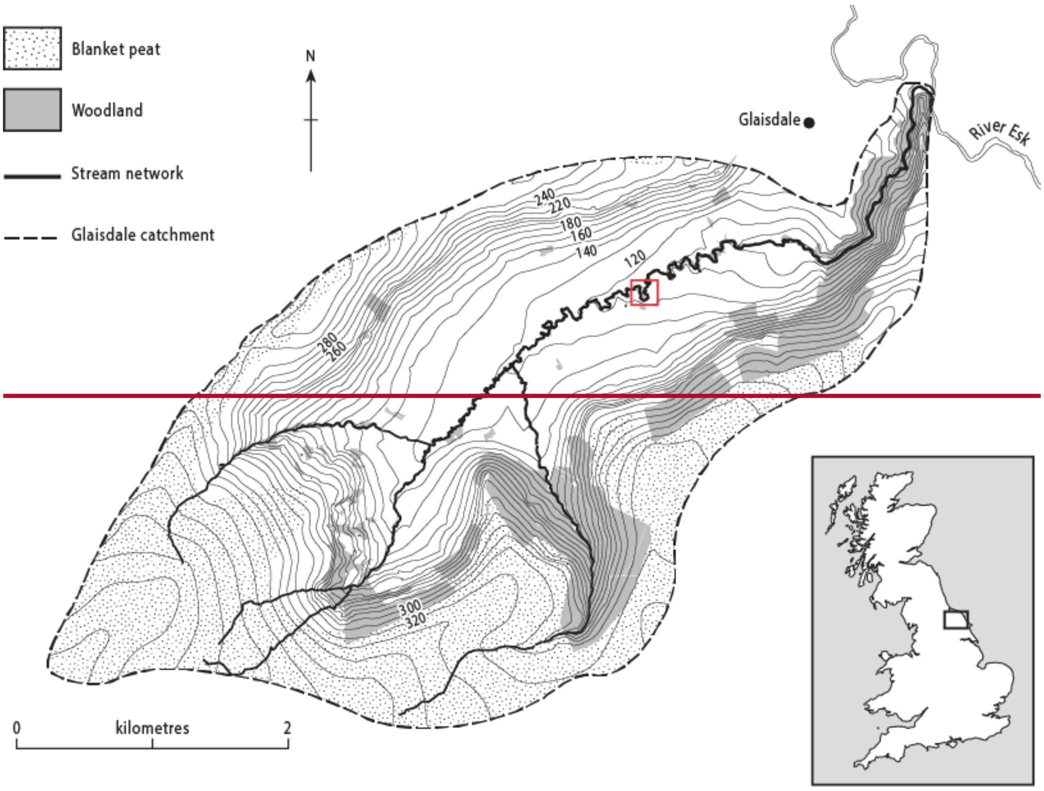
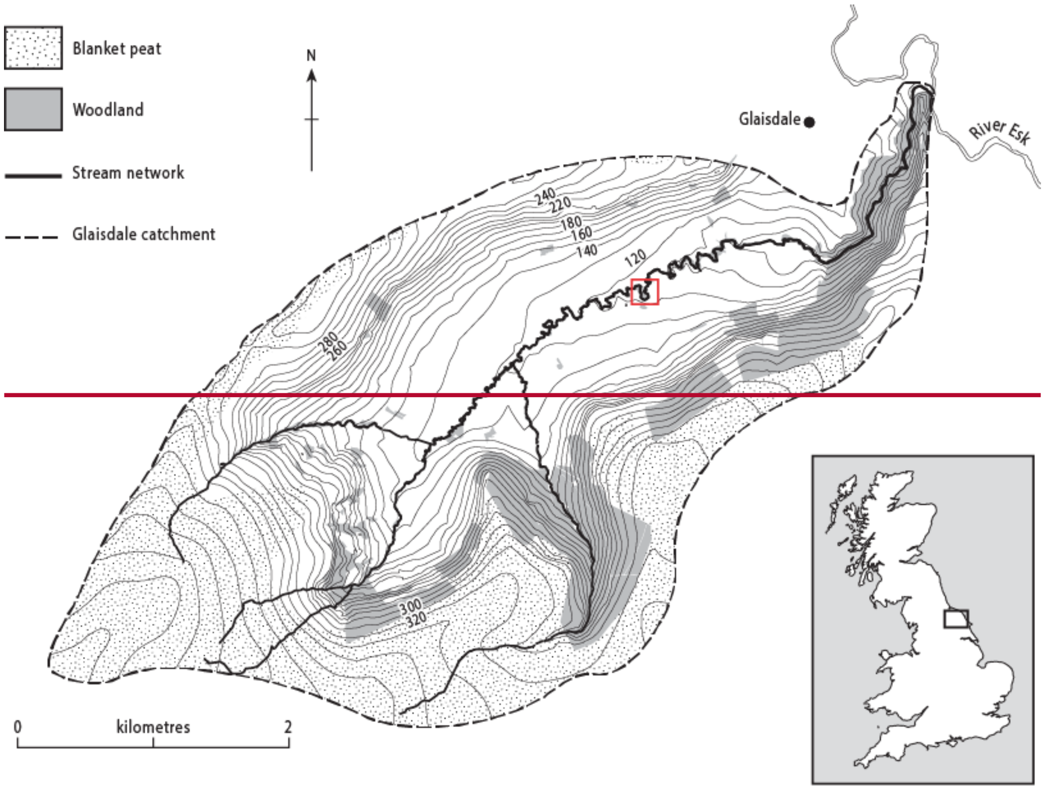
