

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

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1 **Abstract**

2 This paper describes the implementation of a novel mitigation approach and subsequent
3 adaptive management, designed to reduce the transfer of fine sediment ($< 2\text{mm}$) in Glaisdale
4 Beck; a small, predominantly upland catchment in the UK. Hydro-meteorological and
5 suspended sediment datasets are collected over a two year period spanning pre- and post-
6 diversion periods in order to assess the impact of the channel reconfiguration scheme on the
7 fluvial suspended sediment dynamics. Analysis of the river response demonstrates that the
8 fluvial sediment system has become more restrictive with reduced fine sediment transfer. This
9 is characterised by reductions in flow-weighted mean suspended sediment concentrations from
10 77.93 mg L^{-1} prior to mitigation, to 74.36 mg L^{-1} following the diversion. A Mann–Whitney U
11 test found statistically significant differences ($p < 0.001$) between the pre- and post-monitoring
12 median SSCs. Whilst application of one-way analysis of covariance (ANCOVA) on the
13 coefficients of sediment rating curves developed before and after the diversion found
14 statistically significant differences ($p < 0.001$), with both Log a and b coefficients becoming
15 smaller following the diversion. Non-parametric analysis indicates a reduction in residuals
16 through time ($p < 0.001$), with the developed LOWESS model over-predicting sediment
17 concentrations as the channel stabilises. However, the channel is continuing to adjust to the
18 reconfigured morphology, with evidence of a headward propagating knickpoint which has
19 migrated 120 m at an exponentially decreasing rate over the last 7 years since diversion. The
20 study demonstrates that channel reconfiguration can be effective in mitigating fine sediment
21 flux in headwater streams but the full value of this may take many years to achieve whilst the
22 fluvial system, slowly readjusts.

1 **1 Introduction**

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

15

16 Lateral erosion in particular plays an important role in channel migration, meander development
17 and the delivery of fine sediment (< 2 mm) to upland channels (Lawler, 1993; Lawler et al.,
18 2001; Fuller et al., 2003). Documented contributions of bankside sediment sources range from
19 1.5% to over 80% of total fine sediment flux (Bull, 1997; Stott, 1997), with high magnitude
20 episodic events transferring significant volumes of bank-eroded material (e.g. Carling, 1986).
21 However, on a global scale, the magnitude of sediment transfer typically observed in these
22 upland catchments is relatively low (Evans and Warburton, 2005). Changes to runoff generation
23 processes (Marshall et al., 2009; Holden et al., 2015), and the spatial distribution and magnitude
24 of erosion (McHugh, 2007), can however result in the enhanced conveyance of bankside and
25 hillslope eroded material into the fluvial networks draining these catchments (Owens et al.,
26 2005). Drivers of these changes in the uplands of the UK include: farming and forestry
27 operations (Burt et al., 1983; Tilman et al., 2002); moorland burning (Imeson, 1971; Arnold-
28 Forster, 2002; Holden et al., 2015); peat degradation; metal mining (Macklin et al., 1997);
29 artificial drainage (Ramchunder et al., 2009); and channelisation (Brown, 1997; Gilvear and
30 Bradley, 1997), with few catchments remaining that can be described as being in reference
31 condition (Sear et al., 2000; Sear et al., 2009). Enhanced sediment generation and delivery

1 processes place additional pressure on aquatic habitats, increasing the risk of chemical and
2 biological pollution, and habitat decline (Robinson, 1973).

3

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

11

12 To ensure a positive legacy of the continuing and future management of our upland catchments,
13 it is imperative that rehabilitation efforts are based on sound scientific knowledge acquired
14 through the progressive development of a solid evidence base consisting of the
15 fluvial/catchment response to a range of interventions across multiple scales (Brierley et al.,
16 2010). This will allow competent authorities to: a) predict the effectiveness of control measures
17 (e.g. Wilkinson et al., 2013); b) predict the cost-effectiveness of resource allocation (e.g.
18 Posthumus et al., 2013); and c) enable reliable and transparent decisions to be made about future
19 catchment operations (Collins et al., 2012). Comprehensive monitoring is rarely undertaken
20 with few quantitative assessments of whether restoration results in significant improvements in
21 river function (Newson, 2002; Skinner and Bruce-Burgess, 2005; Newson and Large, 2006;
22 Wohl et al., 2015).

23

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

1

2 **2 Regional Setting**

3 **2.1 Context and problem**

4 Glaisdale Beck is located in the North Yorkshire region of England, UK with a catchment area
5 of 15.6 km² (Figure 1). Originating on Glaisdale Moor at an altitude of 382 m, the upland river
6 (as defined by Atherden (1992)) flows 7 km before joining the River Esk. The climate is cool,
7 temperate, with annual average rainfall of less than 1000 mm. The local geology is dominated
8 by Jurassic rocks of the Whitby Mudstone Formation (mudstone and siltstone with calcareous
9 nodule bands) overlain by unconsolidated boulder clay and undifferentiated drift in the valley
10 bottoms (British Geological Survey, 1992). The dominant land-use is moorland, pasture and
11 rough grazing with some woodland, particularly in the lower catchment (Figure 1). Each of
12 these managed land-units creates specific pressures. The presence of artificial drains (or grips)
13 on Glaisdale Moor alter the runoff regime, and the practise of managing the dry heath may
14 result in bare soil exposure, increasing erosion risk. On lower-lying farm land, reported stocking
15 densities of up to 1.51 livestock units per hectare creates diffuse pollution pressures within the
16 catchment (Emery, 2010).

17

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

27

28

[Insert Figure 1]

29

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

11

12

[Insert Figure 2]

13 **2.2 Reconfiguration**

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

27

28 Although a range of measures to control channel readjustment and fine sediment release were
29 recommended, not all could be fully implemented due to local site conditions and the
30 determined specification was not followed in detail. The most important deviation was the use
31 of insufficient material to construct the drop structure located on the new cut-through section

1 (Figure 3, Drop structure A). As a result of this structure becoming undermined, it needed to be
2 later reinforced along with the addition of a drop structure upstream of the diversion (Figure 3,
3 Drop structure B). This additional work was undertaken during February 2008. However, the
4 materials and construction of the upstream drop-structure also deviated from the recommended
5 specifications.

