The Bowmont catchment initiative: An assessment of catchment hydrology and Natural Flood Management measures

Four year summary

Stephen Addy & Mark Wilkinson February 2017

Scottish Government
Riaghaltas na h-Alba
gov.scot

The James Hutton Institute

Executive Summary

Background

The Bowmont Water is a headwater catchment of the River Tweed. It is an upland river and drains a catchment area of 87 km^2 (at Yetholm Mains). The Bowmont valley has a history of significant flood events. Two recent major events in September 2008 and July 2009 caused extensive inundation, changes to river form, disruption and damage to infrastructure. One of the main economic damages caused by the flooding was the loss of large areas of arable and grass farmland through sediment deposition and erosion. The cost to the council of repairing damaged infrastructure was approximately £670,000.

Following these events, Tweed Forum (through the Cheviot Futures initiative) began an initiative to tackle coarse sediment problems and reduce the likelihood of future flood events. Tweed Forum consulted specialists, landowners, farmers and agencies to plan suitable actions that included novel natural flood management measures (NFM). Since February 2012, the James Hutton Institute has been monitoring the hydrological and geomorphic responses to the measures. The following features have been installed and the research into their performance so far is presented in this report:

- Bar apex ELJs in the channel and areas of floodplain to capture and stabilise sediment.
- Bank protection engineered log jams (ELJs) designed to reduce bank erosion and the input of sediment to the river.
- Flow restrictors installed in a steep headwater channel to capture sediment and attenuate peak flows.

Research undertaken

As part of the Scottish Government Rural and Environment Science and Analytical Services Division (RESAS) funded work on “Methods for mitigating and adapting to flood risk”, this project set out to provide data at the local and catchment scales of the role of NFM in mitigating flood risk. It also sought to assess the efficacy of different wooden structures for reducing coarse sediment problems (e.g. riverbank erosion and deposition). This report summarises key findings from four years (2012-2016) of monitoring and outlines the challenges of monitoring in such a dynamic river system.

Hydrology key findings

- The Bowmont catchment is flashy and can respond to storm events within hours; at the catchment outlet of Yetholm Mains (87 km^2) the average lag time of peak flows following rainfall events is under 7 hours.
- Over the period of 1995 to 2015, there is no indication to show that there is an increasing or decreasing trend of yearly rainfall.
- Storm rainfall events are common from July to January (most common in September) but are less likely in the spring. However, the variability in monthly totals between years is large.
- Two large flood events occurred during the four year study period (September 2012 and January 2016) which resulted in damage to infrastructure, measures and significant geomorphic changes to the river channel.
- At present tree planting is on a very small scale (< 1% of the catchment area) and the trees are at a young age. This will not translate into a detectable reduction of peak flows at the catchment outlet. However, long term detection of hydrological response to tree planting in the Calroust catchment may by possible given the larger proportion of catchment area covered relative to other catchments (10.3%).

Local responses to wooden structure measures

Bar apex ELJs (Kelsocleuch, Swindon Haugh and Clifton sites)

- Between August 2012 and March 2016, 5 out of 45 bar apex engineered log jams have been lost and 5 out of the remaining 40 structures have been damaged.
- Significant sediment deposition (> 0.3 m depth) was associated only with a limited number of bar apex ELJs structures (5 out of 45 structures) which are restricted to Swindon Haugh and mostly in response to the September 2012 flood event. This partly reflects the placement locations (on floodplains and on stabilising gravel bars away from the deeper areas of river channel) and the small size of the structures, which have together limited their effectiveness.
- Trees planted within the structures to improve sediment capture and stabilisation had a poor survival rate (14 of 45) due to poor growing conditions (livestock grazing pressure, displacement by floods or soil condition).

Bank protection ELJs (Kelsocleuch Burn site)

- The lower rate of bank erosion at the bank protection ELJs tentatively suggests the structures are effective at reducing riverbank erosion although recently observed removal of backfill and bank vegetation suggests their effectiveness may have been lost.
- The greater lateral resistance created by one of the structures has led to significant toe scour and the formation of a deep channel.
- The removal of backfill and evidence of erosion of the riverbanks close to and behind the structures in some locations means their long term effectiveness may have been compromised.

Flow restrictors (Elm Sike site)

- The hydraulic and sediment capture effects of the flow restrictors were minor due to their limited channel blockage. The trapping of debris was also limited.
- Blockage of flow occurs only during high flows (i.e. approximately bankfull or greater) and together with the steep, confined nature of the channel, reduces the likelihood of backwater effects and flow attenuation.

Implications and guidance

General guidance

- Managing run-off at its source on hill slopes and in valley floor pathway zones by altering land use to forest cover is likely to be the most effective means of attenuating flows or reducing coarse sediment yields.
- The sensitive and dynamic nature of river channels in the Bowmont catchment means any measures installed within the river corridor are susceptible to scour and washout or being bypassed due to channel course change. Measures like engineered log jams, novel bank protection structures or measures like bunds or ponds that are untested in the catchment are thus vulnerable.

Guidance on wooden structures

- Careful placement of wooden installations is needed to ensure their effectiveness whilst at the same time accepting that regular monitoring and maintenance are needed. If possible, modelling based approaches should be used to optimise structure stability and function prior to construction. The following guidance is specific to each measure and should be considered prior to installation:
    - **Bar apex ELJs:** place structures in areas of sediment transport within wetted channels (i.e. avoid placing on floodplains where their function is lost) and sediment deposition. Increase the density (i.e. make the structures more complex and less porous) and size of the structures relative to river size to increase their hydraulic and geomorphic effects.
    - **Bank protection ELJs:** consider first if a riverbank needs to be protected with such a structure; riverbank erosion is an expected and natural process that allows rivers to accommodate inputs of water and sediment. If riverbank protection is needed then tree planting and soft bank protection measures may be more effective and sustainable. If this structure design is used in future, ensure that backfill and vegetation are properly reinstated. Also consider structures that are designed to deflect flow rather than reinforce riverbanks which may be more effective.
    - **Flow restrictors:** these are likely to function better in less steep channels with floodplains (greater scope for temporary water storage). Increasing the degree of channel blockage would increase their hydraulic interference which could translate into more effective discharge attenuation and sediment capture. However consideration needs to be given to ensure fish passage.
- ELJs and other wooden structures should not be used in isolation as they tend to deal with symptoms of a problem rather than dealing with its source (e.g. high rates of sediment transport related to high catchment runoff and extensive eroding riverbank sediment sources).
- Carefully designed and placed wooden structures should be included in a suite of measures (e.g. improved land management and targeted tree planting of sediment source zones) that tackle runoff and sediment problems directly.
- Monitoring of the three different structure designs should continue in the Bowmont catchment as knowledge on the long term effectiveness of in-channel wooden structures (i.e. beyond the 4 years of monitoring undertaken) – needed to inform design and placement strategies in the future – is still limited.

Contents

Acknowledgements 4

1 **Introduction** 5

2 **Aims of the monitoring project** 6

3 **Natural Flood Management in the Bowmont catchment** 6

4 **Monitoring methods** 9

4.1 **Hydrology** 10

4.2 **River geomorphology monitoring** 12

5 **Catchment scale hydrological data analysis** 14

5.1 **Rainfall patterns** 14

5.2 **Multiscale river level monitoring** 18

6 **Evaluation of measures at the local scale: case studies** 24

6.1 **Bar apex engineered log jams** 24

6.1.1 **Introduction and site descriptions** 24

6.1.2 **Aims of monitoring** 26

6.1.3 **Methods** 26

6.1.4 **Results** 29

6.1.5 **Guidance for future installation** 30

6.1.6 **Further work** 30

6.2 **Kelsocleuch bank protection structure** 34

6.2.1 **Introduction and site description** 34

6.2.2 **Aims of the monitoring** 34

6.2.3 **Methods** 35

6.2.4 **Results** 35

6.2.5 **Guidance for future installation** 37

6.2.6 **Further work** 37

6.3 **Elm Sike flow restrictors** 40

6.3.1 **Introduction and site description** 40

6.3.2 **Aims of monitoring** 42

6.3.3 **Methods** 42

6.3.4 **Results** 43

6.3.5 **Further work** 47

6.3.6 **Guidance for future installation** 47

7 **Conclusions and guidance** 47

References 50

Appendix sections (separate document)

A1 **Development of rating curves for monitoring channel disharge**

A2 **Indirect estimates of the 25th of September flood event**

A3 **Cocklawfoot Burn sediment transport monitoring data**

A4 **Swindon Haugh water level record (February 2015 to February 2016)**

A5 **Elm Sike water level recording and bed scour**

A6 **Elm Sike sediment tracer results**

A7 **River planform change at Swindon Haugh and Clifton**

Acknowledgements

Contributors to the report from the James Hutton Institute: Jeanne Vuaille, William Pfeiffer, Martin Salesses, Helen Watson, Carol Taylor, Yvonne Cook, Nikki Dodd, Kirsty Holstead and Dave Riach.

The farmers of the Bowmont valley and Roxburghe Estate for allowing access to field sites and for permitting the installation of instruments.

SEPA for sharing data and commenting on findings from the engineered log jam monitoring sites.

We thank Hugh Chalmers, Luke Comins and Tracy Hall of Tweed Forum for their cooperation during this research.

Marc Stutter of the James Hutton Institute is thanked for commenting on an earlier draft of the report.

This work was funded by the Rural and Environment Science and Analytical Services Division of the Scottish Government (RESAS).

Some plots contain Environment Agency information © Environment Agency and database rights. Thanks to Environment Agency for access to data.

1 Introduction

The Bowmont Water in the Scottish Borders region is a tributary of the River Till and a headwater catchment of the River Tweed (catchment area: 4390 km^2). It is a fourth order upland river and drains a catchment area of 87 km^2 (at Yetholm Mains). The mainstem of the Bowmont is an example of a dynamic wandering gravel-bed river characterised by high rates of movement and a locally divided planform. Further background on the river and physical geography of the catchment is given in MNV (2010), Tipping (2010) and Addy and Wilkinson (2016). The Bowmont valley has a history of significant flood events; large areas of the valley are completely submerged during these events (Figure 1 (Right)). Two recent major events in September 2008 and July 2009 caused extensive inundation, changes to river form, disruption and damage to infrastructure (Figure 1(Left)). SEPA have calculated that the peak discharge of the September 2008 flood was approximately 110m^3/s at Mowhaugh and 150m^3/s at Primsidemill, corresponding to a 1 in 70 year flood event (SEPA pers. comm., 2016). The 2009 flood was of a similar magnitude. Geomorphic changes of both floods included significant changes of river form and redistribution of gravel (Figure 2).

One of the main economic damages caused by the flooding was the loss of large areas of arable and grass farmland through sediment deposition and erosion. Cheviot Futures estimated direct costs of £2-3million to farming and shooting businesses in relation to the 2008 flood event (Oughton et al., 2009). Flooding also led to damage to properties and infrastructure throughout the catchment including a bridge leading to Clifton and various roads throughout the catchment. The cost to the council of repairing damaged infrastructure was approximately £670,000. Several properties at Duncanhaugh in the lower Bowmont valley and at Mowhaugh were damaged by the 2009 event. Following these events, Tweed Forum (through the Cheviot Futures initiative) began an initiative to tackle flooding, coarse sediment problems and reduce the likelihood of future flood events. Tweed Forum consulted specialists, landowners, farmers and agencies to plan suitable actions that included novel natural flood management (NFM) techniques. Since February 2012, the James Hutton Institute has monitored the catchment to characterise the hydrological and geomorphic responses around measures designed to reduce flood risk and coarse sediment problems.

Figure 2: In response to the September 2008 flood, parts of the Bowmont Water experienced marked gravel deposition and changes in channel planform. Images show the Bowmont Water downstream of Attonburn (Imagery from Google Earth).

Figure 1: (Left) Damaged road near Mowhaugh in the Bowmont valley after the July 2009 flood (© Gordon Common) and (Right) inundation of the floodplain at Venchen downstream of Town Yetholm during the 25th of September 2012 flood event (© Hugh Chalmers, Tweed Forum).

2 Aims of the monitoring project

As part of the Scottish Government Rural and Environment Science and Analytical Services Division (RESAS) funded work on "Methods for mitigating and adapting to flood risk", this project set out to provide data at the local and catchment scales of the role of NFM in mitigating flood risk. It also sought to assess the efficacy of different wooden structures for reducing coarse sediment problems that are associated with floods (e.g. bank erosion and deposition). The principles of NFM are widely understood (e.g. SEPA, 2016), however, there is a paucity of objective data on how effective different techniques are and in what combination different measures may work in the landscape and at the catchment scale.

This report summarises four years (2012-2016) of monitoring highlighting key findings from the data and identifying the challenges of monitoring in such a dynamic river system. This report is separated into four parts: Firstly, it presents information about the measures that have been installed in the catchment and the methods that have been used to monitor them. Secondly, hydrological data from the monitoring network is then presented. Thirdly, we describe, using three case studies, the results of monitoring of novel wooden structures at the local scale that are designed to address coarse sediment problems associated with floods (bar apex log jams and bank protection structure) and also attenuate flows (flow restrictor structure). Finally, we then summarise the main findings and present key guidance and future recommendations.

3 Natural Flood Management in the Bowmont catchment

NFM is the alteration, restoration or use of landscape features to reduce the severity of flooding. It is seen as necessary to reduce flood risk in the Bowmont catchment as traditional techniques are more costly or damaging (e.g. dredging and flood embankments). Funding through the SEPA restoration fund and SRDP was secured to allow these measures to be installed across the catchment. The work was carried out through the Cheviot Futures initiative, part of the Tweed Forum (a catchment partnership who have been delivering NFM measures across the Tweed catchment (see **http://www.tweedforum.org/**)

The following features have been installed since 2012:

1. Bank protection engineered log jams (three different types) designed to reduce bank erosion and the input of sediment to the river (see - **http://www.cheviotfutures.co.uk/phpdocuments/ELJ.pdf**).
2. Bar apex engineered log jams (BELJs) in the channel and areas of floodplain to capture and stabilise sediment (see - **http://www.cheviotfutures.co.uk/phpdocuments/ELJ.pdf**)
3. A long, wide hedge to increase rainfall interception and infiltration.
4. Planting of native trees in less productive areas of floodplain and gullies to reduce runoff and strengthen riverbanks.
5. Novel bank protection using willow spiling, timber palisades and compost socks to reduce river bank erosion and sediment input to the river. These features were not formally monitored but a number of photographs were taken to assess how these measures performed over time.

Table 1: Catchment summaries of proposed measures and densities of tree planting (totals include what has been implemented and upcoming proposed measures). See Figure 3 for sub-catchment locations.