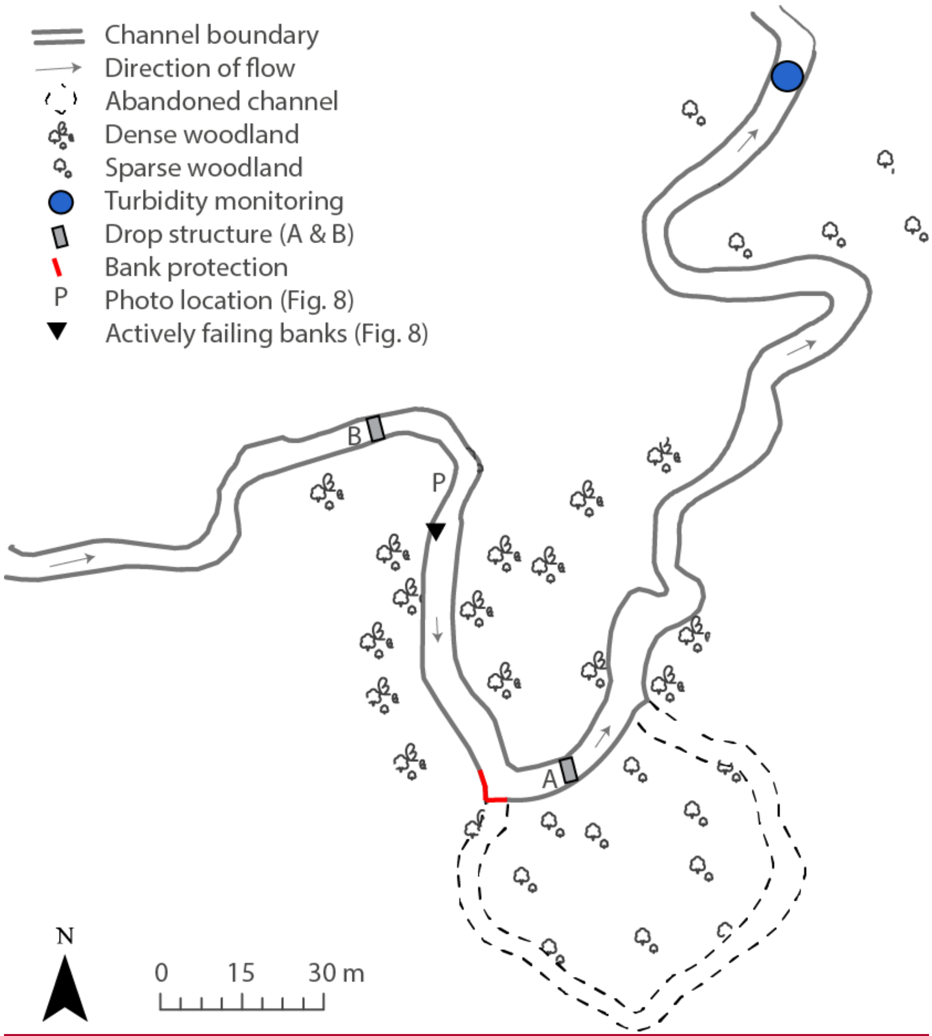