6

7

[Insert Figure 3]

8

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

18

19 **3 Materials and Methods**

20 **3.1 Physical Data Collection**

21 An assessment of the fluvial sediment system of Glaisdale Beck was undertaken by monitoring
22 the fine sediment dynamics immediately prior to and in response to the realignment work. An
23 in-stream monitoring station was located 250 m downstream of the diversion (Figure 3). This
24 included a McVan Analite 395 turbidity probe and PDCR 1830 Campbell Scientific pressure
25 transducer connected to a CR10X data-logger, alongside an ISCO 3700 automatic water
26 sampler. Monitoring of turbidity and level began on 21st September 2007, providing 19 days
27 of data prior to the engineering work, which took place on the 10th October 2007. Monitoring
28 continued following the diversion for two years. Turbidity and river level data was collected at
29 15-minute intervals with discharge estimated through the combination of river stage and
30 velocity estimates (cf. Perks et al., 2014). The turbidity probe was deployed as a surrogate for

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

21

22 **3.2 Data Treatment**

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

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[Insert Table 1]

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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:

$$\text{LogSSC} = \log a + b \cdot \log \hat{Q} \tag{1}$$

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) 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.

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

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’ was 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 ($\text{MJ ha}^{-1} \text{mm}^{-1}$) for each rainfall event r is calculated from the empirical function proposed by Brown and Foster (1987):

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

1 where i is the rainfall intensity during the time interval (mm h^{-1}). The event rainfall erosivity
2 index $Ei30$ ($\text{MJ mm ha}^{-1} \text{h}^{-1}$) is subsequently calculated as follows (Meusburger et al.,
3 2012; Sheridan et al., 2011; Angulo-Martínez et al., 2009):

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

6 where v is the rainfall depth (mm) and I_{30} is the maximum rainfall intensity during a period of
7 30-minutes during the event (mm h^{-1}). Finally, the median rainfall erosivity index is calculated
8 for each season, taking account of all observed storm events.

10

11 **4 Results**

12 **4.1 Pre-Diversion**

13 During the short pre-diversion monitoring period, \hat{Q} and SSC were highly correlated (Kendall's
14 Tau = 0.66; $p < 0.001$). The flow-weighted mean concentration was 77.93 mg L^{-1} with a SSC_{50}
15 of 35.19 mg L^{-1} , range spanning $15.37 - 671.21 \text{ mg L}^{-1}$ and median absolute deviation of 12.15
16 mg L^{-1} . This available data indicates that prior to diversion, the river conditions were
17 unfavourable for the freshwater pearl mussel populations due to the exceedance of a 10 mg L^{-1}
18 critical threshold (Stutter et al., 2008), and may also be sub-optimal for Salmonid and Cyprinid
19 fish populations due to SSCs at low flow exceeding 25 mg L^{-1} (Bilotta et al., 2010; Collins and
20 Anthony, 2008).

21 **4.2 Disturbance**

22 During channel diversion, no measures were put in place to minimise downstream transfer of
23 fine sediment. Consequentially, the maximum observed instantaneous SSCs reached 2468 mg
24 L^{-1} , nearly 3600% greater than the upstream concentration (Figure 4). Although this declined
25 rapidly, concentrations were still 510% greater two hours after the breakthrough, with
26 downstream concentrations of 359 mg L^{-1} . Such disturbances have been observed elsewhere;
27 with sediment loads immediately downstream of in-stream works measuring between 40 and
28 150% more than those immediately upstream (Brookes, 1987; Sear and Archer, 1998). The
29 observed duration and concentrations may have short-term impacts on the primary productivity
30 and the free-living ecology of the river such as reduced natural penetration of light; increases

1 in the rate of drift and reduced abundance of invertebrates (Rosenberg and Wiens, 1978; Doeg
2 and Milledge, 1991); and modified Salmonid feeding and foraging behaviour (Robertson et al.,
3 2007). However, a longer term concern was the potential for this material to clog Salmonid
4 redds, reducing oxygen availability (Carling, 1984). Positively, annual survey data indicated no
5 decline in the numbers of Salmonids the following year (Environment Agency, 2011).

6

7

[Insert Figure 4]

8 **4.3 Impact**

9 During the two year's of flow and SSC monitoring following the diversion, \widehat{Q} and SSC were
10 highly correlated (Kendall's Tau = 0.36; $p = 0$). The flow-weighted mean concentration falls
11 by 5% to 74.36 mg L⁻¹. SSC₅₀ is 18.98 mg L⁻¹, which is significantly different to the pre-
12 diversion median SSC with a reduction following the diversion (Mann-Whitney U test; $p <$
13 0.001). The monotonic trend in \widehat{Q} is positive (Kendall's Tau = 0.05; $p < 0.001$), whilst the SSC
14 trend is negative (Kendall's Tau -0.05; $p < 0.001$). Following diversion, median concentration
15 falls below the 25 mg L⁻¹ threshold of the (now repealed) EU Freshwater Fish Directive
16 (2006/44/EC); however it still exceeds the 10 mg L⁻¹ level recommended for the protection of
17 freshwater pearl mussel habitats (Stutter et al., 2008). These thresholds are exceeded 33.75 and
18 94.11% of the time respectively.