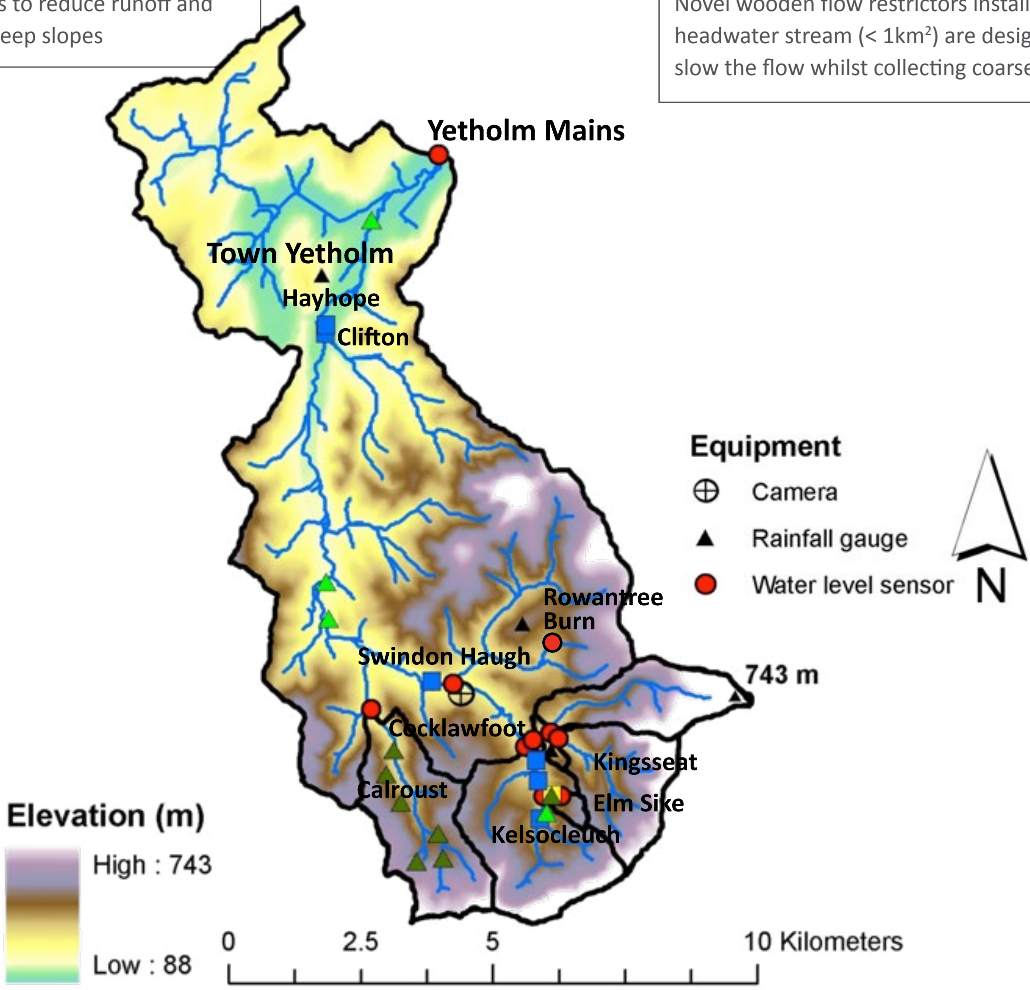
Sub-catchment	Calroust	Kelsocleuch	Cocklawfoot	Kingsseat	Cheviot	Rowantree	Elm Sike	Bowmont: Hayhope	Bowmont: Yetholm Mains
Sub-catchment of	*Hayhope, Yetholm Mains*	*Hayhope, Yetholm Mains*	*Hayhope, Yetholm Mains*	*Cocklawfoot, Hayhope, Yetholm Mains*	*Cocklawfoot, Hayhope, Yetholm Mains*	*Hayhope, Yetholm Mains*	*Kelsocleuch, Hayhope, Yetholm Mains*	*Yetholm Mains*	*All sub-catchments*
Catchment area (km^2)	5.9	6.5	7.8	3.9	3.5	0.49	0.36	65.8	87.9
Stream order (Strahler)	3	3	3	3	2	1	2	4	4
Mean elevation (m)	380.6	387.8	430.1	411.1	466.8	430.8	361	323	281.9
Mean slope (°)	23.5	23.5	28.7	29.3	29.1	21.9	23.7	24.1	21
Proposed measure(s)	Trees	Trees, hedgerow and ELJs	Trees	Trees	Trees	Trees	Trees/flow restrictors	Trees, hedgerows, SRDP management and ELJs	Trees, hedgerows, SRDP management and ELJs
Area of proposed planting (km2)	0.61	0.11	0.23	0.08	0.13	0.03	0.0029	1.25	1.32
% of catchment area of proposed planting	10.34	1.74	2.95	2.13	3.64	6.73	0.81	1.90	1.50
Number of engineered log jams and flow restrictors upstream	None	40	None	None	None	None	16	78	78
Measures achieved as of July 2016	Yes	Yes	No	No	No	No	Yes	Partially	Partially

Upland gully tree planting

Gully tree planting aims to reduce runoff and riverbank erosion on steep slopes

Flow restrictors

Novel wooden flow restrictors installed on a headwater stream (< 1km^2) are designed to slow the flow whilst collecting coarse sediment



Floodplain tree planting

Floodplain tree planting aims to attenuate runoff and reduce riverbank erosion

Engineered log jam

Engineered log jams are designed to trap sediment and reduce riverbank erosion

Figure 3: Distribution of NFM measures, sub-catchments and monitoring sites in the Bowmont catchment.

4 Monitoring methods

Figure 4 summarises the timing of key NFM activities, monitoring undertaken and other important events in the catchment. Sections 4.1 and 4.2 give an overview of the aims and techniques of the variety of monitoring approaches undertaken to measure the effectiveness of NFM measures implemented in the Bowmont catchment. The monitoring methods also help to provide an insight into the hydrology and geomorphology of a catchment that hitherto was poorly studied.

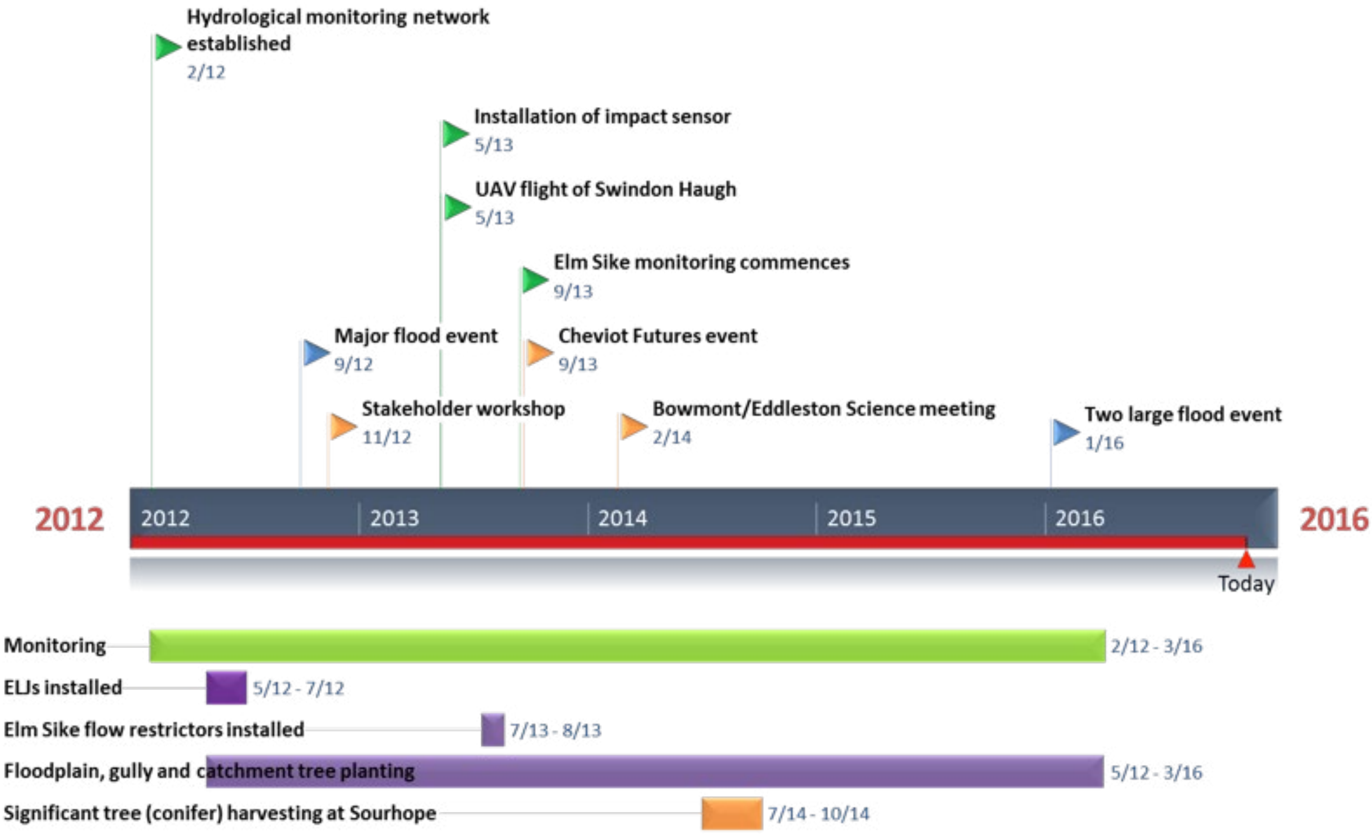


Figure 4: Summary timeline of key NFM and monitoring activities in the Bowmont catchment.

4.1. Hydrology

The James Hutton Institute has been working in the Bowmont catchment for many years at the long term Environmental Change Network (ECN) site at Sourhope. There is a long term weather station and hydrological dataset (Rowantree: Table 1, Figure 5 and Figure 6 (Right)) available that dates back to 1995). In early 2012, The James Hutton Institute established a multiscale hydrological monitoring network in the Bowmont catchment with the aim of understanding the impact of Tweed Forum's planned NFM actions on reducing flood peaks and managing sediment (Figure 5). In 2012, five sub-catchments were established for hydrological monitoring in the southern headwaters of the catchment (Figure 5 and Figure 6 (Left)). Evidence from other studies (e.g. Belford in Northumberland) has shown that at a scale of ~5-10 km^2 it is possible to see impacts of wide spread NFM measures (which include high flow data; Quinn et al. 2013). A station was installed in Calroust to monitor the impacts of widespread tree planting by the landowner in the Calroust Burn sub-catchment (Table 1). The station at Kelsocleuch was positioned to monitor the hydrological effects of floodplain and gully (steep streams) tree planting and wood placement work. Gully and floodplain tree planting was planned for the Cheviot and Kingseat catchments. Stations were installed at the outlets of these catchments and downstream of the confluence of the two streams at Cocklawfoot Farm. Various other NFM approaches highlighted in Section 3 were installed downstream of these sub-catchments, therefore larger scale monitoring stations were installed at Hayhope and Yetholm mains (Figure 5 and Table 1).

A wide range of measures have been installed over the four year project, however, not at the extent that was previously envisaged (owing to difficulties in gaining permission for tree planting in all the proposed areas summarised in Table 1). However, in some places new, novel measures have been installed (such as flow restrictors) and the density of these measures at the smaller scale is greater than first envisaged. Therefore in some cases the emphasis in the monitoring strategy has switched from a large catchment scale analysis to local scale monitoring of hydrological and geomorphic responses to determine the impact of these novel approaches. The monitoring strategy has been adapted in order to capture the most relevant scientific information around the installed NFM measures. These changes have included (dates are summarised in Table 2):

- The decommissioning of the Hayhope gauging station: This station was decommissioned owing to difficulties maintaining the site. Also, due to the lack of widespread tree planting at this scale, it was decided to focus on one large scale monitoring site (at Yetholm Mains).
- The decommissioning of Cheviot gauging station: Owing to technical issues with the station and the lack of measures in this catchment, a decision was made to close this station down.
- Additional hydrological monitoring in the Kelsocleuch sub-catchment. There is a greater density of measures in this catchment than was first envisaged. Three water level monitoring stations have been installed in the Elm Sike sub-catchment (a tributary of Kelsocleugh burn). The importance of monitoring in the Kelsocleuch sub-catchment is elevated and this work is highlighted later (Section 6.3).
- Timelapse cameras have been installed at Swindon Haugh and Elm Sike to provide a further record of the status of measures and qualitative information on the characteristics of high flows (e.g. inundation extent, depth and timing). The cameras also give qualitative information of the interaction between flows and structures during floods.
- A water level sensor has been installed around the ELJ measures at Swindon Haugh. This sensor, during high flows, records river levels around these measures (Section 6.1).

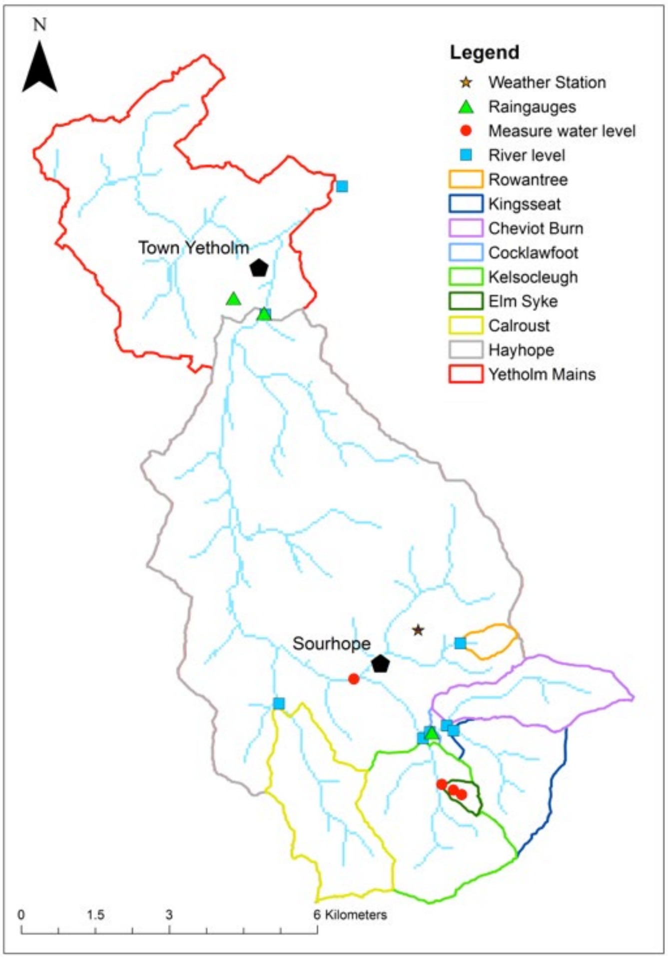


Figure 5: Monitored sub-catchments in the Bowmont catchment and sensor locations (see Table 2 for catchment areas).

Table 2: Site summary information for hydrological monitoring in the Bowmont valley (see Figure 5 for locations)

MULTISCALE RIVER LEVEL MONITORING NETWORK

Catchment	Outlet location (Eastings, Northings)	Catchment area (km²)	Operational dates	Measures (within each catchment area)
Rowantree	386026, 620422	0.5	05/1995 - ongoing	*None planned*
Cheviot	385796, 618693	3.6	02/2012 - 07/2015	*Future planting proposed*
Kingseat	385843, 618683	3.9	02/2012 - ongoing	*Future planting planned*
Cocklawfoot	385506, 618620	7.8	02/2012 - ongoing	*Future planting planned*
Kelsocleuch	385298, 618511	6.6	02/2012 - ongoing	Bar apex ELJs, bank protection ELJs, grade control structures, flow restrictors, riparian and gully tree planting, hedgerow
Calroust	382390, 619193	5.6	03/2012 - ongoing	Tree planting (riparian and upland)
Hayhope	382078, 627087	65.8	03/2012 - 06/2013	As above + further riparian planting and ELJs
Yetholm Mains	383664, 629675	85.9	02/2012 - ongoing	As above + tree planting and bank protection measures

WATER LEVEL MONITORING AROUND MEASURES

Catchment	Location (Eastings, Northings)	Catchment area (km²)	Operational dates	Measures
Elm Sike R1	385899, 617447	0.4	08/2015 - ongoing	None
Elm Sike R2	385809, 617503	0.45	09/2013 - ongoing	None
Elm Sike R3 (with camera)	385650, 617541	0.5	09/2013 - ongoing	Flow restrictors & gully planting
Swindon Haugh ELJs (with camera)	383314, 620925	27.8	02/2014 - ongoing	ELJs (fencing and floodplain tree planting planned for the future)

OTHER MONITORING

Site name	Sensor type	Location(Eastings, Northings)	Elevation (m)	Operational dates
Sourhope (Fassett Hill)	Weather station	385314, 620925	370	01/1995 - ongoing
Yetholm Resorvoir	Raingauge	381457, 627400	170	03/2013 - ongoing
Hayhope	Raingauge	382078, 627087	110	03/2012 - 09/2012
Cocklawfoot	Raingauge	385506, 618620	235	02/2012 - ongoing

Figure 6: Downloading data at the water level monitoring station on the Kingseat Burn (left) and the existing ECN Sourhope weather station on top of Fassett Hill (right).

4.2 River geomorphology monitoring

Geomorphic changes associated with floods including change of river channel course, bank erosion and sediment deposition can create problems. For example bank erosion and sediment deposition can lead to the loss of land, damage to infrastructure (roads and bridges) and deposition of sediment can reduce the conveyance capacity of channels causing increased local flood risk. Traditionally these issues have been dealt with a combination of piecemeal and often unregulated dredging, channel realignment and bank protection measures in the Bowmont valley. These measures can damage habitat, create adverse consequences (e.g. destabilise channels) and may be unsustainable in dynamic, sediment rich catchments like the Bowmont. Geomorphic monitoring has been applied to the Bowmont Water to address the following aims:

- To better understand the rates and thresholds of sediment transport (using particle tracer experiments and an impact sensor).
- To understand the rates and styles of channel morphology changes and the causes at different scales (using historical photo analysis and contemporary field surveys).
- To assess the effectiveness of novel in-channel structures to trap sediment and reduce its onward movement (flow restrictors and bar apex ELJs).
- To assess the effectiveness of a novel log jam structure for reducing bank erosion (Kelsocleuch bank protection structure).