Blanket peat
Woodland
Stream network
Glaisdale catchment
N
Glaisdale
River Esk
240
220
180
160
140
120
280
260
300
320
0 kilometres 2

Figure 1. ~~Catchment~~ M~~m~~aps illustrating (a) ~~of~~ Glaisdale~~–~~ catchment and associated land-units~~Beck~~. Contours are displayed at 10m intervals. The box identifies the reach of Glaisdale Beck experiencing extensive landslide inputs, which was subsequently diverted. This is shown in detail in (b). The location of Glaisdale Beck in the regional and national context is provided in (c) and (d) respectively.



~~Figure 1. Catchment map of Glaisdale Beck, the area within the red box represents the modified reach. Catchment location is displayed on the inset map of the UK. Contours are displayed at 10m intervals.~~ © Crown Copyright/database right 2015. An Ordnance Survey/EDINA supplied service.

Figure 2. View looking upstream at a steep, 3m high, near vertical bank of unconsolidated sediment exposed along Glaisdale Beck. This is at the distal end of a large hillslope failure complex.



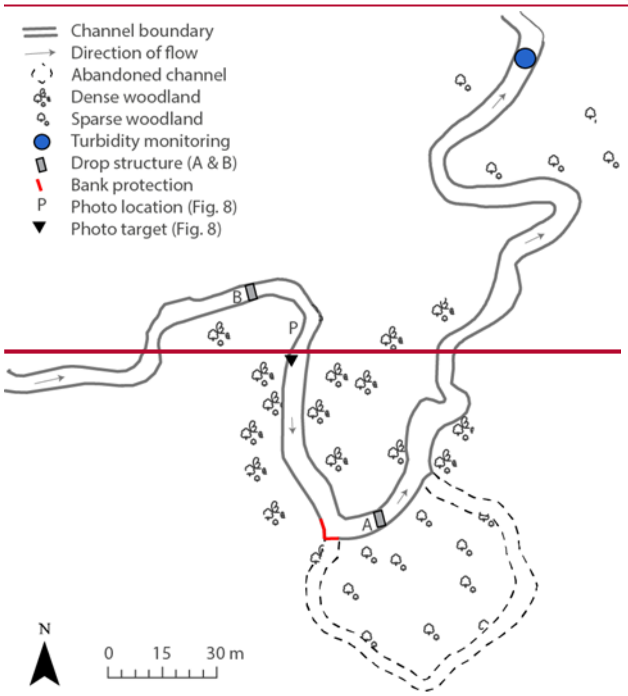


Figure 3. Map showing the diversion location with control measures and monitoring site.

Figure 44. View looking downstream of the channel diversion during the construction phase. Photograph taken on day of diversion works; 10th October 2007.