19 **4.3.1 Parametric Time-series Analysis**

20 Regression of Log C on Log \widehat{Q} provides a linear model, which when back-transformed predicts
21 SSC from discharge for the pre- and post-diversion monitoring periods (Table 2), resulting in
22 the development of empirical models which meet the acceptance threshold for analysis utilised
23 by Syvitiski *et al.*, (2000). However, above a \widehat{Q} threshold value (Tv) of 4.6 m³ s⁻¹ the suspended
24 sediment response is poorly replicated by a power-law model; the SSC response to increasing
25 discharge becomes dampened. This results in curvature in the \widehat{Q} -SSC relationship in log space
26 which is inadequately characterised by the model (Figure 5). This reduced sensitivity is
27 demonstrated when the dataset is partitioned at Tv and the creation of two discrete models: one
28 for low flows and one for high flows. The resulting b coefficient shifts from 1.13 (when $\widehat{Q} < Tv$)
29 to 0.23 (when $\widehat{Q} > Tv$) (Table 2). The form, explained variance and error associated with the
30 partitioned model (when $\widehat{Q} < Tv$) is similar to the original model incorporating all observed

1 discharges (Table 2). However, the partitioned model (when $\widehat{Q} > Tv$) has poor explained
2 variance and large errors associated with it ($R^2 = 0.07$; $RMSE = 174.54$). This is indicative of
3 a complex and highly variable SSC response at moderate and high discharges in Glaisdale Beck.
4 This is related to the supply-limited nature of the fluvial sediment system which is related to
5 either a reduction in the availability of fine sediment sources e.g. through the exhaustion of
6 readily available material temporarily stored on the river bed (Gao and Josefson, 2012) and/or;
7 a reduction in rainfall effectiveness as the storm progresses (Wood, 1977). These dynamics
8 cannot be adequately characterised using a simple power-law.

9
10 [Insert Table 2]

11
12 [Insert Figure 5]

13
14 The observed rating curve coefficients are within the normal range of what would be expected
15 for temperate rivers (Reid and Frostick, 1987; Syvitski et al., 2000), however following
16 diversion, the Log a coefficient decreases from 1.76 to 1.42, whilst the b exponent also
17 decreases from 1.57 to 1.14. These coefficients have been shown to respond to patterns of
18 sediment production, availability and transport capacity, with reductions being associated with
19 a move to a more restrictive sediment transport system (Warrick and Rubin, 2007; Asselman,
20 2000; Yang et al., 2007). To test whether these changes are statistically significant and to
21 confirm the impacts of modification, a one-way analysis of covariance test (ANCOVA) was
22 conducted on the log-model coefficients. For this to be a valid comparison, only discharge data
23 within the range observed pre-diversion was utilised (i.e. normalised discharge $< 2.37 \text{ m}^3 \text{ s}^{-1}$).
24 Results indicate highly significant differences between the pre- and post-diversion monitoring
25 period for both Log a and b coefficients (Table 3). This confirms that modification of Glaisdale
26 Beck has resulted in a suspended sediment regime which responds significantly differently to
27 changes in flow, likely as a consequence of the changes to local shear stress and sediment
28 availability following the diversion. Encouragingly from a river remediation point-of-view, a
29 \widehat{Q} of $2.37 \text{ m}^3 \text{ s}^{-1}$ prior to modification would have yielded a typical SSC value of 221.77 mg L^{-1} ,
30 whereas the modified system would typically result in a SSC of 70.33 mg L^{-1} ; equivalent to
31 a 68% reduction. These findings suggest differences in flow effectiveness, with flows following
32 diversion failing to have the same erosive impact (Hicks et al., 2000; Wolman and Miller, 1960).

1

2

[Insert Table 3]

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4

4.3.2 Non-parametric Time-series Analysis

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

19

20

[Insert Figure 6]

21

22 The maximum positive LOWESS residuals are identified as occurring during the construction
23 of the channel diversion ($+1054 \text{ mg L}^{-1}$) and as a result of SS spikes occurring immediately
24 prior to, and independent of storm events during November 08 and 09 ($+849.5$ and $+1038 \text{ mg}$
25 L^{-1} respectively; Figure 6b). The maximum negative residuals occur during storm events in
26 January and December 08, resulting in deviations between observed and predicted
27 concentrations of -263.5 and -292.1 mg L^{-1} respectively. Upon the calculation of the median
28 LOWESS residuals for each monitored storm, and by season, striking patterns are observed
29 (Figure 7 a-b). For each storm occurring prior to diversion, highly positive median residuals are
30 produced as a result of the LOWESS model underestimating concentrations. During this unit

1 of analysis (storm and base flow component), the median of the residuals is 13.86 mg L⁻¹; the
2 highest observed during the entire monitoring period. During the following three seasons
3 (autumn 08 – spring 09), the median of the residuals are negative with a range spanning -2.64
4 to -4.63 mg L⁻¹. Negative residuals are also produced for the same seasons during the second
5 year of monitoring, although their magnitude is greater (with the exception of spring). The
6 seasonal pattern of the residuals is quasi-cyclic with largest post-diversion residuals occurring
7 during the summer months, followed by the spring months. However, there are no observable
8 relationships between the erosivity index of the rainfall and the residuals produced by the
9 LOWESS model, therefore this observed pattern is not believed to be influenced by seasonality
10 in the storm intensity and erosion potential (Figure 7 c-d). Whilst the role of land management
11 activities, natural variability of sediment supply across the wider catchment, and additional
12 stressors, or mediating factors cannot be excluded, it is significant in the context of this research
13 that the trend in the residuals is negative, with the suspended sediment response becoming
14 increasingly dampened throughout the monitoring period.

15

16

[Insert Figure 7]

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18 4.3.3 Long-term Geomorphic Impact

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

25

26

[Insert Table 4]

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28 As a result of these erosive events during this period, continued erosion in the form of a
29 headward migrating knickpoint (visible as a step in the clay of the river bed substrate) has
30 resulted in a progressive wave of channel instability that has migrated upstream. This is the

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

22

23

[Insert Figure 8]

24

25

[Insert Figure 9]

26

27 The temporal sequence of images in Figure 8 A to C are also labelled on Figure 9 to cross
28 reference the local erosion observed at a point in relation to the progression of the eroding
29 knickpoint upstream. Over the seven year observation period the point of observed bank
30 undercutting and bed instability, shown by a small step in the river bed long profile, has
31 migrated 187 m upstream at an average annual rate of approximately 30 m per year. Over time

1 this rate has slowed dramatically from an initial rate, in the first two months since diversion, of
2 nearly 1.4 m per day to an eventual rate of less than 1 mm per day; a decrease in rate of
3 approximately 1400% (Figure 9). This reduction in the rate of knickpoint migration follows an
4 exponential trend with the rate slowing dramatically towards the present (2014). The most
5 recent observations suggest the headward migration of the channel knickpoint has now almost
6 ceased and there is little evidence of further bank instability much beyond 200 m upstream of
7 the point of the original channel diversion. The increase in slope caused by the diversion has
8 largely been accommodated by adjustments to the channel bed slope and cross-section
9 morphology. It is estimated that the channel diversion increased the local reach slope from
10 approximately 0.0061 (following the old meandering course) to 0.05 in the freshly engineered
11 diversion reach (Table 5). Following seven years of channel readjustment the contemporary
12 2014 channel slope has now returned to the pre-diversion state, which explains why further
13 upstream knickpoint migration and erosion have largely ceased.