Table 3 and Figure 7 summarise the range of techniques that have been applied to improve understanding of the geomorphology of the Bowmont catchment channels and assess the efficacy of measures to manage coarse sediment problems. The case studies in Section 6 give more details about the site specific methods used and the results. The Appendix presents additional results.

The poor rate of recovery of particle tracers (Appendices A3 and A6) and loss of the sediment impact sensor at Cocklawfoot (Appendix A3) in January 2016 highlight the difficulty of monitoring sediment transport in such a dynamic catchment. Sediment tracers could be improved by attaching Passive Intergrated Transponder (PIT) tags but ensuring a replacement impact sensor remains in place is more challenging due to the lack of bedrock for attachment and risk of displacement or burial during floods.

Figure 7: Geomorphic monitoring techniques used in the Bowmont valley. (A) an Unmanned Aerial Vehicle (UAV) used to survey the the river corridor at Swindon Haugh in May 2013, (B) topographical survey of a cross section of the Bowmont Water at Yetholm Mains in February 2012, (C) painted stone tracers in position in the Cocklawfoot Burn in October 2014 and (D) sediment impact sensor before installation on the bed of the Cocklawfoot Burn close to the gauging station.

Table 3: Geomorphic monitoring work undertaken in the Bowmont catchment.			
Site name and location (Eastings, Northings)	**Methods**	**Purpose**	**Duration of monitoring**
Elm Sike flow restrictor site 385899, 617447	Regular visual inspection of bar apex ELJs	To monitor structure condition and geomorphic effects	Ongoing since September 2013
	Topographical survey (annual and post-flood)	To quantify erosion and deposition responses to structure placement	Ongoing since September 2013
	Sediment tracer experiment	To gain an understanding of the coarse sediment movement regime and sediment capture effect of the structures	August 2014 to January 2016. Majority of tracers washed away and not recovered.
Kelsocleuch Burn bar apex ELJ site 385606 617554	Regular visual inspection of bar apex ELJs	To monitor structure condition and geomorphic effects	Ongoing since July 2012
	Historical aerial photo analysis	To provide an insight into past river channel dynamics	1946, 1965, 2007 and 2010
Kelsocleuch Burn bank protection ELJ site 385427 618335	Regular visual inspection of structures	To monitor structure condition and geomorphic effects	Ongoing since July 2012
	Topographical surveys (biannual and post-flood)	To quantify erosion and deposition responses to structure placement	Ongoing since July 2012
	Sediment surveys (photographic sampling)	To understand the range of sediment sizes at the site	Ongoing since July 2012
	Historical aerial photo analysis	To provide an insight into past river channel dynamics	1946, 1965, 2007 and 2010
Cocklawfoot Burn 385506, 618620	Topographical channel cross section surveys	To quantify erosion and deposition responses to relate to impact sensor data	October 2012, July 2014 and July 2015
	Sediment impact sensor	To understand coarse sediment dynamics in a catchment lacking measures	April 2013 to January 2016. Instrument washed out and not recovered.
	Sediment tracer experiment	To gain an understanding of the coarse sediment movement regime	July 2014 to January 2016. All tracers washed away and not recovered.
Swindon Haugh bar apex ELJ site 383314, 620925	Topographical survey (annual and post-flood) of bars and channel cross sections.	To quantify erosion and deposition responses to structure placement	Ongoing since July 2012
	UAV survey (high resolution topography data and colour photographs)	To provide additional topographical information for hydraulic modelling and provide information of river channel change	Undertaken once in May 2013
	Sediment surveys (pebble counts and photographic sampling)	To understand the range of sediment sizes at the site and effect of structures on sediment texture	August 2012, October 2012, July 2014 and March 2016
	Regular visual inspection of bar apex ELJs	To monitor structure condition and geomorphic effects	Ongoing since July 2012
	Historical aerial photo analysis	To provide an insight into past river channel dynamics	
Clifton bar apex ELJ site 381485 626400	Topographical survey around ELJs and channel cross sections.	To quantify erosion and deposition responses to structure placement	August 2012 and October 2012. Concentrating on Swindon Haugh ELJs instead.
	Sediment surveys (photographic sampling)	To understand the range of sediment sizes at the site	August 2012.
	Regular visual inspection of bar apex ELJs	To monitor structure condition and geomorphic effects	Ongoing since July 2012
	Historical aerial photo analysis	To provide an insight into past river channel dynamics	Photos from 1948, 1968, 2007 and 2010 analysed.

5 Catchment scale hydrological data analysis

Empirical, field based data is essential for assessing the performance of NFM at different scales. The hydrological network in the Bowmont was established to give an understanding of how NFM measures potentially delay and attenuate peak flows. However, two factors need to be considered. Firstly, long empirical datasets are required to detect any changes in catchment hydrological processes such as those that may result from NFM measures. Secondly, there needs to be a large area or number of measures installed in order to detect catchment scale impacts. Therefore both these factors have made it difficult to assess the impact of NFM at the catchment scale (as detailed in the previous section, the data has only been collected for a few years and limited measures have been installed). As a result the following section gives a baseline dataset at larger scales to compare with in the future and may help to inform the scale of interest and types of measures to put in to place that will be effective.

5.1 Rainfall patterns

Rainfall has been measured since 1995 at the ECN weather station at Sourhope (Elevation: 370 m, Location NGR: 3846 6202; Figure 6 (Right); however, the location of the station moved slightly on the farm during 2004). Coupled with this, the Environment Agency has been logging rainfall in the nearby Glen catchment (in the next valley to the east of Sourhope) at the Goldscleugh monitoring station (Elevation: 305 m, Location NGR: 3914 6232). Figure 8 highlights the yearly rainfall totals from both these sites. The annual average rainfall for Sourhope is 1011 mm and 1157 mm at Goldscleugh. The totals at Goldscleugh are slightly higher than Sourhope. It is a possibility that the Goldscleugh station is less exposed to high winds that effect rainfall capture than Sourhope. The two wettest years on record are 2008 and 2012 whilst the driest have been 1997 and 2003. There is no indication in the data to show yearly rainfall trends are increasing or decreasing.

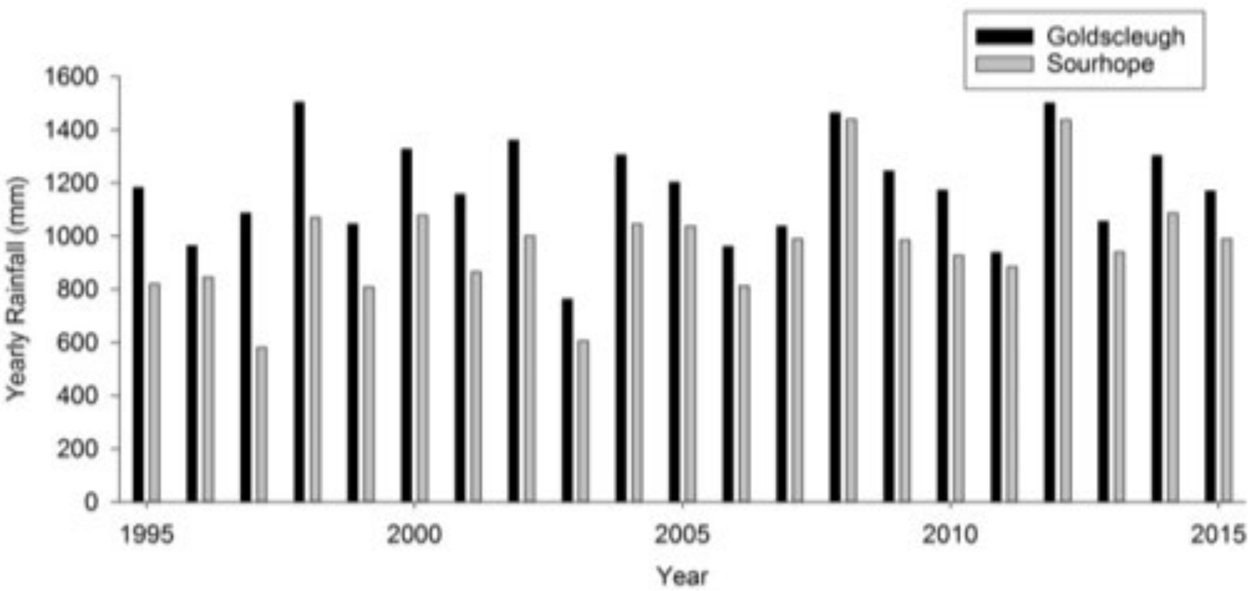


Figure 8: Yearly rainfall summary from the ECN Sourhope weather station [Goldscleugh: Contains Environment Agency information © Environment Agency and database right]

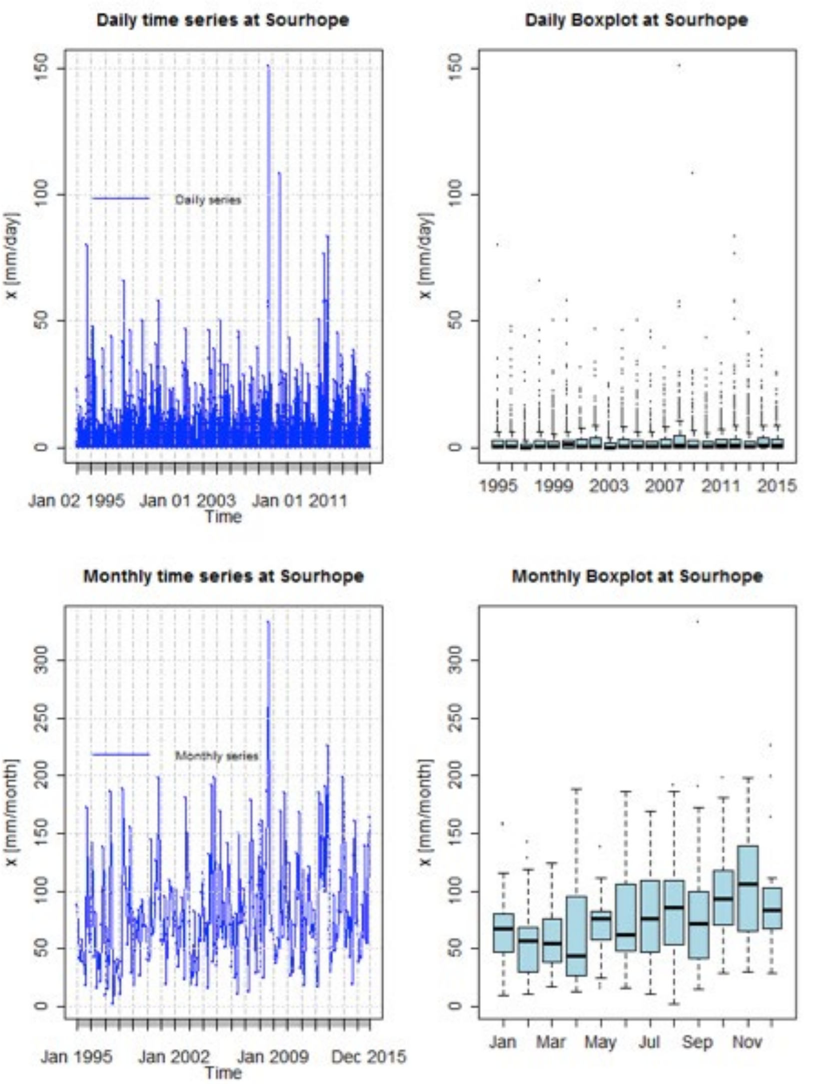


Figure 9: Rainfall data distributions summarising the full data record from the ECN Sourhope raingauge (Note: x = rainfall amount).

Data distributions of the 20 year data set shows that the wettest months in the catchment are from July through to January with the remainder of the year experiencing less rainfall (Figure 9: bottom-right). However, the variability in monthly totals is large with many months having a wide range in totals (Figure 9: top left: bottom right) and this also can be seen for daily rainfall totals (Figure 9: top right). By far the wettest month on record was September 2008 (Figure 10) with totals of 334 mm. The second wettest month was December 2012 with a total of 225 mm of rainfall. Figure 10 indicates that the summer months can be as equally wet as the winter months. This is equally the case for Goldscleugh (Figure 11). Flooding is therefore an issue throughout the year (however, less likely in spring) and NFM measures need to be designed to withstand intense convective events as well as long duration winter events.

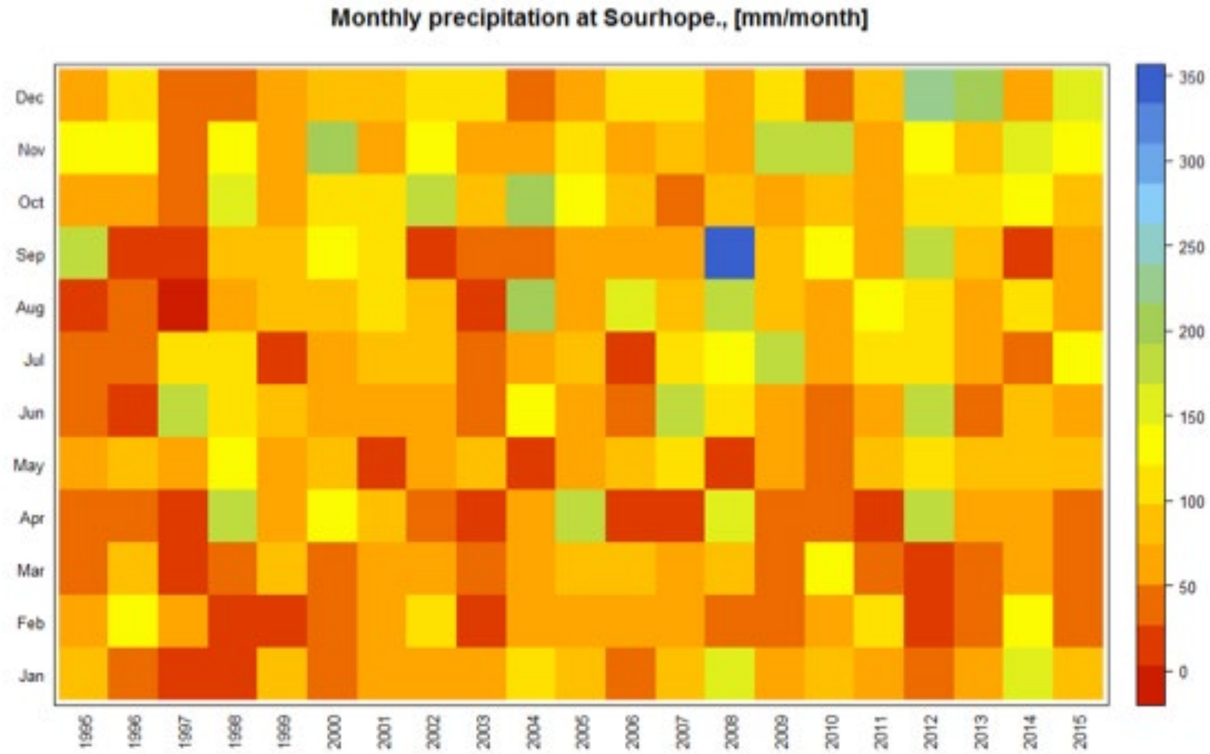


Figure 10: A matrix plot summarising monthly rainfall totals from the ECN Sourhope raingauge.