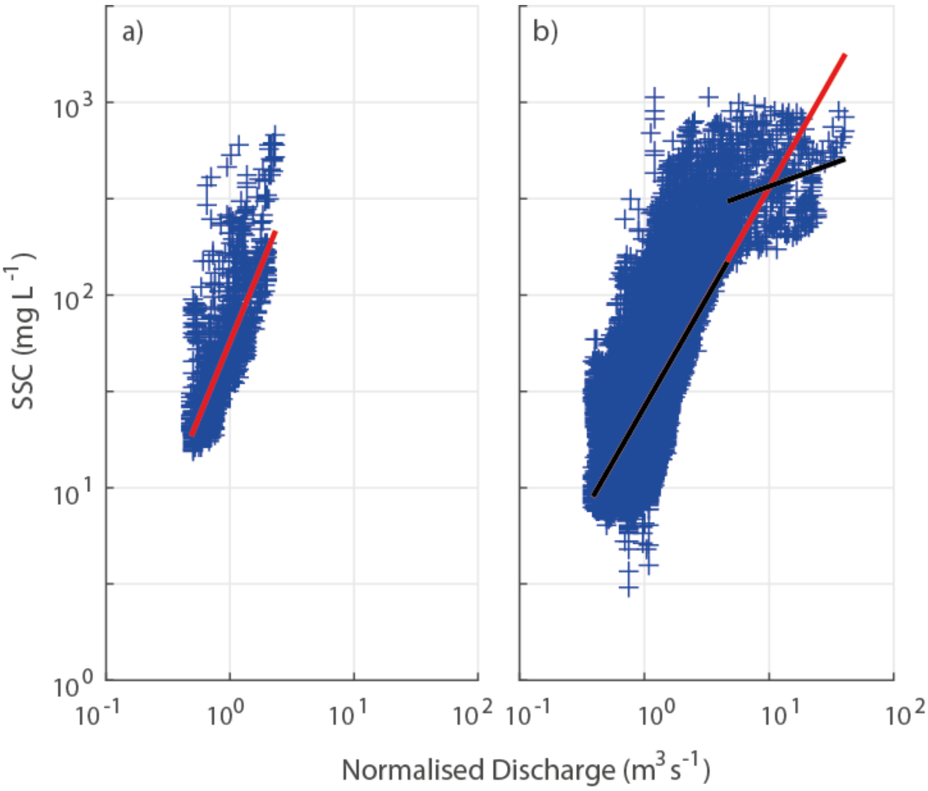


Figure ~~5~~5. Relationship between normalised discharge and suspended sediment concentrations a) before and b) following the diversion of Glaisdale Beck. The red line represents all the available data for the time-period. The broken black line represents the threshold models for normalised discharge within the range of greater than and less than 4.6 m^3 s^{-1}.

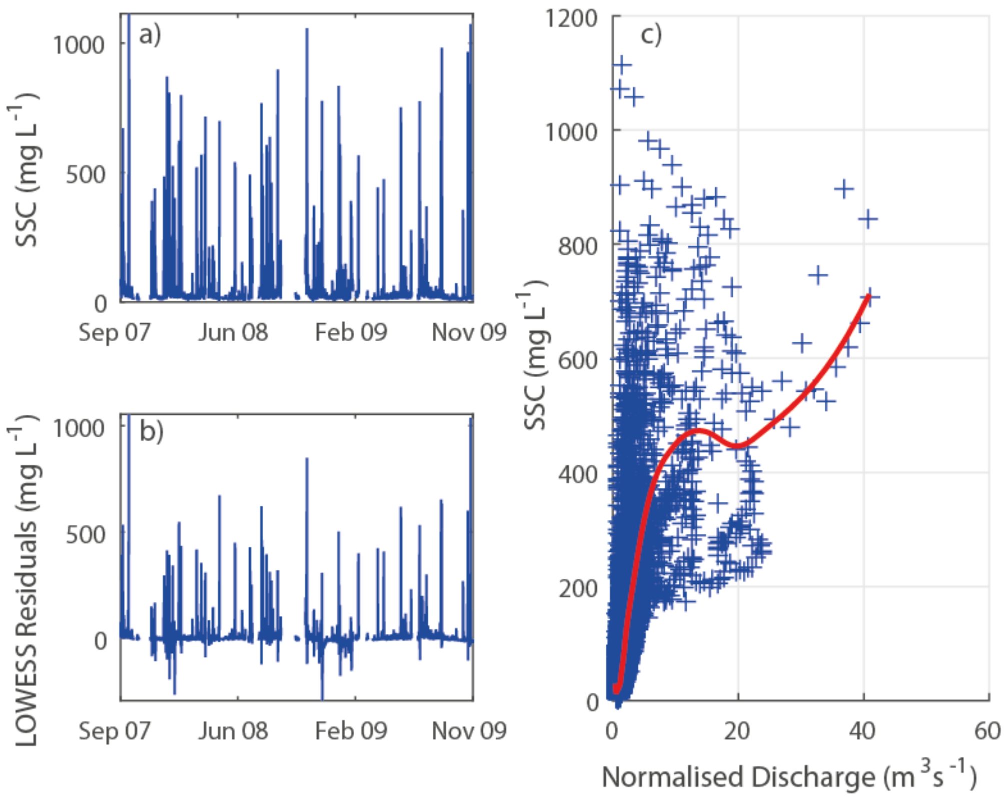


Figure 66. a) Suspended sediment concentrations and b) residuals over the entire monitoring period as a result of c) the LOWESS model developed between normalised discharge and suspended sediment concentrations