14

15

[Insert Table 5]

16

17 The thalweg profile along the reconfigured channel reach was surveyed in detail on two
18 occasions in March 2009 and April 2014 spanning a period of 5 years. A comparison of the two
19 channel long profiles (Figure 10) supports the observations of the sequence of bank collapse
20 (Figure 8), and headward progression of the eroding knickpoint (Figure 9). The period between
21 March 2009 and April 2014 (500 to 2400 days since diversion) spans the period of adjustment
22 following major channel degradation which occurred in the first 500 days following the
23 engineering works (Figure 9). Nevertheless the channel was still degrading over this period and
24 some significant local variations in channel sedimentation were observed (Figure 10). In Figure
25 10, A and B represent locations of the two drop structures (weirs) and the dashed rectangle is
26 the zone of rapid channel change associated with bank collapse shown in Figure 8. Above the
27 upper weir, apart from a deep scour pool below a piece of large woody debris (c. 10 m) upstream
28 of the grade control structure, the channel has aggraded slightly over time. Downstream of the
29 lower weir, although the level of the main bars has remained relatively consistent between 2009
30 and 2014, the degraded pools remain over deepened with bed levels lower by almost 0.5 m in
31 places. Between these two sub-reaches is the dynamic reach affected by the large scale bank
32 collapses (Figure 8); here local adjustments in bed level dominate with erosion and deposition

1 varying by up to +/- 0.5 m although the overall pattern is next degradation of the reach. The
2 dynamic response of these three sub-reaches to the channel reconfiguration characterises nicely
3 the ongoing adjustment of the stream. Above the upper weir the channel is largely stable with
4 net aggradation; in the areas of bank collapses local adjustments continue; and below the lower
5 weir the channel still shows signs of bed lowering.

6

7

[Insert Figure 10]

8

9 **5 Discussion**

10 **5.1 Channel Evolution and Stability**

11 The changes observed in Glaisdale beck following channel reconfiguration were predicted
12 beforehand (Warburton, 2007). It was anticipated that channel bed instability would result from
13 the steepening of the newly aligned river channel and without appropriate engineering measures
14 the channel would erode in a headward direction. However, lack of experience and appreciation
15 of techniques for creating stable grade control structures, by the contractor and a dearth of
16 suitable materials on-site resulted in the control measures becoming undermined. In the
17 immediate vicinity of the channel diversion, rip rap successfully confined the stream to the
18 desired location restricting the risk of lateral instability and channel migration. However,
19 vertical down cutting, initially focused upstream of the grade control (drop) structures was
20 triggered by local scouring which was exacerbated by steepening of the stream profile and the
21 associated headward propagating knickpoint. The diversion of the channel resulted in a
22 steepening of the local slope to a gradient close to 5% (Table 5), which shifted the channel into
23 the range of slopes typical of step-pool streams (Chin et al., 2009). Under these conditions a
24 new channel morphology needs to be considered and step-pools need to be considered as a
25 suitable channel engineering structure. In this case study, a single large step was engineered to
26 create the new channel morphology and ultimately this was unsuccessful and failed. Chin et al.
27 (2009) list a set of important considerations relating to the design, construction and maintenance
28 of step pool structures that should be followed when restoring high gradient channels. With the
29 benefit of hindsight a staircase of multiple steps, constructed of large rock (imported to the site),
30 spaced appropriately in the diversion reach would have been more effective in mitigating
31 headward degradation (Chin et al., 2009). Overall however, the scheme effectively slowed the

1 downslope movement of the large landslide complex which was destabilising valuable farmland
2 and contributing significant quantities of fine sediment to beck. By disconnecting the river
3 channel from the distal end of the landslide, and preventing over-steepening of the toe, the
4 landslide crept into the old abandoned channel where movement was arrested.

5 **5.2 Channel Realignment as River Restoration**

6 Connectivity between potential sediment source areas and drainage networks in the uplands of
7 the UK results in the mobilisation and transfer of fine sediment from a range of point and diffuse
8 sources across a catchment (e.g. Foster and Lees, 1999; Johnson et al., 2008). In order to
9 identify areas of enhanced fine sediment transfer within the Esk catchment, research followed
10 spatially nested-hierarchical principles (Brierley et al., 2010). This knowledge of sediment
11 transfer processes enabled better understanding of the diversity and pattern of river character
12 and behaviour across the catchment system. Areas within the catchment with atypical sediment
13 dynamics compared with similar sub-catchments were identified. More focussed
14 geomorphological surveys then identified key critical areas within the sub-catchment units.
15 This process led to the identification of a specific reach along Glaisdale Beck as a key
16 contributor to fine sediment loadings in the Esk catchment, prompting action from local
17 authorities (Bracken and Warburton, 2005; Warburton, 2007). The authorities, primarily
18 concerned by the potential loss of salmonid spawning and freshwater pearl mussel habitats
19 following large quantities of fine sediment being mobilised by a progressive landslide and
20 associated localised bank erosion, responded by consulting with local stakeholders over the
21 available options before finally choosing to divert the river from the easily accessible sediment
22 source. Inherent in this approach was the assumption that the risk to in-stream habitat was
23 greater by doing nothing than by attempting to divert the channel away from the primary fine
24 sediment pollution source. Due to the sensitivity of the site, it was agreed that in order to
25 alleviate the problem effectively efforts should be directed towards a hard-engineering
26 approach, which should minimise the potential risk of failure. In the case of the channel
27 realignment option, the channel was designed to be laterally stable with grade control measures
28 in place (Warburton, 2007). This approach had the inherent potential to remove natural
29 variability and heterogeneity in channel morphology, flow dynamics and available river
30 habitats along the affected reach, whilst contradicting the popular movement from hard to soft
31 engineering solutions (Hey, 1996; Richards, 2001; Raven et al., 2010; Newson, 2012).
32 However, the clear identification of a manageable critical point source of fine sediment