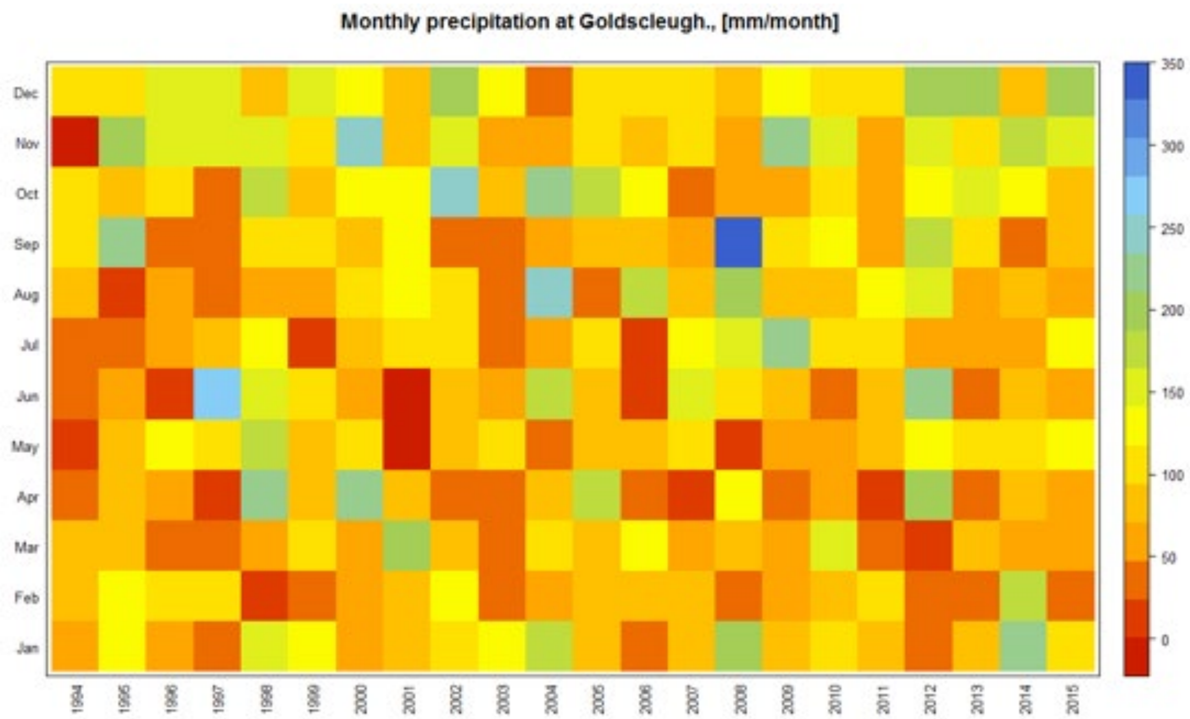


Figure 11: A matrix plot summarising monthly rainfall totals from Environment Agency Goldscleugh raingauge [Contains Environment Agency information © Environment Agency and database right].

Focusing on the study period of 2011-2015, it is apparent that 2012 was the wettest year and recorded four out of the top five wettest months (Figure 12). There appears to be a trend over the five years that the months at the start of the year are generally drier than those at the end (Figure 12: bottom right). Again, this is not taking into account snowfall.

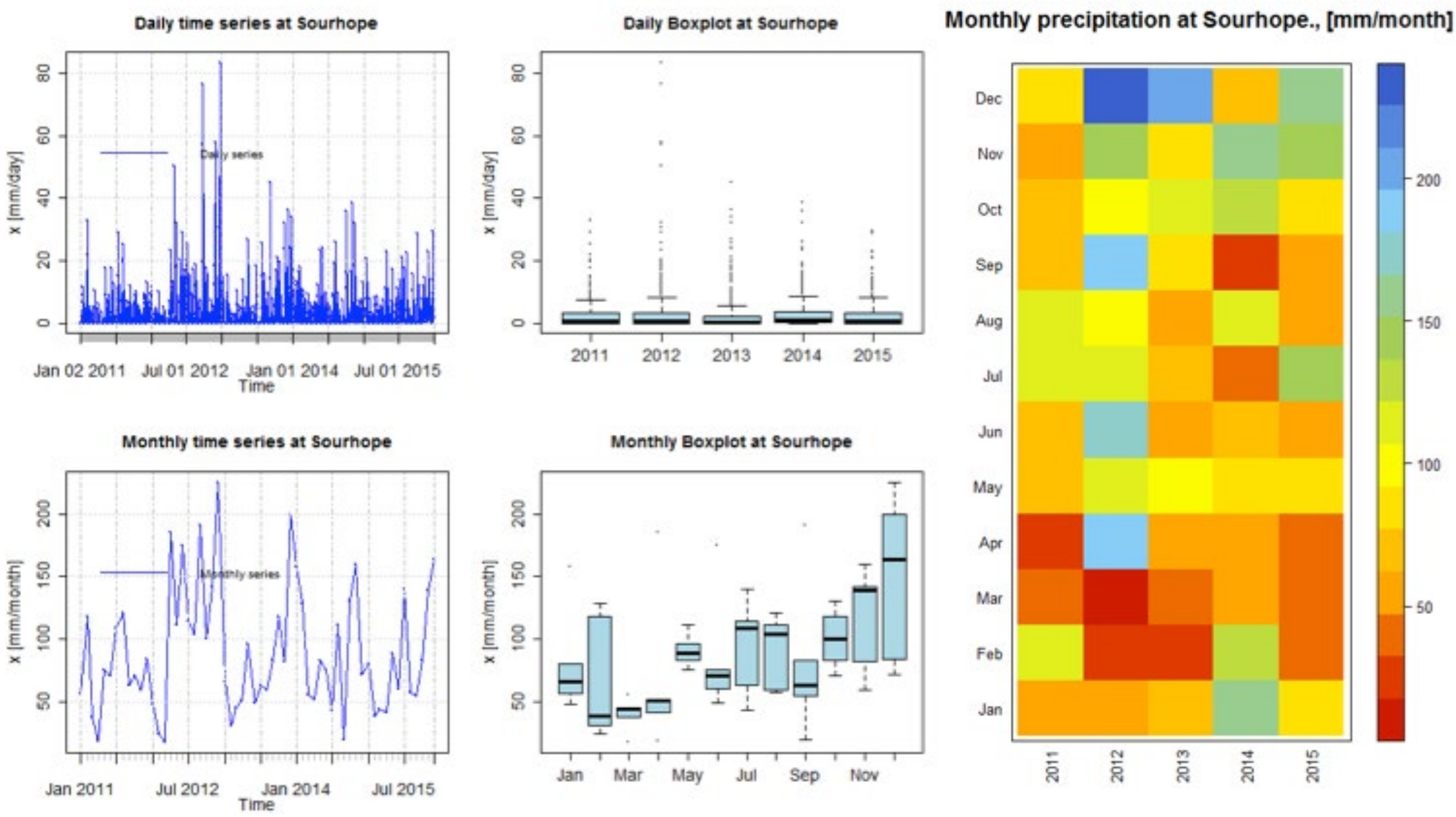
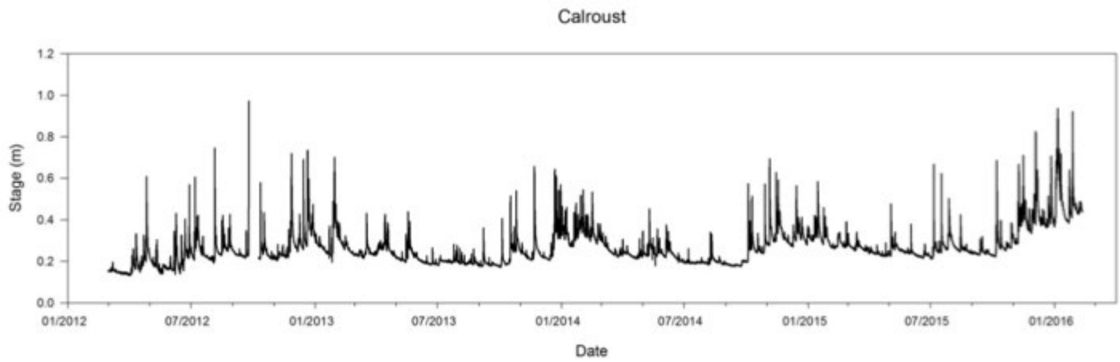
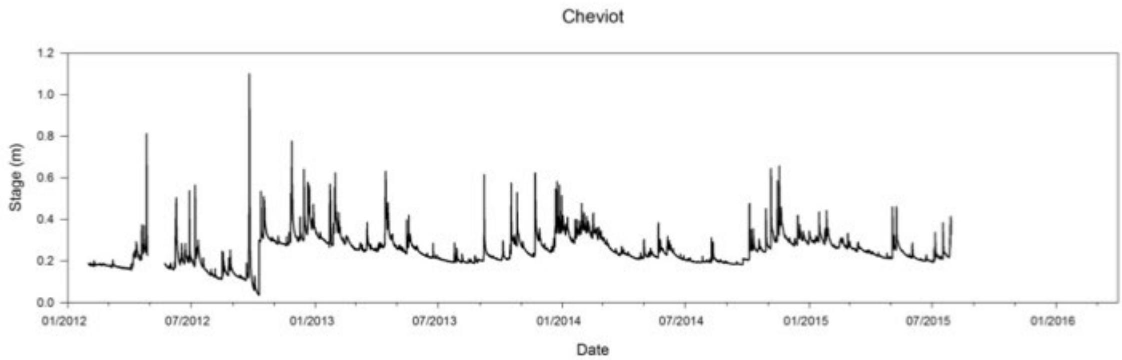


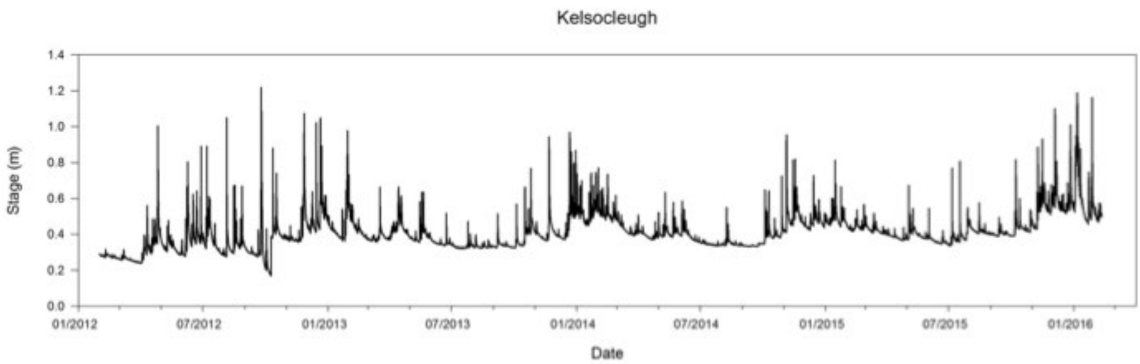
Figure 12: Rainfall data distributions summarising the five year data record (2011-15) from the ECN Sourhope raingauge (Note: x = rainfall amount).

5.2 Multiscale river level monitoring

Since 2012, seven river level monitoring stations have recorded water level data at 15 minute intervals (with only two being decommissioned during the five year project and replaced by local scale measurements – see Section 4.1). The five year river level history is presented in Figure 13. Water level data is shown instead of discharge because of the difficulty of producing robust water level (stage) – discharge relationships in the catchment (see Appendix A1). Figure 13 highlights the, common pattern for rivers in the UK (high winter base flow compared to summer and a greater frequency of high flow events over the winter months). However, it shows that 2012 was an exceptionally wet year with many high flow events being recorded. The graphs also indicate that the winter of 2015/2016 resulted in a series of high flows and increased base flow levels (compared to other winters). The major event on the 25th September 2012 resulted in damage to a number of stations (e.g. Cheviot; Appendix A2). At Kelsocleuch (Appendix A2) and Calroust, the stations were affected by sensor damage and alteration of channel cross sections through riverbed erosion and deposition. All the records indicate that the September 2012 flood event was the largest recorded during the four years of monitoring. Appendix A2 gives estimates of the peak flow conditions of this flood event at selected sites as based on a post-flood survey of channel geometry and high water level markers.







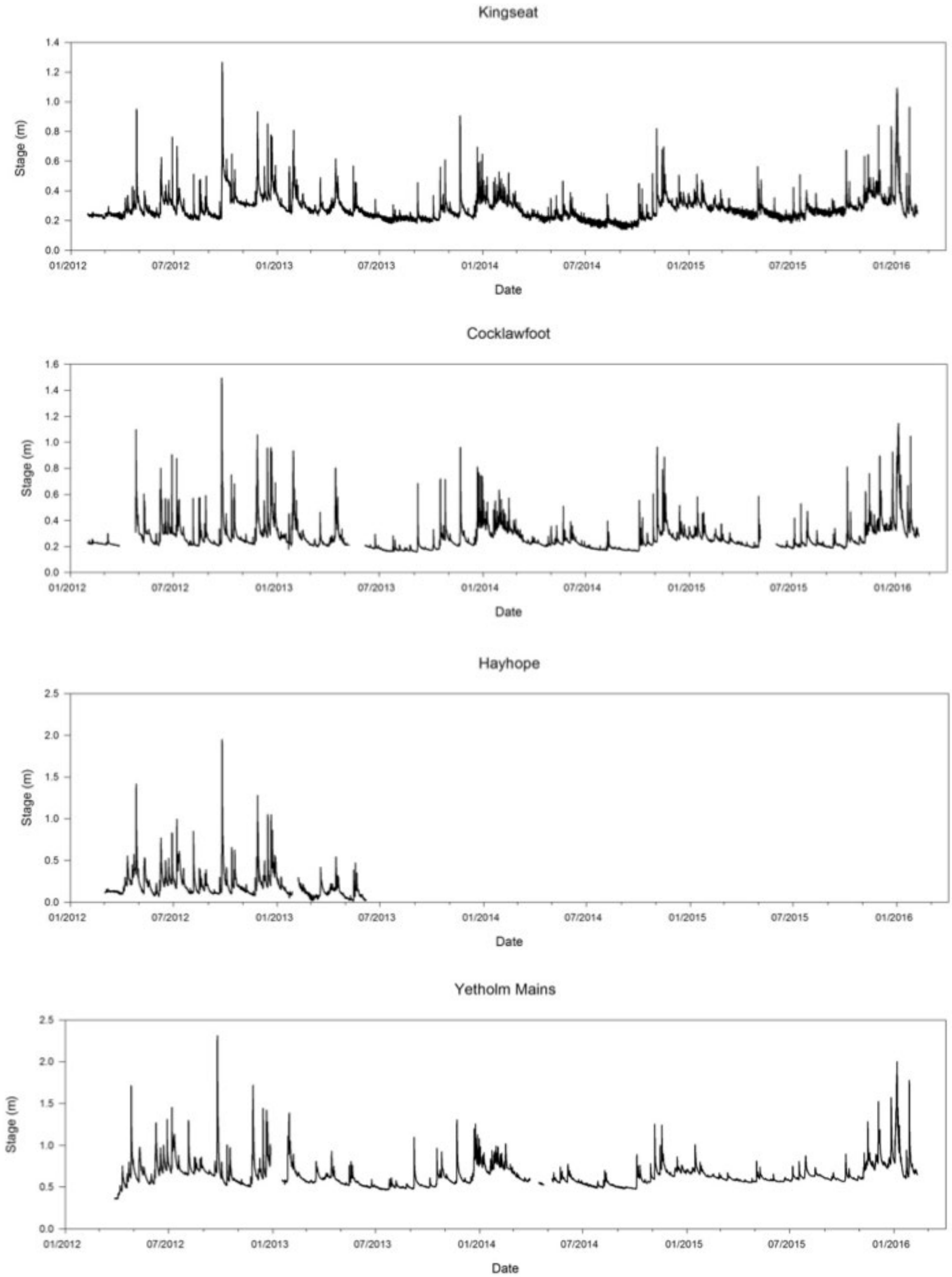


Figure 13: Hydrographs from the river monitoring locations (Figure 5; Table 2) for the five year monitoring period.

Most of the records are complete apart from some small data gaps at the Yetholm Mains gauging station (technical issues) and flood damage to the Calroust station during the 2012 event. Also, the position of the water level sensor was changed at the Cheviot station after the bed was eroded during the September 2012 event. Due to progressive bed erosion and animal damage to the logger, a decision was taken to decommission this station in August 2015.

Figure 14 to 17 present storm hyetographs and high flow hydrographs for the annual maximum recorded event (AMAX). Figure 14 presents the largest event for 2012 which was also the largest event in the 2012 – 2016 record. The flood comprised a single peak which was the result of a long duration intense storm event; 132 mm of rainfall was recorded over a 48 hour duration. The river levels rose rapidly due to the onset of a 6 hour period of rainfall with an intensity greater than 6 mm/hr. The event caused widespread infrastructure damage (e.g. Sourhope ford erosion and damage to tracks and bridges by Cocklawfoot Farm) and damaged gauging station sites. All catchments responded to the rainfall in a similar manner suggesting the storm was uniform and widespread.