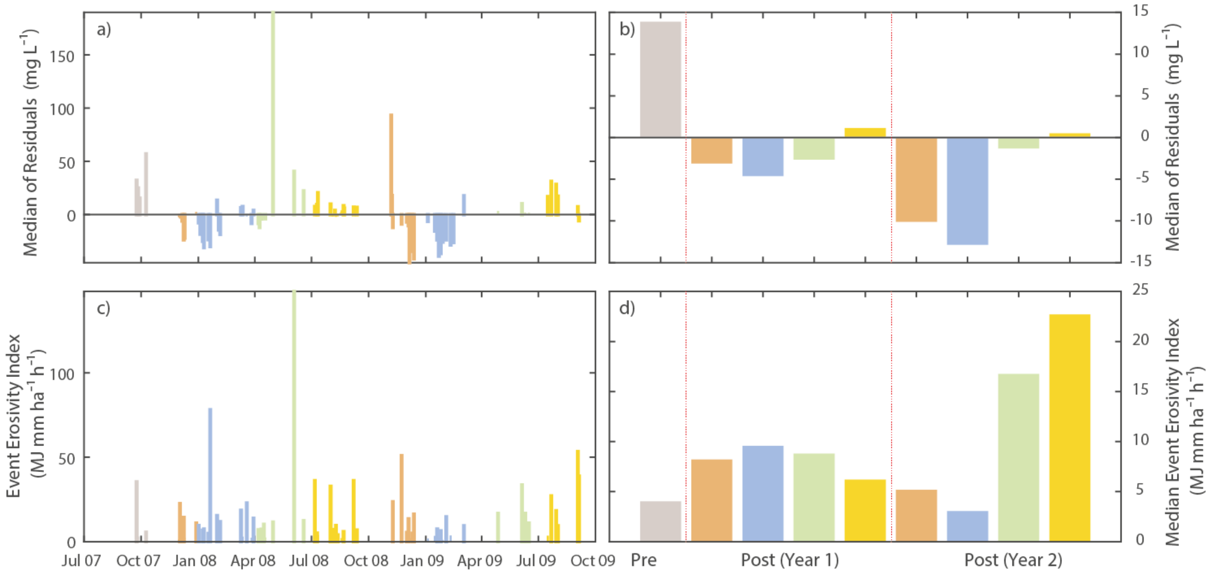


Figure ~~7~~7. Median of the LOWESS model residuals grouped by a) individual storm event and; b) season, and the rainfall erosivity index grouped by; c) individual storm event and; d) season. The colours represent the different seasons with brown representing autumn; blue – winter; green – spring and; yellow – summer.