1 provided an opportunity to significantly reduce degradation of the system and to enhance the
2 overall ecological integrity of the river beyond that of the reach scale (Palmer et al., 2005).
3 Nevertheless as Wohl et al. (2015) suggests, reconfiguring channels is fraught with difficulty
4 and often is only partially successful due to the local focus on the reach-scale. This case study,
5 through long-term monitoring, has demonstrated this limitation but more importantly shown
6 how the engineered reach, through longer-term natural adjustment, eventually reconnects with
7 the larger river network to deliver large scale benefits.

8

9 **6 Conclusions**

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

- 20 • Reductions in median SSC from 35.19 to 18.98 mg L⁻¹.
- 21 • 5% reduction in flow-weighted mean SSC.
- 22 • Negative trend in SSCs (Kendall's Tau; $p < 0.001$).
- 23 • Development of sediment rating curves with statistically different coefficients following
24 diversion. Both the Log a and b coefficients were smaller following the diversion.
- 25 • Decline in LOWESS residuals over time indicating an overestimation of SSCs as the
26 channel stabilises over time.

27 This monitoring campaign has indicated that prior to the diversion; Glaisdale Beck was
28 experiencing enhanced fine sediment flux, with conditions unlikely to be favourable for
29 Salmonids or pearl mussel populations. Following channel diversion, a prolonged period of
30 disturbance lasting approximately 7 years was observed. During this time, the channel and
31 sediment regime are highly dynamic, with order of magnitude changes in fine sediment

1 response occurring over short temporal scales. This is a result of disequilibrium in the fluvial
2 sediment system following diversion with readjustment to the new channel configuration
3 resulting in variations in the supply of fine-grained material. Despite this transient behaviour,
4 there is evidence of non-stationarity in the fine sediment flux signal and it is anticipated that
5 providing allogenic controls do not force further threshold changes, suspended sediment
6 transfer will remain at lower levels than that of pre-diversion conditions, with a fine sediment
7 transfer regime becoming established that is commensurate with the newly imposed conditions.

8

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

19

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4

1 **Tables**

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

	Calibration	SSC Range (mg L ⁻¹)	R ²	Uncertainty (95%)
Glaisdale Beck (<i>n</i> = 58)	$y = 1.1298x$	1.65 – 1266.20	0.92	22.96%

4

1 Table 2. Summary of the developed empirical models for the prediction of suspended sediment
 2 concentrations from normalised discharge. Tv is the normalised discharge threshold value for
 3 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	$\hat{Q} < Tv$	56106	$1.4188 + 1.1292x$	0.40	$26.23x^{1.13}1.1919^*$	0.38	36.03
After	$\hat{Q} > Tv$	547	$2.3303 + 0.2332x$	0.08	$213.94x^{0.23}1.0961^*$	0.07	174.54

4

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

	Log <i>a</i> (T and <i>p</i> values)		<i>b</i> (T and <i>p</i> values)	
Before vs. After	22.72	0.00	13.21	0.00

3

4

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

Condition	Mean	Median	Maximum	Exceedance Probability		
	(m)	(m)	(m)	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

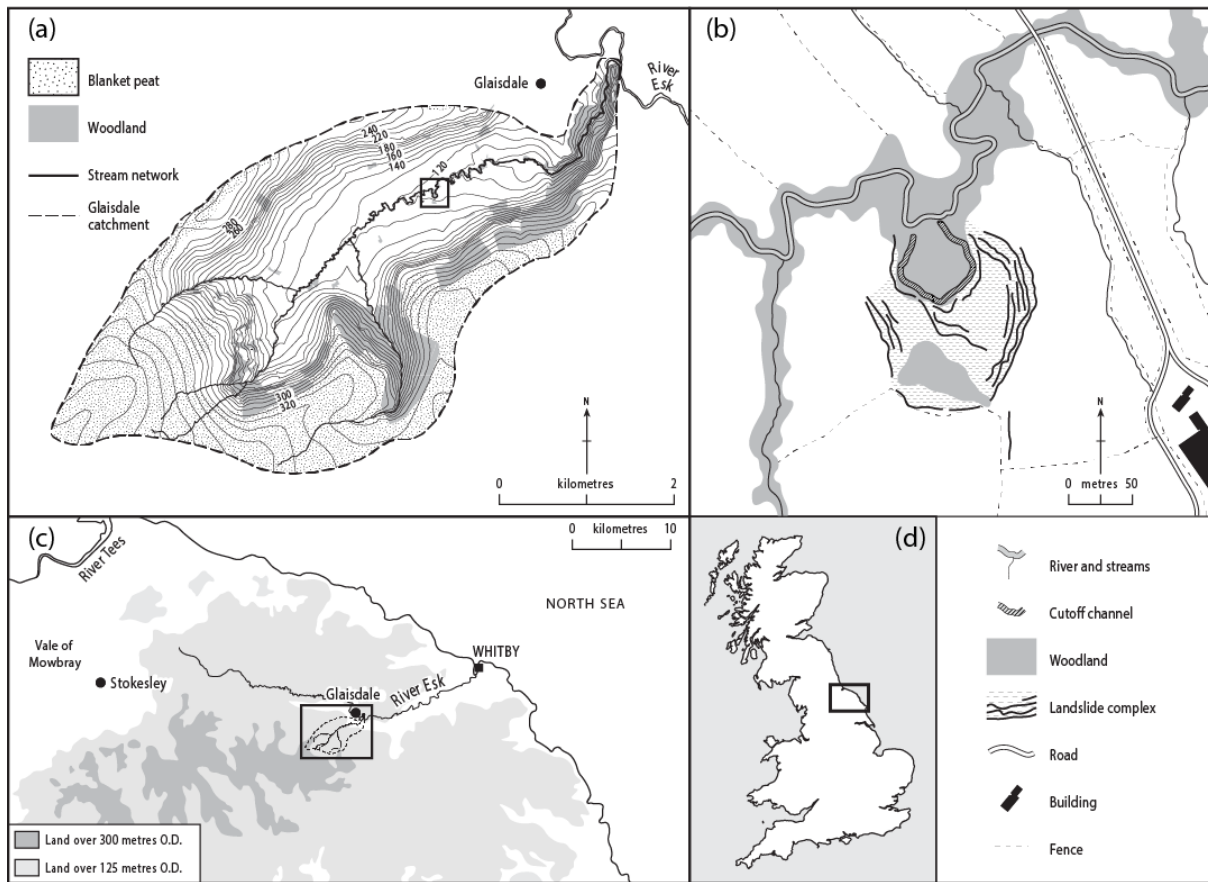
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8