In contrast the highest recorded event during 2013 was snowmelt driven. Figure 15 indicates much lower rainfall totals during the January to February 2013 event (only 14 mm of rainfall fell in the first three days of this event which corresponds to the largest flood peak). However air temperature records at Sourhope show an increase in temperature from freezing at the onset of the storm. The resulting high flows did not cause any significant out of bank flow or infrastructure damage, however, it did result in the further destabalisation of some river banks, notably around the Clifton ELJ structures (these were weakened as a result of the September 2012 event).

The highest recorded flows during 2014 occurred during early November (Figure 16). As with 2013, this event did not cause significant out of bank flooding or infrastructure damage. The peak flows on the 5th and the 18th of November were roughly of equal magnitude. Approximately 45 mm of rainfall fell in the 48 hour storm period on the 5-6th November and 38 mm fell in a similar period during the 17-18th November storm. This event is an example of a multiday event whereby the first storm causes the catchment to become saturated resulting in wet antecedent conditions. These conditions reduce the storage potential to absorb further rainfall and accentuate runoff. This is illustrated in Figure 16; the second and third storms are smaller but result in a similar high flow event.

Finally, Figure 17 highlights the highest recorded event during 2015 and the current highest recorded event for 2016. These occurred over December 2015 and January 2016. In 2015 the UK Met Office began naming storm events. The two largest flood events of 2015 were a result of storms Desmond (which caused widespread flood damage in NW England and SW Scotland) and Eva (which caused flood damage in N England). The resulting flood peaks did not cause infrastructure damage nor did they result in significant out of bank flow. Rainfall totals for these two events were 27 mm and 39 mm respectively. Both events increased baseflow levels, in fact base flows had not returned to normal levels when the largest event of 2016 was recorded. Over the week following the 1st of January 2016, just over 200 mm rainfall was recorded. This resulted in sustained high flows for a long period. Levels were not as high as the 2012 event; however, this event lasted for a longer period. This event did result in some localised infrastructure damage (e.g. erosion around the Sourhope ford and landslip on a section of nearby road), caused significant out of bank flow and appreciable geomorphic change (Section 6).

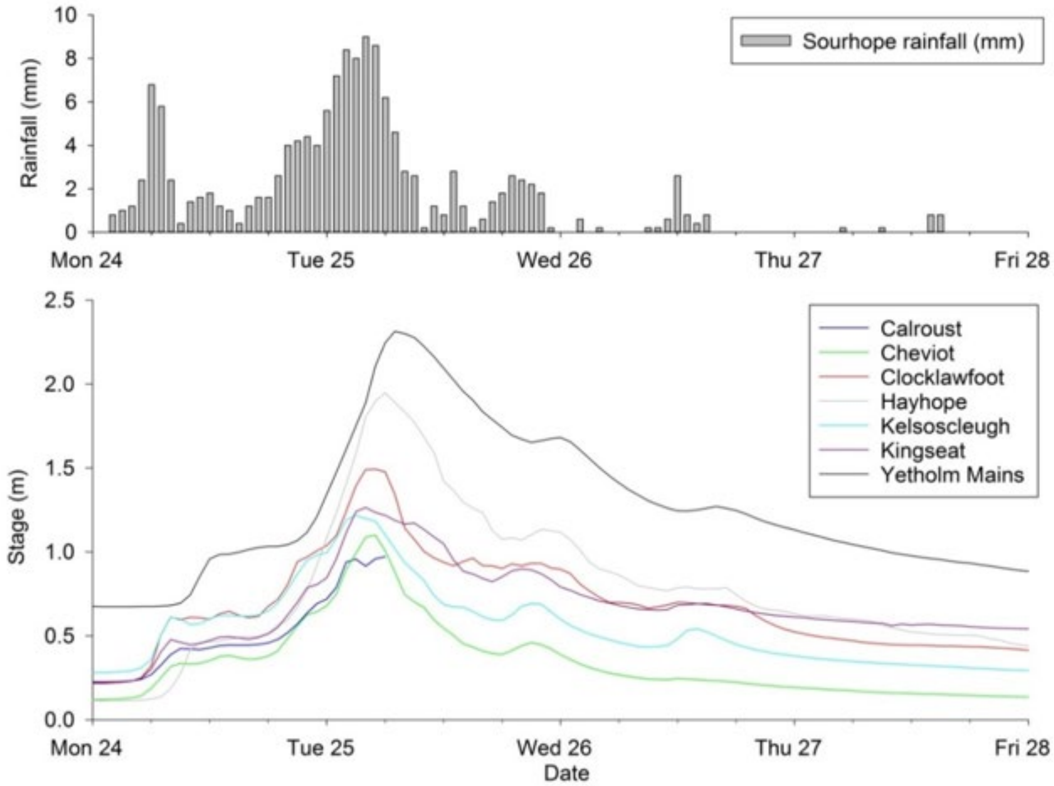


Figure 14: Rainfall hyetograph and flood hydrographs for the September 2012 storm event.

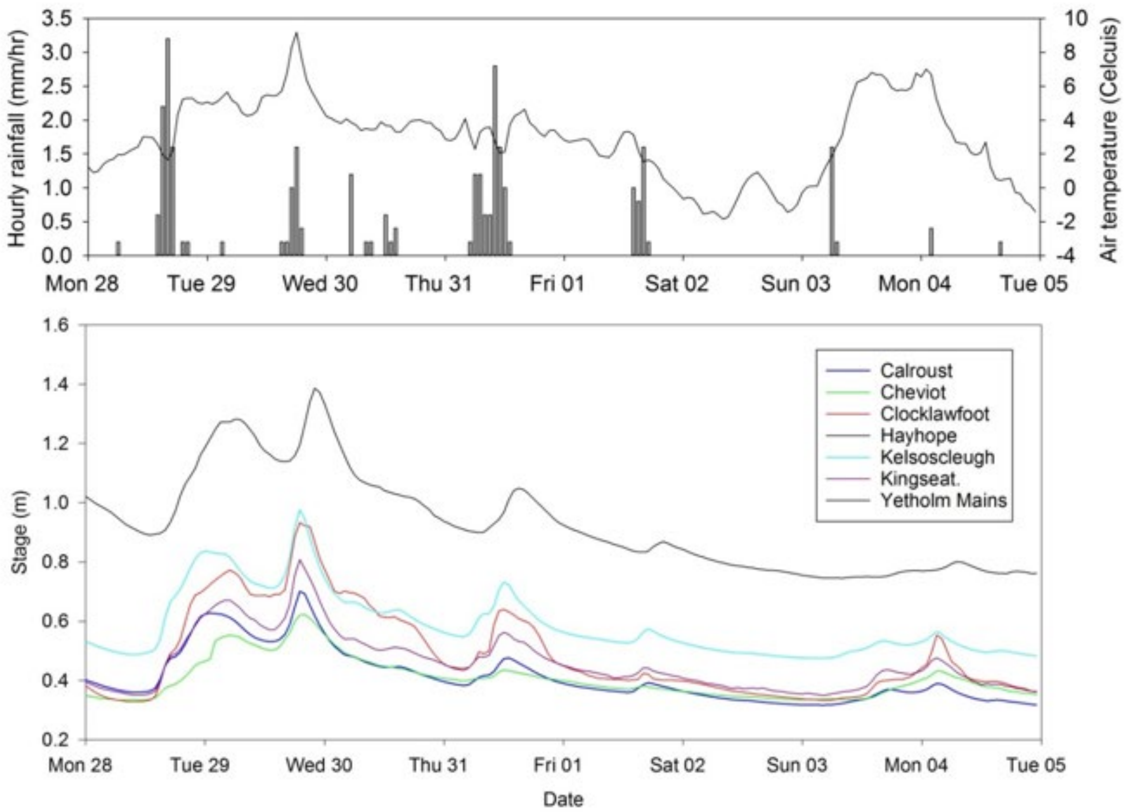


Figure 15: Rainfall hyetograph (including air temperature as a surrogate for snow melt rate) and hydrographs for the January/February 2013 event [2013 annual maximum].

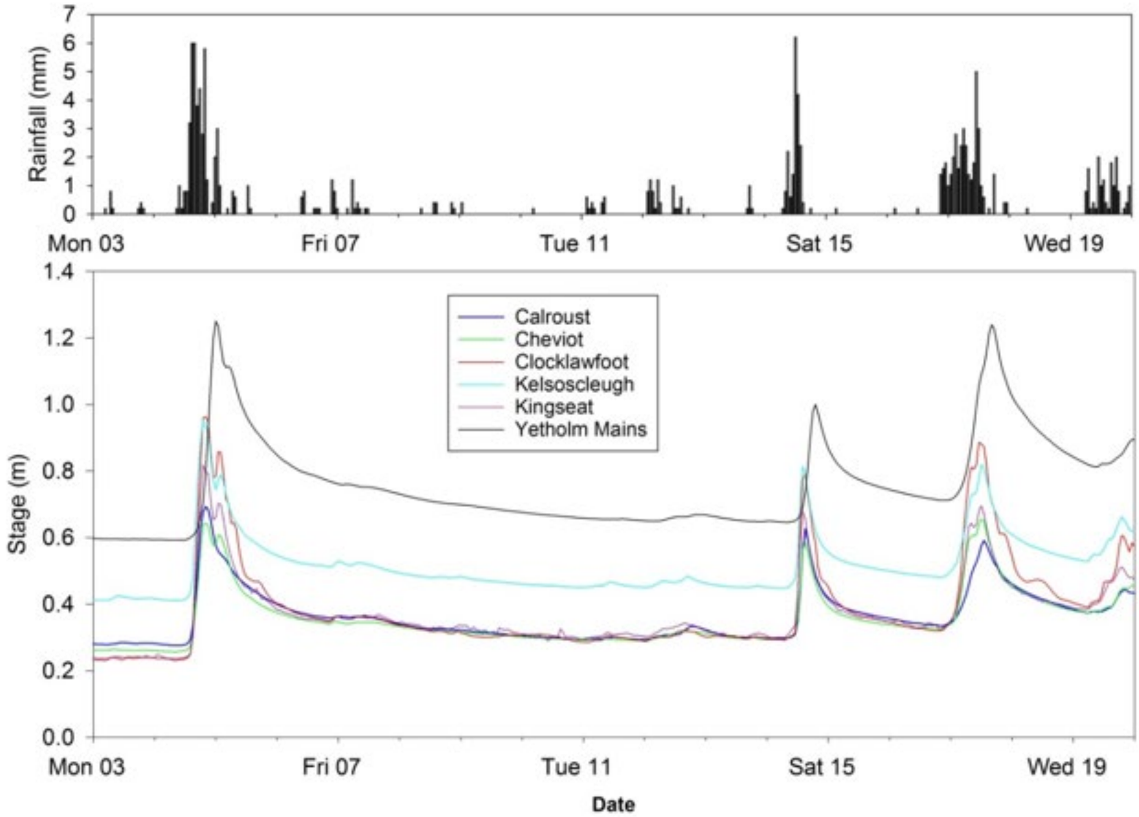


Figure 16: Rainfall hyetograph and hydrographs for the November 2014 storm events (2014 annual maximum).

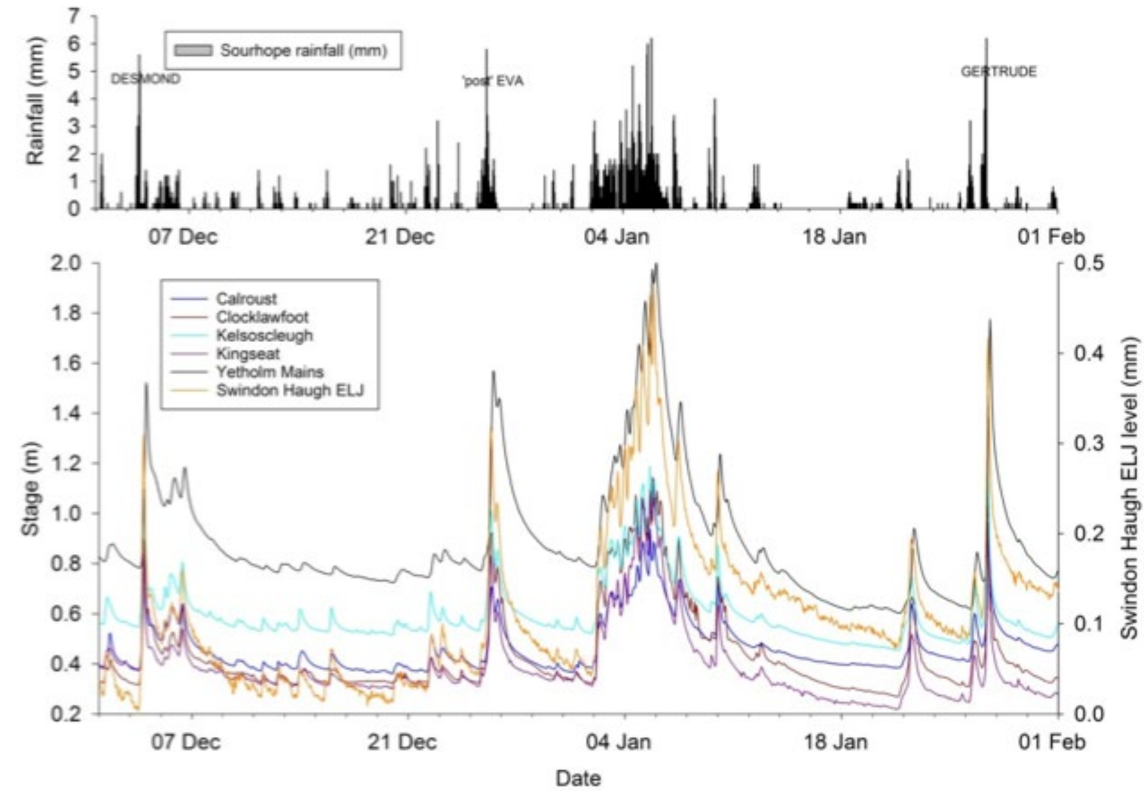


Figure 17: Rainfall hyetograph and flood hydrographs for the winter 2015/16 storm events (including Met Office Storm names where appropriate) [includes annual maximum flood for 2015].

Using data from the long term monitoring station at Sourhope, it is possible to compare storm (rainfall) events during the four year study period to the longer dataset available from the ECN Sourhope site and the Environment Agency gauging station at Kirknewton (Table 4: 1995 to 2015 – 20 year dataset). It can be seen that the largest events on record are still the 2008 and 2009 events (which corresponds to Figure 9). However, the 2012 event is the 5th largest event in the 20 year data history. Equally, it can be seen that the largest rainfall events do not necessarily correspond to the largest flood events. This is reflects the influence of snowmelt or antecedent catchment conditions. It is also evident that September is the most common month for an extreme event (recording the 1st, 5th and 6th largest rainfall events).

Similarly, utilising data from a number of storm and high flow events from the multiscale monitoring network, it is possible to examine the lag time (response) of a storm. This is the time from the centroid of the rainfall storm to the peak of the flood. This indicates how quickly a catchment responds to rainfall or how 'flashy' it is. This time usually increases with catchment area. The data from Table 5 utilises rainfall data from the Sourhope and Cocklawfoot raingauges to create a catchment average rainfall. Table 5 indicates that the lag time of the small catchments in the southern headwaters varies from 2-3 hours. This highlights the responsive nature of these catchments. At the larger scales lag time varies between 6-8 hours.

Table 4: Top 8 largest recorded storms (by full, 24hr and 12hr duration) in the Bowmont catchment (Sourhope raingauge) and how the rainfall total rank relates to the flood peak rank (from the Environment Agency Kirknewton gauging station). As the Kirknewton gauging station was decommissioned in 2011, no rank can be given to the September 2012 flood. Units of rainfall (storms totals) are mm and units of duration are hours.

		Storm total	duration	24 max total	12 max total	FLOOD RANK
1st	07 September 2008	259	63	166	87.6	1st
2nd	18 July 2009	154	40	141.8	99.4	2nd
3rd	07 March 2001	126	47	99.8	73	-
4th	24 June 2004	128	40	90	54.4	-
5th	25 September 2012	120	46	90	73.2	NEW SITE
6th	09 September 1995	110	37	89	78.2	-
7th	29 May 1998	99	46	87	65	5th
8th	07 November 2000	166	65	85	48.8	3rd

Table 5: Average lag time (time from centroid of storm to flood peak) for the monitored catchments (based on an average of eight large events).