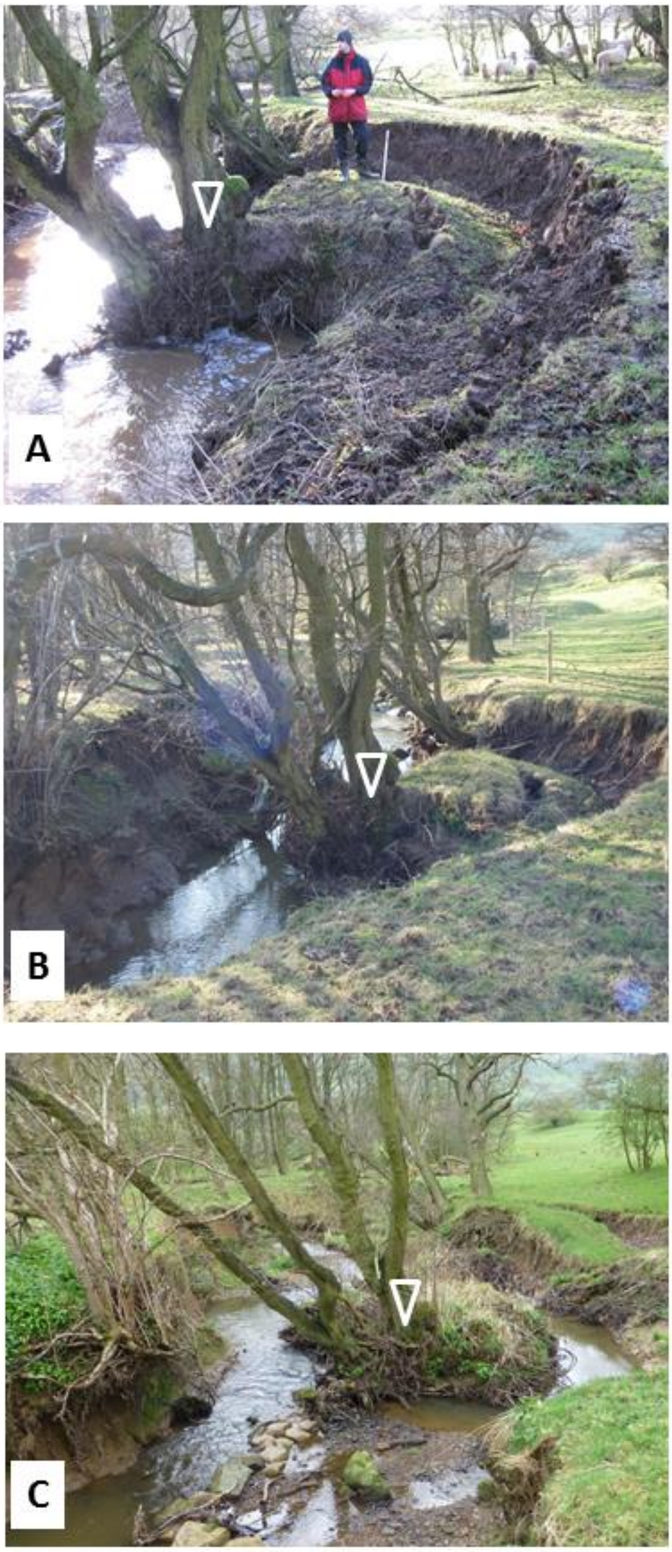
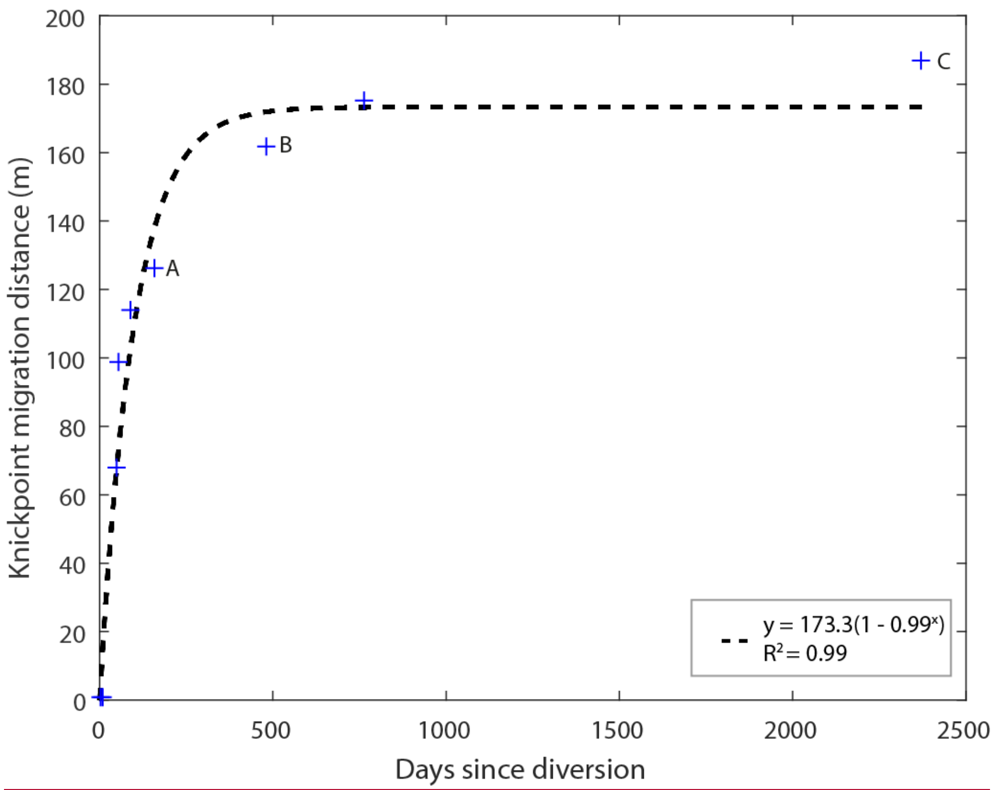