1 Table 5. 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

2

1 Figures



2

3 Figure 1. Maps illustrating (a) Glaisdale catchment and associated land-units. Contours are
4 displayed at 10m intervals. The box identifies the reach of Glaisdale Beck experiencing
5 extensive landslide inputs, which was subsequently diverted. This is shown in detail in (b). The
6 location of Glaisdale Beck in the regional and national context is provided in (c) and (d)
7 respectively. © Crown Copyright/database right 2015. An Ordnance Survey/EDINA supplied
8 service.

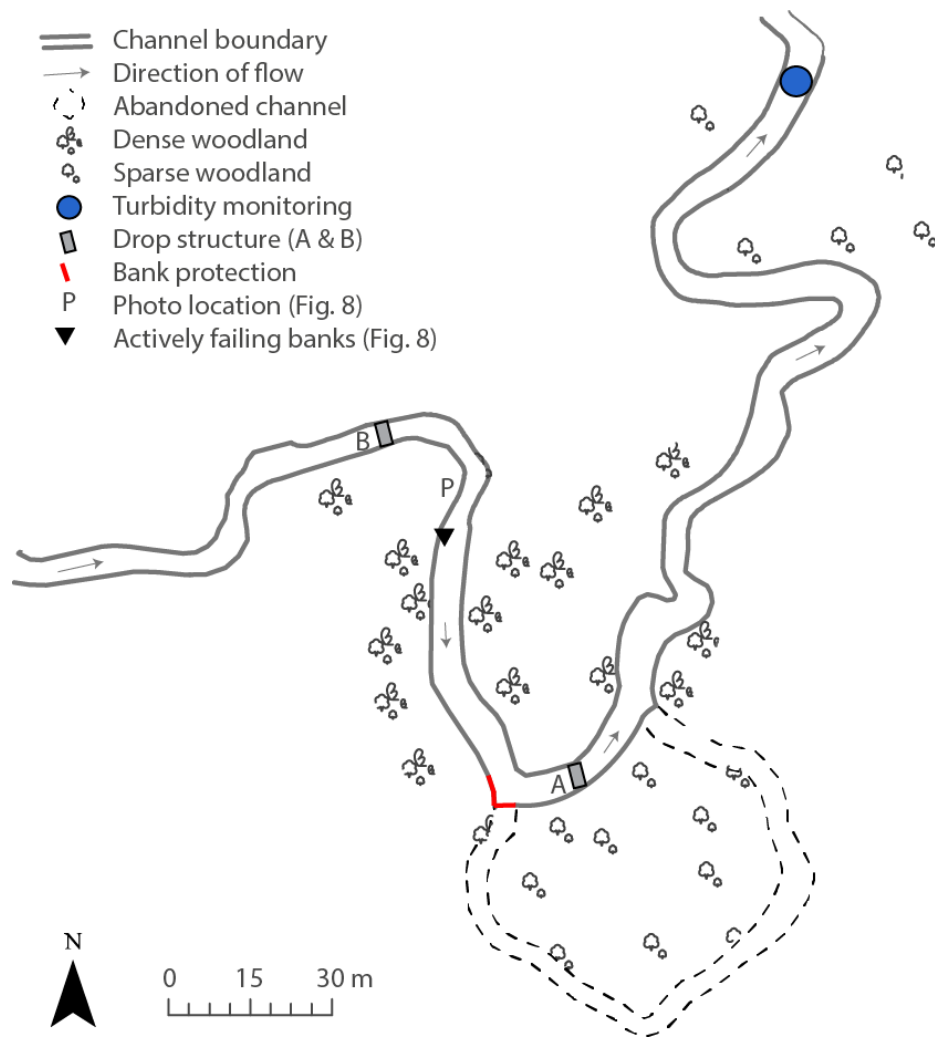
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1