Catchment	Area (km2)	Lag time (hh:mm)
Kingsseat	3.9	02:25
Cheviot	3.6	02:42
Cocklawfoot	7.8	02:47
Rowantree	0.5	02:27
Kelsocleugh	6.6	02:57
Calroust	5.6	03:47
Hayhope	65.8	05:35
Yetholm	85.9	06:55
Pawston	115	08:22

6 Evaluation of measures at the local scale: case studies

Five different types of 'log jam' have been trialed in the Bowmont valley (see - **http://www.cheviotfutures.co.uk/phpdocuments/ELJ.pdf**). The monitoring has concentrated on two types in particular: the bar apex engineered log jam (BAELJ) and the Kelsocleuch bank protection log jam which are summarised in Sections 6.1 and 6.2. The performance of the other experimental but smaller scale wooden in-channel structures, the flow restrictors, are summarised in Section 6.3.

6.1 Bar apex engineered log jams

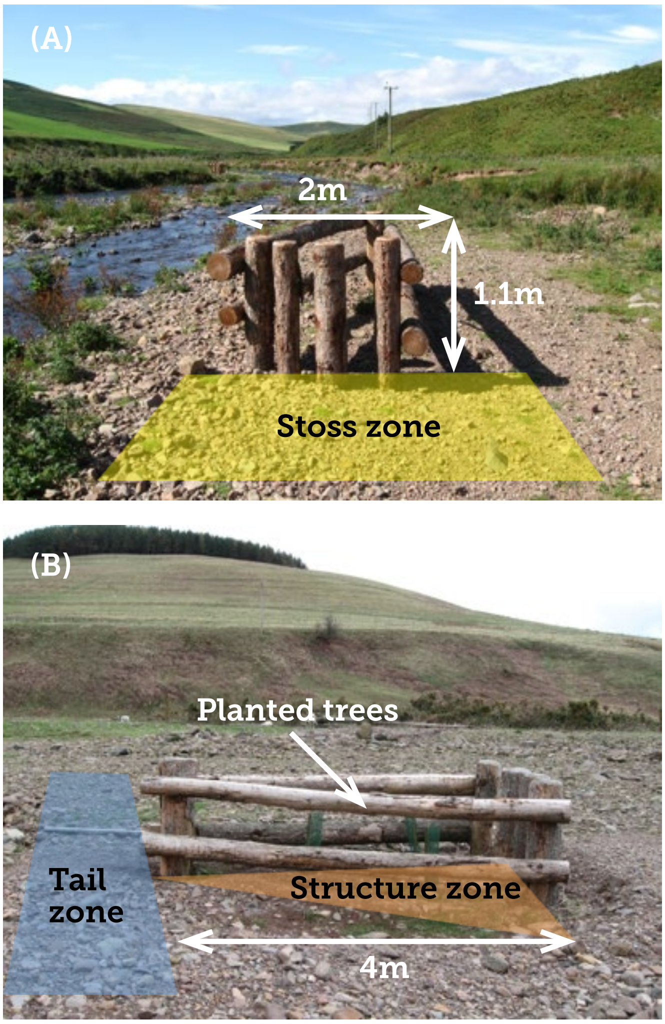


Figure 18: Typical dimensions of the bar apex log jam design constructed in the Bowmont valley and definition of zones used to analyse morphological change associated with the structures. (A) Front end view of log jam S5 at Swindon Haugh. (B) Profile view of log jam S12 at Swindon Haugh.

6.1.1 Introduction and site descriptions

The BAELJ structure is designed primarily to reduce the movement of coarse sediment downstream by capturing bedload and stabilising existing bars. This aim was set because it was perceived that excessive coarse sediment was accumulating in the mainstem of the Bowmont Water potentially causing problems of loss of channel capacity to convey flow, increased channel instability (e.g. greater likelihood of riverbank erosion and channel course changes) and deposition over fields. A secondary aim was to create diverse bar habitat and provide dead wood for insects (although ecological monitoring was not a focus of this study). Figure 18 summarises the typical dimensions of the design.

Untreated conifer timbers (diameters range: 0.19 – 0.23 m) were used in the construction and the vertical pile anchors were machine driven to a depth of 1 m. Horizontal timbers were attached to the anchors using metal fastenings. The structures were anchored due to concerns about structure displacement and were not installed in areas submerged during low flow conditions to allay concerns over disruption of fish passage. Structures were orientated parallel to the direction of the adjacent low flow channel. Each structure cost £230 in materials and construction. In Spring 2013, three trees were planted in the middle of each structure to improve sediment capture and stabilisation.

The design of the Bowmont BAELJs is unique and hitherto has not been evaluated before; structures used in the USA and Australia tend to be larger and more complex. Structures in these countries have been installed on the heads (apices or upstream end) of existing medial bars or in mid-channel areas to create new bars and small scale landforms analogous to those created by natural wood accumulations. Landforms created by naturally occurring bar apex wood jams include cresentic pools and bars upstream and tail wake bars downstream (Abbe and Montgomery, 1996). These landforms were predicted to be created by the BAELJs in the Bowmont.

Forty-five structures were installed at three different reach sites along the Bowmont valley in summer 2012 (Figure 19(A)). The sites were chosen based on support from landowners and farmers and to allow testing of the structure's effectiveness at different catchment scales. Within each of the reaches, log jams were placed following consultation with a geomorphologist in existing stabilising gravel bars or areas of floodplain (Figure 19(B-D)). Further details about the study sites, structure placement strategy and effectiveness of the structures in response to the September 2012 flood event can be found in Addy and Wilkinson (2016).

The Kelsocleuch Burn reach site has a catchment area of 4.1 km^2, a gradient of 0.026 m/m (based on OS map) and the channel has a meandering morphology with a history of moderate channel movement (Figure 19(C)). The floodplain is used for rough grazing and there are no records of recent or historical channel management in this reach. Seven structures (K1 – K7) were constructed on the floodplain each within 30 m of the active channel. The remaining five structures (K8-K12) were constructed along the course of an old channel that carries flow during flood events.

The Swindon Haugh reach has a catchment area of 27.7 km^2, a gradient of 0.01 m/m and the channel currently has a wandering morphology. The channel course and extent of deposited gravel has changed significantly over time indicating that this reach is highly sensitive to flood events (Figure 19(B); Appendix A7). The floodplain is used for sheep grazing and the reach has been dredged and realigned at least once in the past (August 2009). Limited gravel extraction (Bar 2) has been practiced since the monitoring commenced in August 2012 and gravel was moved in early 2013 close to S14 presumably to concentrate water flow in a chute channel created during the September 2012 flood (Figure 19(A)). The majority of structures were installed in stabilising (as indicated by vegetation colonistation) bars (S1-S14; S18 and S21) with the remaining structures being installed in floodplain areas close to meanders (S15-S17) or along a floodplain flowpath connected during floods (S19 and S20).

At the Clifton monitoring reach, the catchment area is 56.5 km^2, channel gradient is 0.011 m/m and the channel currently has a wandering morphology that is divided around a vegetated medial bar. The channel course has changed over time especially in the upper part indicating that it is also sensitive to change (Figure 19(B); Appendix A7). In contrast to the other sites, the riparian vegetation includes scrub and tree vegetation and the banks are occasionally used for watering and grazing by cattle. Part of the left (western) branch by the medial bar is protected by a stone wall and there has been gravel extraction and movement practiced within the right (eastern) branch (often a dry channel during average flow conditions) since September 2012. Nine of the structures were built on stabilising bars (C1-C5 and C9-C12) and the remaining three (C6-C8) were built on the floodplain close to the outer side of a meander.

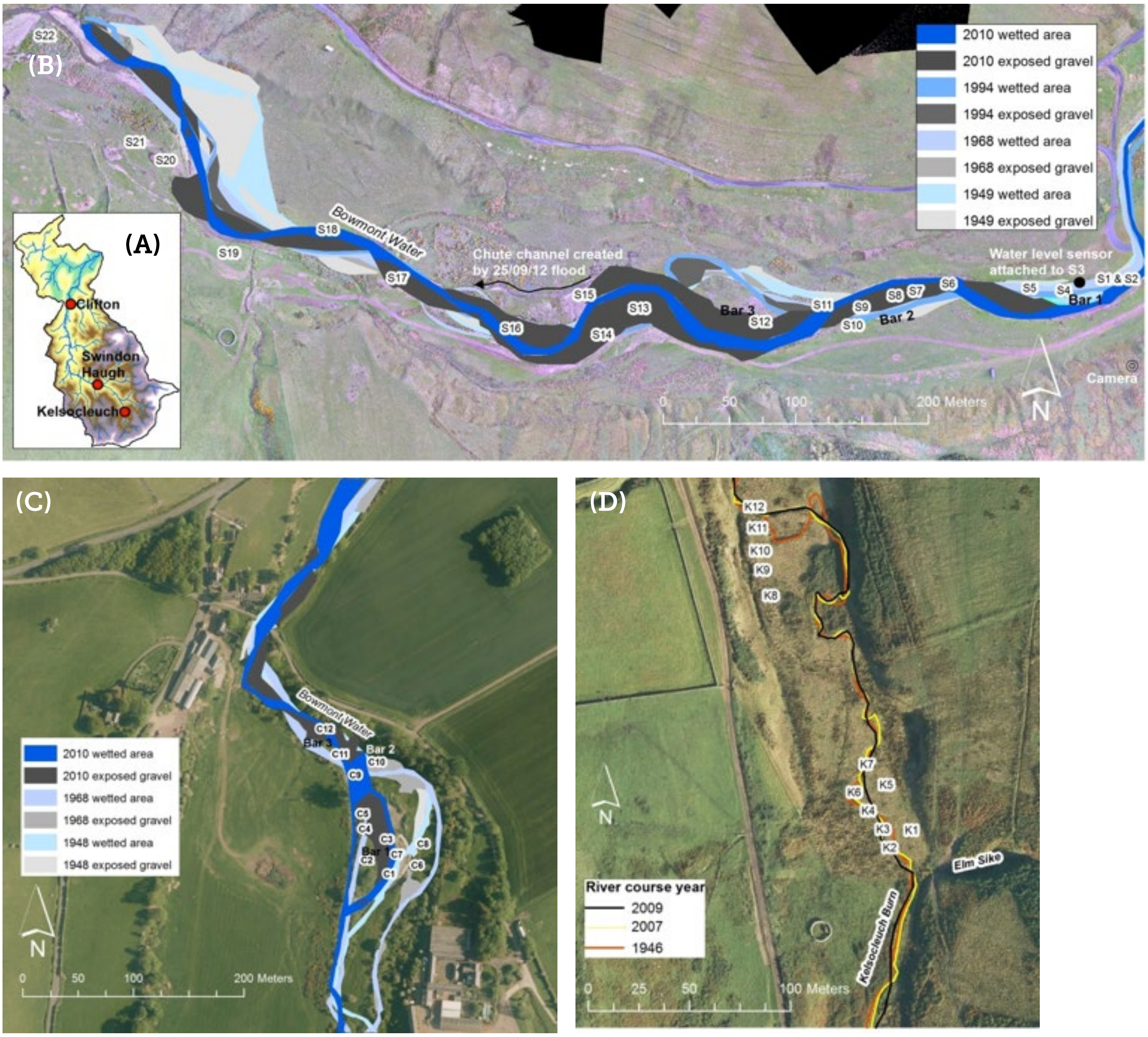


Figure 19: Locations of bar apex ELJ study sites. Locations of the bar apex ELJs and river planform characteristics over time at (B) Swindon Haugh (May 2013 UAV aerial background image shown for reference), (C) Clifton (2007 aerial photograph: Copyright Getmapping plc.) and (D) Kelsocleuch Burn (2007 aerial photograph: Copyright Getmapping plc.).

6.1.2. Aims of monitoring

1. To assess the stability of the structures in response to floods.
2. To assess the scour and deposition response created by the structures to evaluate their ability to satisfy the sediment capture goal
3. To assess the survival of planted trees and assess any habitat benefits created by the structures.
4. To inform guidance to optimise their design and placement.

6.1.3 Methods

Assessing morphological change

To quantify erosion and deposition responses adjacent to the ELJ structures, topographic surveys were undertaken at the Clifton and Swindon Haugh sites. At Clifton, limited surveys (i.e. areas within 10 m around selected structures) were undertaken in August 2012 and in October 2012. Of the three monitoring sites, the Swindon Haugh site was focused on due to the range of settings in which the structures were installed and suitability for the topographic survey method used. At Swindon Haugh limited and bar-scale surveys were undertaken in August 2012, October 2012, April 2013, April 2014, July 2015 and March 2016. For brevity, and given the lack of floods needed to initiate tangible geomorphic responses at the ELJ sites, the morphological responses attributed mainly to the September 2012 and January 2016 flood events are shown. A Leica GeoSystems 1200 Differential Global Positioning System (dGPS) rover combined with a Leica GeoSystems GPS 500 base station were used to conduct the surveys (survey point accuracy of ca. ±0.02 in plan and ± 0.03 m in elevation). The morphological changes and sediment volumes eroded and deposited were estimated using ArcGIS Version 10.1 and the GCD software to reduce uncertainty in the results (see Addy and Wilkinson, 2016 for more details).

In May 2013, an unmanned aerial vehicle (UAV) survey was undertaken for the Swindon Haugh reach (Figure 19(A)). High resolution geo-referenced photographs and digital terrain models were produced from the data gathered to give additional information on river change associated with the September 2012 flood event. The additional floodplain topographical data can also be used to set up hydraulic models to explore the influence of the structures on flow.

Field observations

Qualitative observations of state of repair, captured sediment and debris were made at each structure at annual intervals and following floods since summer 2012. Fixed point photographs were taken of each structure on a regular basis. Unfortunately not all of the Kelsocleuch structures were photographed before the September 2012 flood event. In March 2016, each structure was checked to assess the survival of trees planted in Spring 2013.

Figure 20: Selected examples of different responses at BAELJs (see Figure 19 for locations of structures). (A) deposition on the upstream side of a Kelsocleuch structure, (B) capture of debris and formation of scour pools at Bar 1, Swindon Haugh, (C) capture of debris and deposition of a gravel sheet upstream of a structure at Bar 2, Swindon Haugh (see Figure 19 for locations). Figure 20 continues overleaf.

Figure 20 continued. (D) stabilisation of gravel deposited by the September 2012 flood event through vegetation colonisation and (E) erosion of floodplain and material surrounding the piles of a structure at Clifton caused by natural channel movement. Note the removal of two of the pile anchors presumably by the December 2015 or January 2016 floods (see Figure 19 for locations).

6.1.4 Results

General findings

- There have been fourteen flow events (based on assessment of Yetholm Mains stage record; Figure 13) that have approached or exceeded bankfull discharge with the September 2012 and January 2016 floods standing out. At all BAELJ monitoring sites, both large events resulted in channel widening, riverbank erosion and gravel deposition (Figure 20).
- Geomorphic change was most pronounced at the Swindon Haugh site in both flood events. Formation of a new chute channel and extensive gravel deposition was associated with the September 2012 event. The January 2016 flood resulted in the progression of a headcut near Bar 3, gravel deposition over bars (especially at Bar 1) and channel avulsion (sudden change of channel course; near S21).
- Reflecting the moderate flows during the monitoring period, the gravel deposited over bars during the September 2012 flood event was stabilised by vegetation colonisation at all three sites and showed little signs of reworking until the floods that occurred in December 2015 and January 2016.
- Between August 2012 and March 2016, 5 out of 45 structures have been lost and 5 of the 40 structures that have remained in place have been damaged (Figure 21(A) e.g. Figure 20(E).
- The survival reflects the structure stability offered by the pile anchors and placement in low energy settings (floodplain and bar depositional zones) rather than high energy settings (e.g. mid-channel locations). However, the complete washout of some structures or damage to timbers show they are vulnerable if placed in sensitive locations (e.g. close to the outer sides of meander bends where bank erosion tends to be concentrated; Figure 20(E)).
- Trees planted in Spring 2013 have in most places not survived (31 out of 45) presumably reflecting grazing pressures or displacement by floods (Figure 21(B)). Survival may have also been influenced by the soil conditions; trees planted on gravel bars have in particular not fared well perhaps due to the poor growing conditions of the freely draining alluvium.
- Where installed in zones of sediment transport (i.e. within areas low flow wetted channel areas and adjacent bars submerged during floods), the structures create diversity of sediment texture by altering sediment transport patterns; sediment tended to be finer (sand and silt material) within the footprint of each structure due to slowing of the flow causing settlement of sediment. At the local level this may influence vegetation diversity.
- At Swindon Haugh, scour pools associated with structure S1 that were created by the September 2012 flood have been used by spawning frogs and small fish. Debris trapped at one structure at Clifton and another at Swindon Haugh have been used by nesting birds.