Figure ~~8~~8. Time lapse sequence of a right river bank collapse approximately 50m upstream of channel diversion. Images show the sequence: (A) 3rd February 2008; (B) 2nd March 2009; and (C) 7th April 2014. The white inverted triangle shows a fixed point of reference at the base of a tree which appears in all the images.



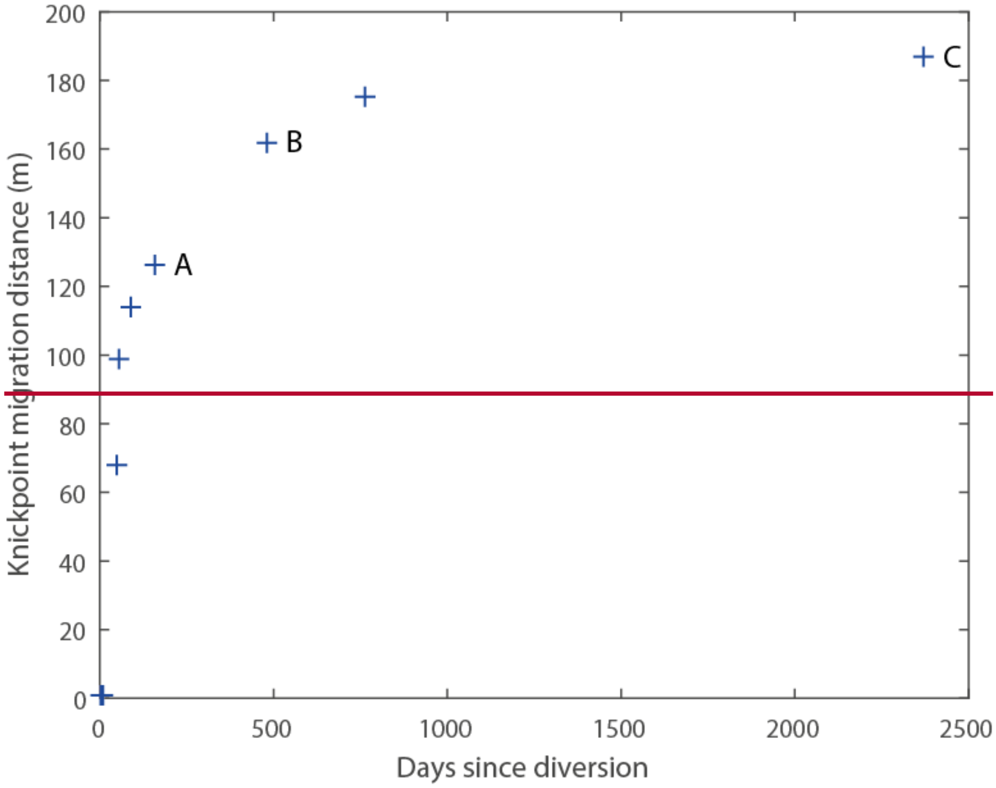
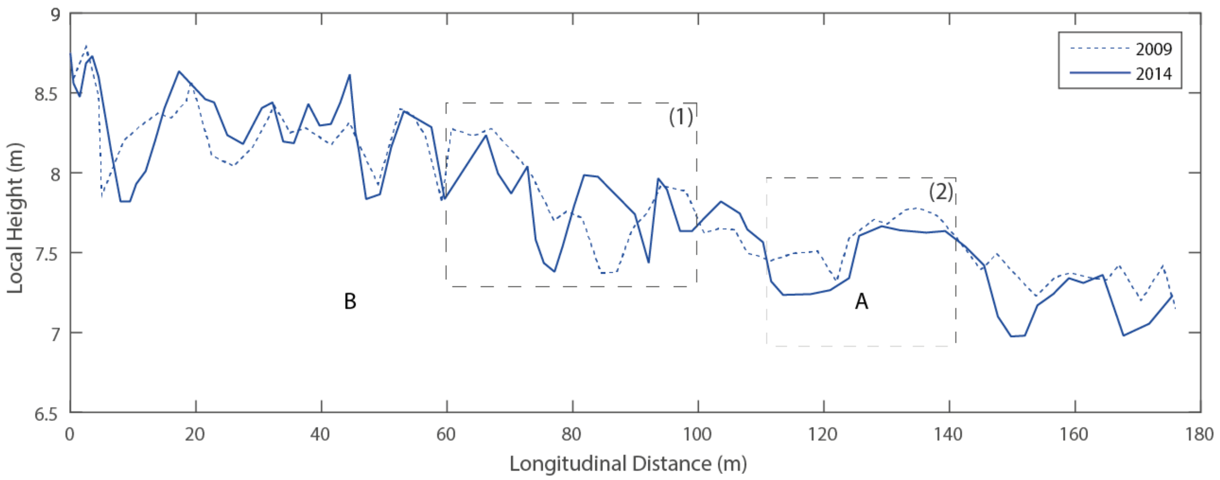