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

5



1

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

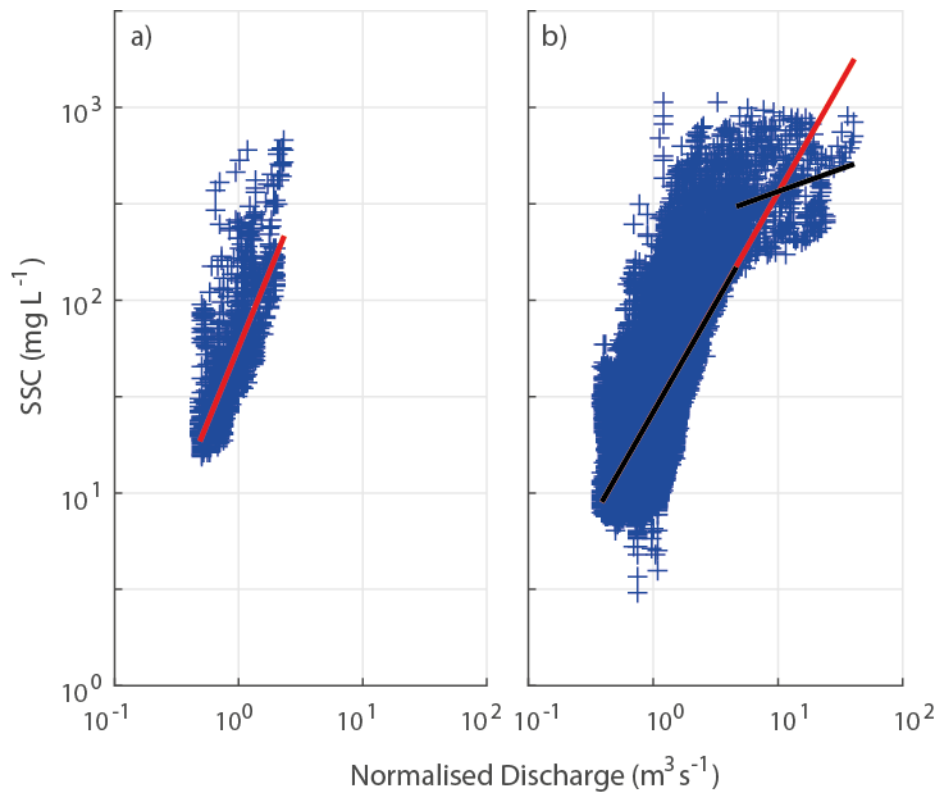


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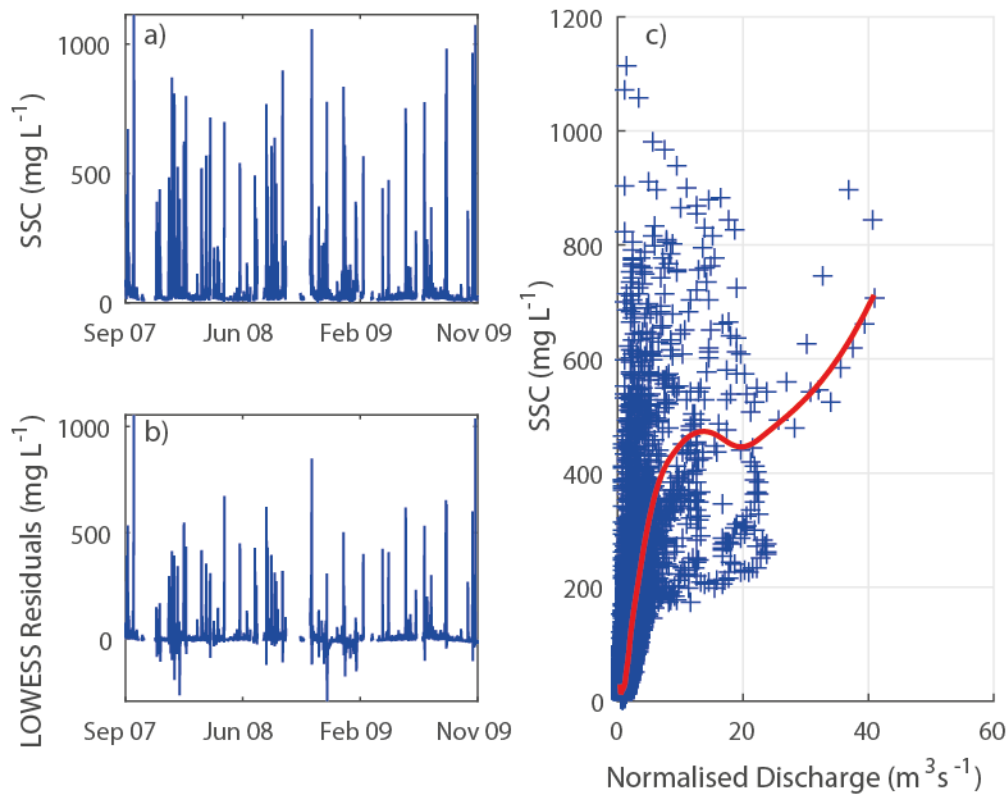
2 Figure 4. View looking downstream of the channel diversion during the construction phase.

3 Photograph taken on day of diversion works; 10th October 2007.

4

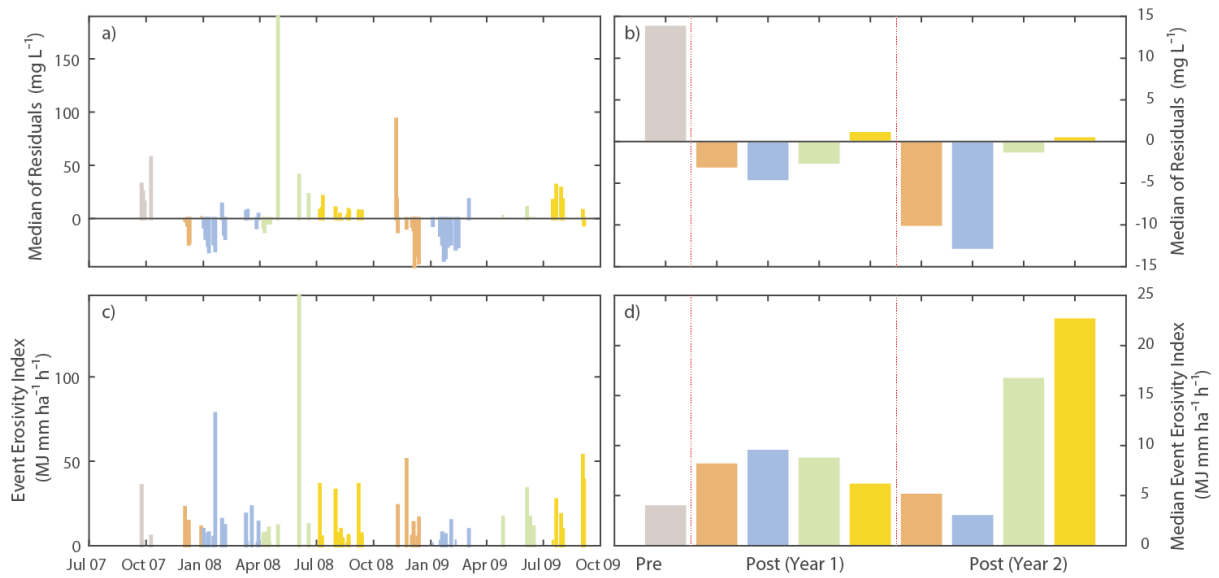


1
 2 Figure 5. Relationship between normalised discharge and suspended sediment concentrations
 3 a) before and b) following the diversion of Glaisdale Beck. The red line represents all the
 4 available data for the time-period. The broken black line represents the threshold models for
 5 normalised discharge within the range of greater than and less than $4.6 \text{ m}^3 \text{ s}^{-1}$.
 6