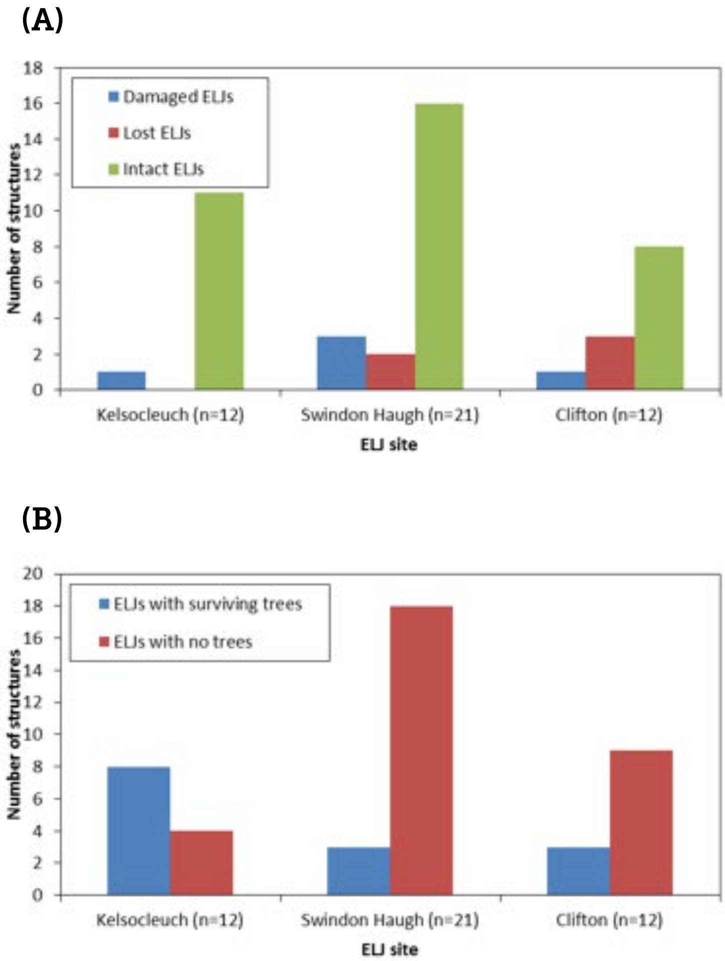


Figure 21(A): Bar apex ELJ structure state of repair as of March 2016. (B): Status of trees planted in Spring 2013 and assessed in March 2016.

Morphological change

- Large (> +0.3 m depth) sediment deposition is associated only with a limited number of structures restricted to Swindon Haugh and mostly in response to the September 2012 flood event (Figure 22). The large sediment deposition around these structures partly reflects the re-accommodation of sediment in the bars after gravel management was undertaken in 2009 rather than simply the presence of the structures.
- Morphological signatures associated with influential structures include the formation of scour pools at the sides, stalled coarse sediment sheets upstream and wake tail deposits (Figure 20, Figure 23 and Figure 24). However, no structure was associated with the full suite of these landforms presumably reflecting local differences in sediment transport.
- For both flood events considered, the majority of structures were associated with minor sediment deposition (< 0.3 m depth) suggesting the structure design and their placement are insufficient to capture significant volumes of sediment (Figure 22).
- Structures placed in stable areas of floodplain did not capture sediment due to being outside the main channel where sediment transport is focused but some did capture minor amounts of debris especially during the earlier flood event.
- Sediment deposition was more concentrated in stoss and tails zones compared to the inside of structure footprints (Figure 25: Net volumetric changes (deposition and erosion volumes added together) according to structure associated zone (see Figure 18).
- The September 2012 flood event was associated with the greatest geomorphic change and sediment capture adjacent to the structures in comparison with the January 2016 flood event (Figure 23, Figure 24 and Figure 25). The most significant sediment capture in response to the later flood event was associated with the structures in Bar 1 at Swindon Haugh but the volumes were considerably less than the earlier flood event.
- The large deposition of sediment around structures S7 and S8 (up to the half-height of the piles; Figure 23) at Swindon Haugh means their sediment trapping capacity may have been compromised. Continued deposition and expansion of bars could deflect flows towards opposite banks and increase bank erosion rates.

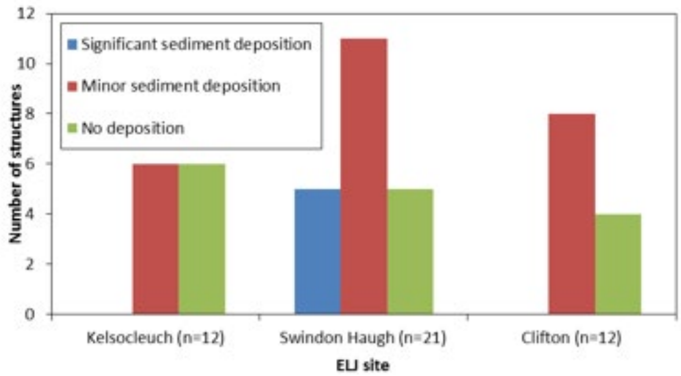
6.1.5. Guidance for future installation

- Log jams should be placed in areas of sediment transport (wetted channel and active gravel bar areas). Log jams placed in stable areas of floodplain are ineffective by being outside the zone of sediment transport and are unlikely to have an appreciable effect on flow attenuation. They are also vulnerable to damage or displacement through the erosion of material into which pile anchors are driven.
- The structure design needs to be improved to make it less porous to increase hydraulic effects and sediment capture effectiveness. The effectiveness of the installed structures could be increased by adding woody material to frontal piles.
- By increasing the size of the structure and through careful placement that considers river channel size, structures can block more than 10% of the channel cross section and increase the likelihood of hydraulic and geomorphic effects.
- Trees planted within structures need to be better protected to ensure they can survive grazing and flooding. Consideration should also be given to the soil conditions.

6.1.6 Further work

Continued field checks of structure condition (i.e. timber decay and displacement) and geomorphic change at all bar apex ELJ monitoring sites is required to make a long term assessment of 'lifespan' and effects. Further topographical surveys after floods at Swindon Haugh (primary monitoring site) are necessary to quantify geomorphic effects in detail. In addition, one-dimensional flow modelling of the Swindon Haugh ELJs is required to characterise their hydraulic effects and help explain the geomorphic responses observed. Modelling can also be used to explore the hydraulic effects of the structures under different flow and structure design scenarios which could help refine the structure design.

(A)



(B)

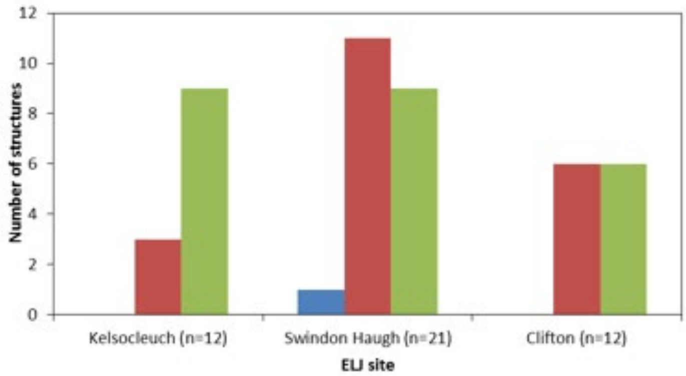


Figure 22(A): Sediment capture effectiveness in response to the (A) September 2012 and (B) January 2016 flood events. Significant sediment deposition is defined as over 0.3 m in height of material deposited (> mean natural deposition thickness of 0.25 m caused by the September 2012 flood at Swindon Haugh) and minor deposition defined as less than 0.3 m of deposition. No deposition defined when no signs of deposition were observed.

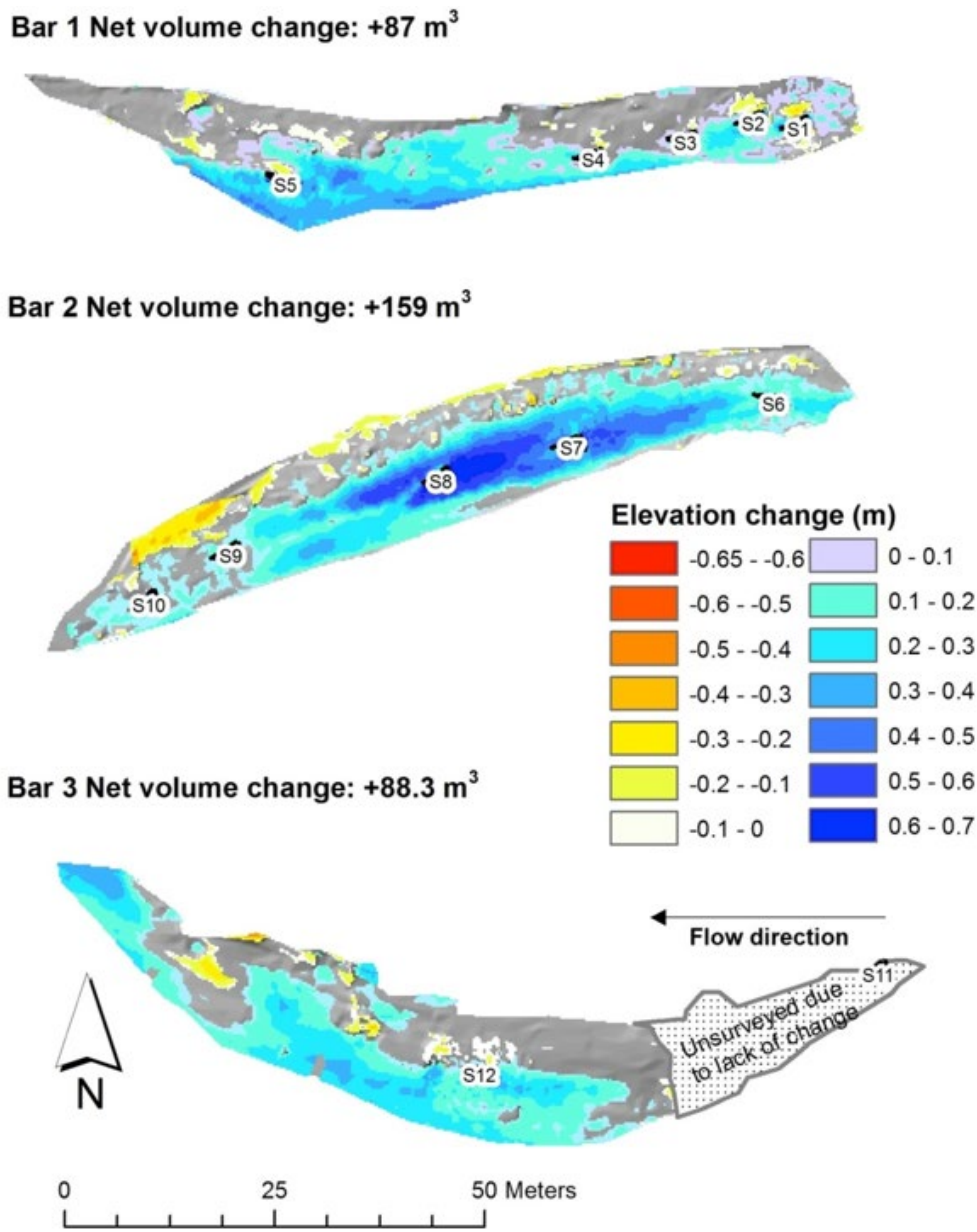


Figure 23: Distribution of elevation changes showing erosion and deposition response for Bars 1 to 3 at Swindon Haugh between August 2012 and October 2012 (see Figure 19(B) for locations of bars). Hill-shaded topography map (based on August 2012 survey) shown in the background for context.

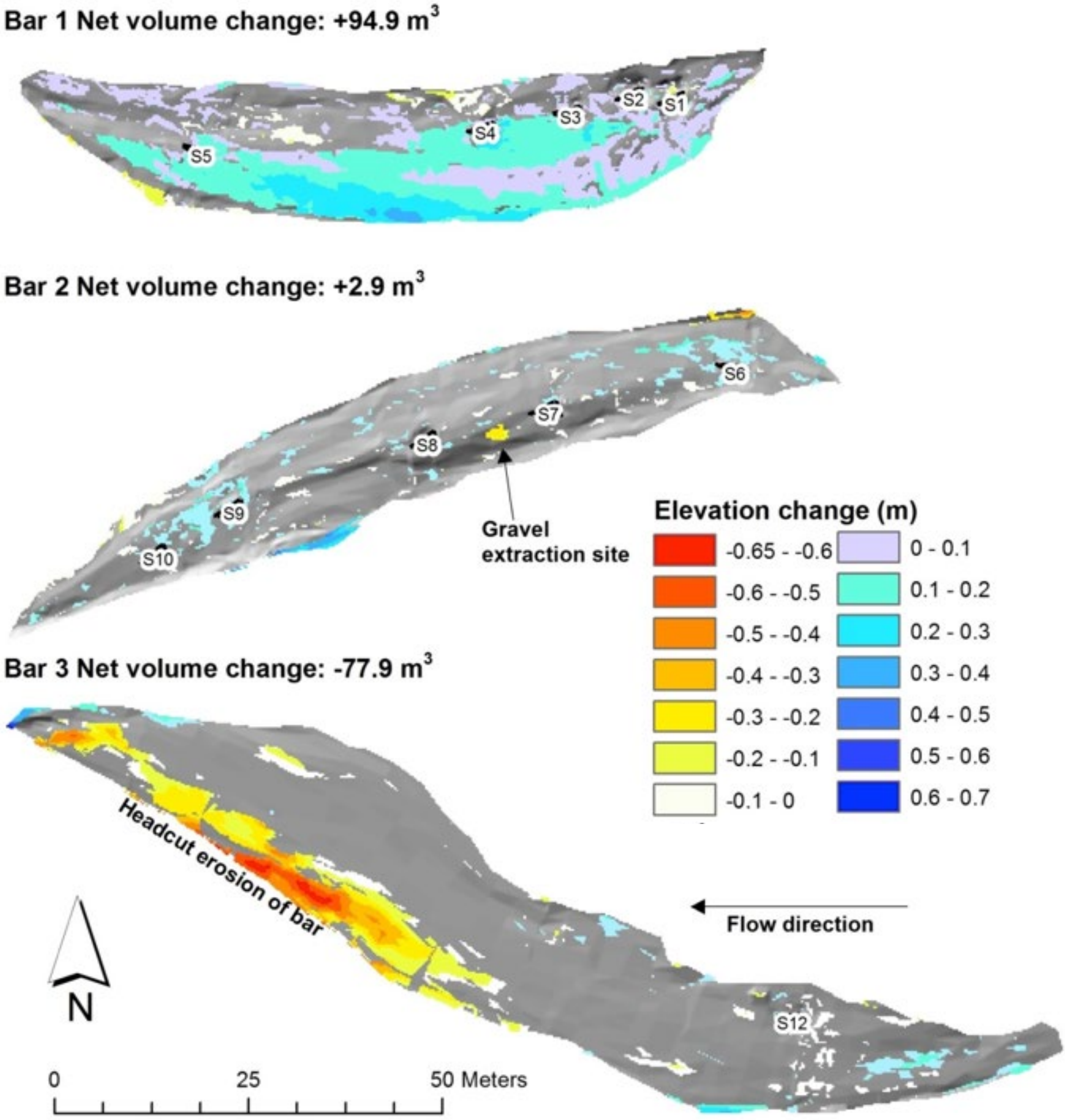
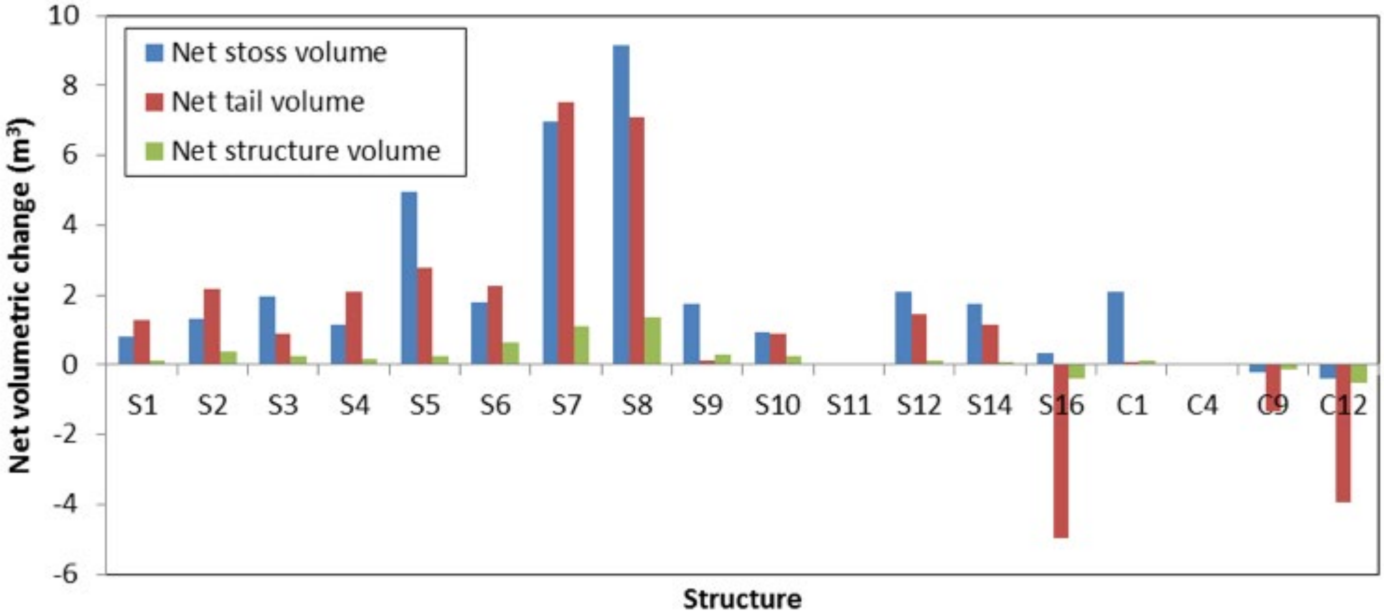


Figure 24: Distribution of elevation changes showing erosion and deposition responses for Bars 1 to 3 at Swindon Haugh between July 2015 and March 2016 (see Figure 19(B) for locations of bars). Hill-shaded topography map (based on July 2015 survey) shown in the background for context.