Figure 99. Plot between days since diversion and distance of headward knickpoint migration (m). Letters A – C correspond to the sequence of images in Figure 88.



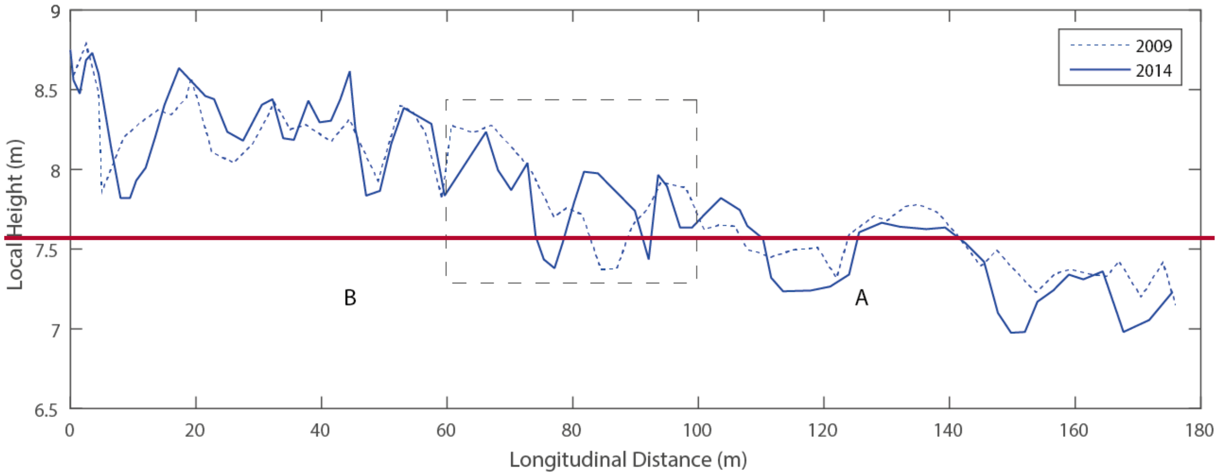


Figure 110010. Comparison of long profile surveys of the channel diversion reach at Glaisdale Beck: 2nd March 2009 to 7th April 2014. The dashed box labelled (1) shows the zone of lateral bank instability shown in Figure 88. The dashed box labelled (2) shows represents the realigned section of the channel. ‘A’ and ‘B’ indicate the positions of the two main drop structures (weirs) on the river bed (locations also shown in Figure 3).