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Figure 6. 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



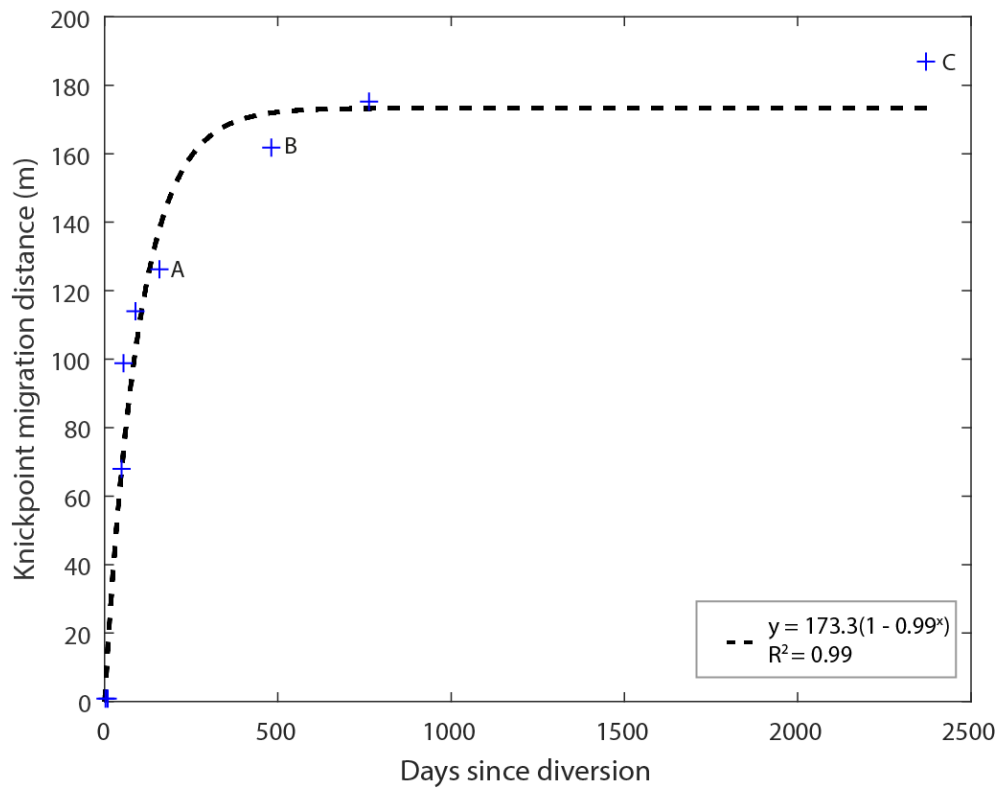
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 2 Figure 7. Median of the LOWESS model residuals grouped by a) individual storm event and;
 3 b) season, and the rainfall erosivity index grouped by; c) individual storm event and; d) season.
 4 The colours represent the different seasons with brown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

6



1

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

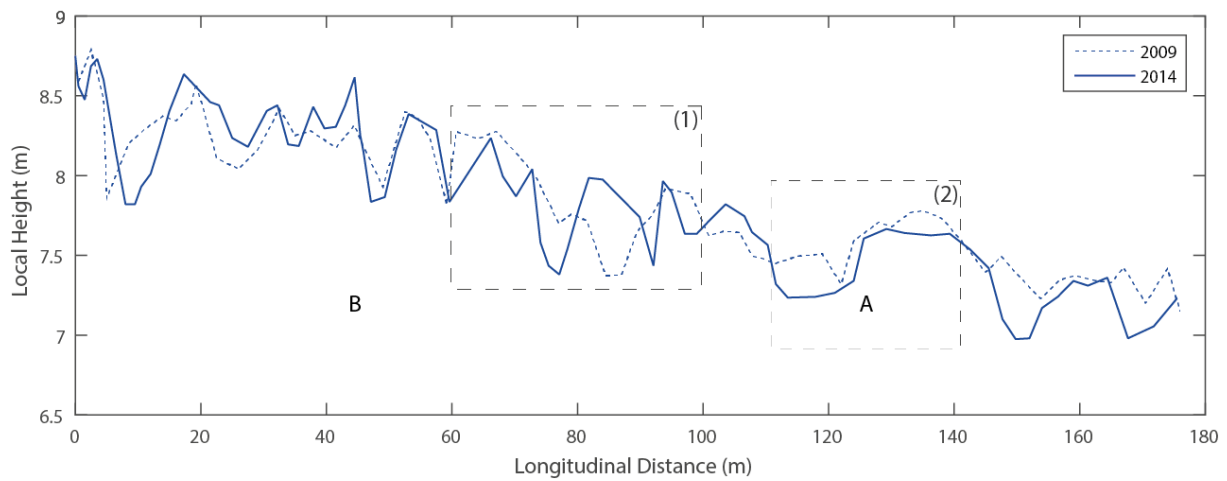


1

2 Figure 9. Plot between days since diversion and distance of headward knickpoint migration (m).

3 Letters A – C correspond to the sequence of images in Figure 8.

4



1

2 Figure 10. Comparison of long profile surveys of the channel diversion reach at Glaisdale Beck:
 3 2nd March 2009 to 7th April 2014. The dashed box labelled (1) shows the zone of lateral bank
 4 instability shown in Figure 8. The dashed box labelled (2) shows represents the realigned
 5 section of the channel. A and B indicate the positions of the two main drop structures (weirs)
 6 on the river bed (locations also shown in Figure 3).

7

8