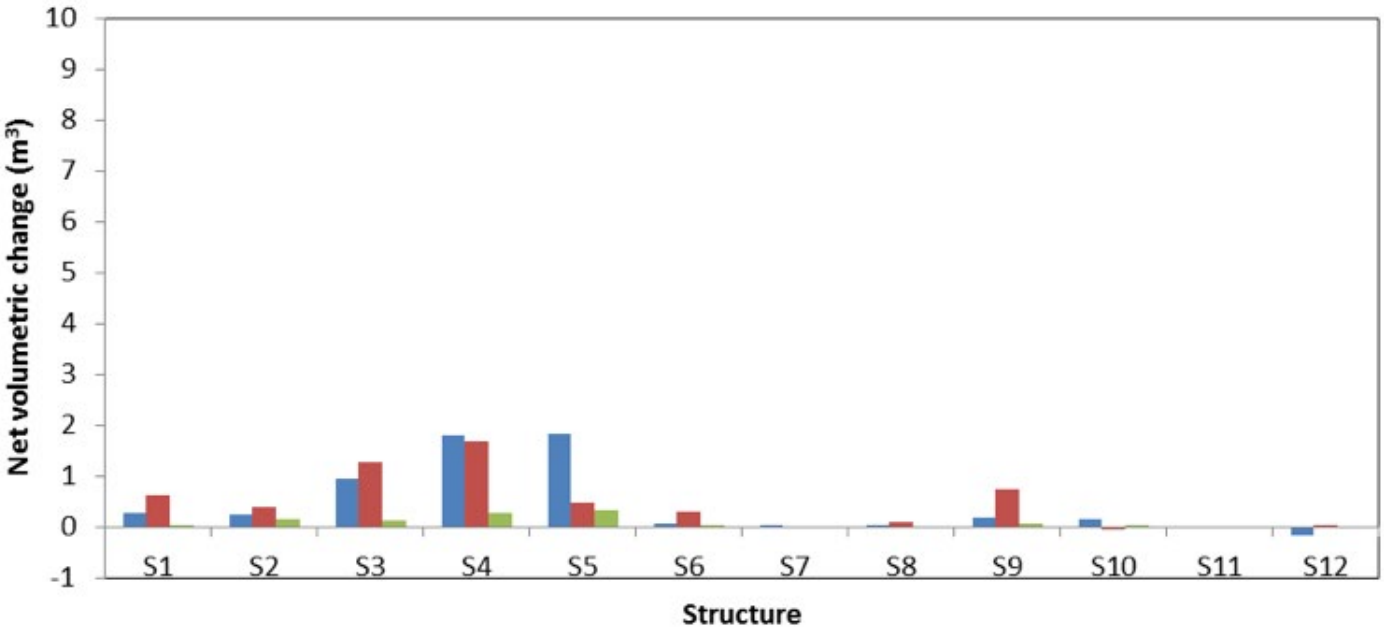


Figure 25: Net volumetric changes (deposition and erosion volumes added together) according to structure associated zone (see Figure 18 for definition of zones). (A) Between August 2012 and October 2012 at Swindon Haugh and (B) between July 2015 and March 2016 at Swindon Haugh.

6.2. Kelsocleuch bank protection structure

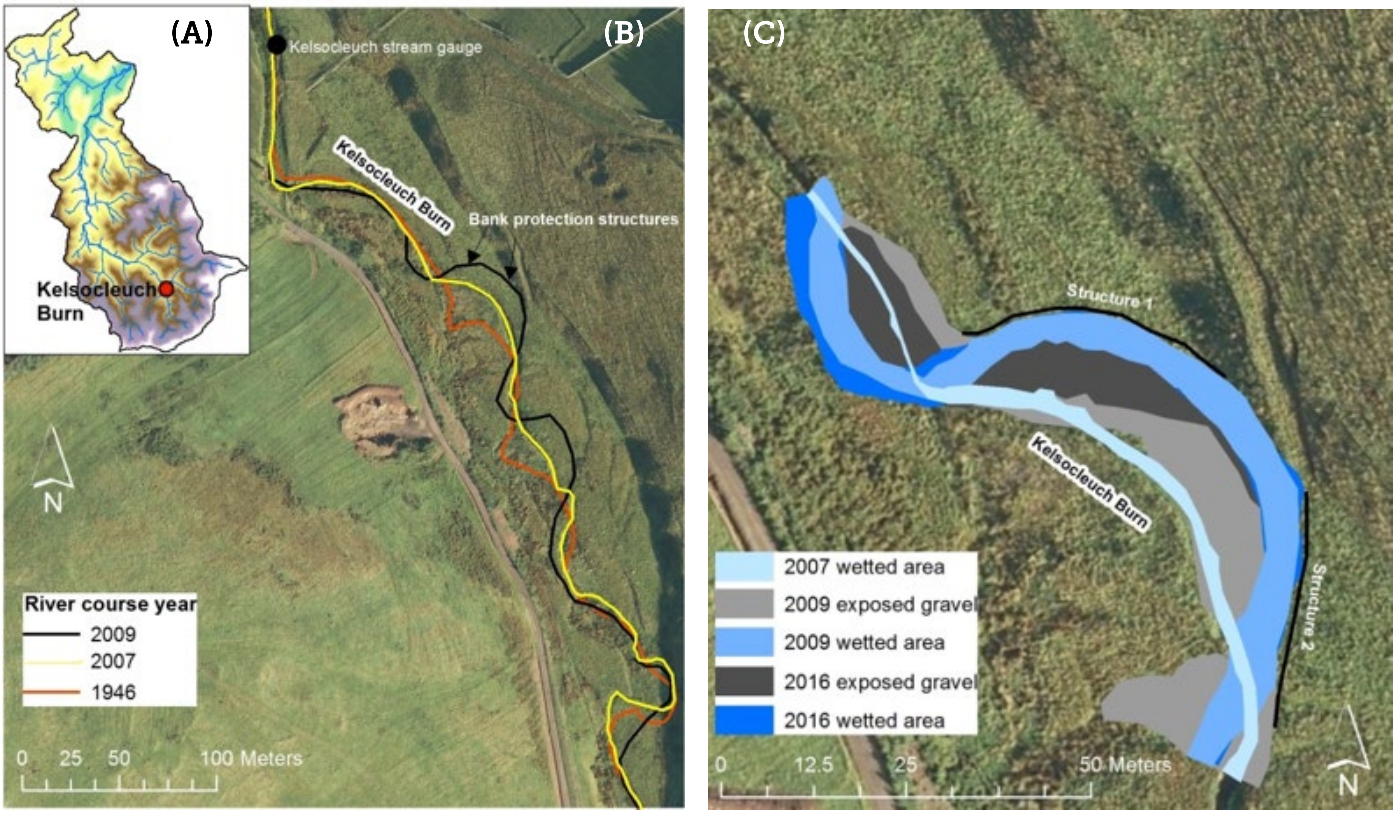


Figure 26: (A) Location of the riverbank protection structures on the Kelsocleuch Burn. (B) Channel changes for the lower Kelsocleuch Burn between 1946 and 2009 based on historical aerial photograph interpretation. (C) Wetted channel and exposed gravel area changes between 2007 and 2016 at the monitoring site. Based on aerial photographs and recent ground surveys (2007 aerial photograph: Copyright Getmapping plc.).

6.2.1. Introduction and site description

The Kelsocleuch Burn is a 3rd order headwater stream of the Bowmont catchment that drains the northern flanks of the Cheviot Hills along the Scotland/England border (Figure 26(A)). At the catchment outlet where it joins the Cocklawfoot Burn at Cocklawfoot, the drainage area is 6.5 km^2 (near the stream gauge; Figure 26(B)). The lower stream has a meandering morphology with alternating pools, glides and riffles that occupies a wide alluvial valley fringed by steep glacial till bluffs. The dynamic nature of the stream is indicated by the presence of multiple old channel courses in the floodplain clearly visible in aerial photographs. Interpretation of channel course change since 1946 using historical aerial photographs shows it has shifted appreciably (Figure 26(B)).

Figure 26(C) gives an overview of the bank protection log jam site that has been monitored since August 2012. The active channel area (i.e. including both wetted channel and gravel bar areas) has widened considerably since 2007 and the meanders have become more pronounced; the largest meander is now confined by the hillslope on the east side of the valley. These responses mainly reflect the geomorphic impact of the major floods of 2008 and 2009. The gradient of the riverbed is 0.017 m/m and the median sediment size in exposed gravel bars is 33.9 mm (data based on August 2012 survey).

The two bank protection log jam structures were installed in July 2012 by a local contractor with the aim of reducing riverbank erosion and coarse sediment input to the channel. The structures cost approximately £7,000 in total and were placed along the outside edge of the meander using the same design (Figure 26(C)). Untreated conifer pile timbers that lacked brash and rootwads were machine driven over a metre into the bank and wetted margin of the channel. These were reinforced by horizontal timbers that were secured in a zig-zag pattern with metal fastenings to the piles. Loose gravel material and turfs were then added as backfill between the piles to add further protection.

6.2.2. Aims of the monitoring

1. To assess the structure condition over time.
2. Evaluate the ability of the structures to reduce riverbank erosion.
3. Assess the potential wider effects of the structures on geomorphic processes in the adjacent stream reach.

6.2.3. Methods

Assessing morphological change

Morphological changes created by erosion and deposition have been monitored by using repeated topographical surveys of the stream bed and banks. Surveys were undertaken in August 2012 (following construction), October 2012 (following the 25th of September 2012 flood event), September 2014 and March 2016. The locations of the structure timbers were also surveyed at the start of the monitoring period. A Leica GeoSystems GPS 1200 dGPS and a GPS 500 base station were used to conduct the surveys (survey point accuracy of ca. ±0.02 in plan and ± 0.03 m in elevation). The morphological changes and sediment volumes eroded and deposited were analysed using ArcGIS Version 10.1 and the GCD software to reduce uncertainty in the results (see Addy and Wilkinson, 2016 for more details). To compare erosion rates in sections protected by the structures to those not protected, the bank top edges of 5 eroding banks upstream and 1 downstream of the structures were surveyed with the dGPS for the latter three survey dates.

Photography

In addition to the topographical surveys undertaken, photographs were taken give a record of structure condition over time and provide further evidence of erosion and deposition changes in the reach. Sixteen photos of exposed gravel bar surfaces were taken in October 2012 and analysed using the Sedimetrics software to give information on the sediment size distribution.

6.2.4. Results

Figure 27: Downstream section of Structure 1 between August 2012 and March 2016. Note the erosion of placed gravel backfill and turf followed by progressive erosion of the bank.

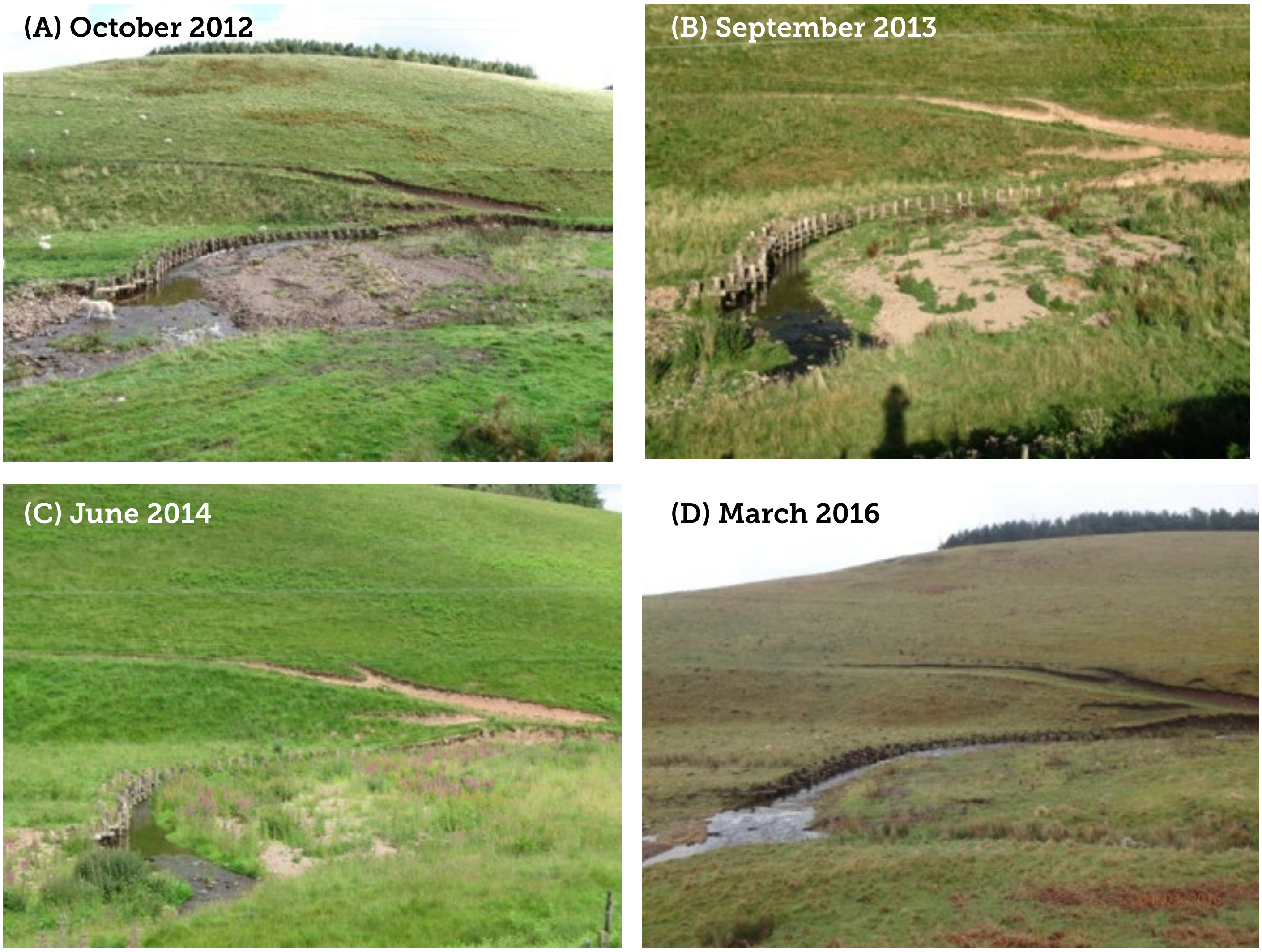


Figure 28: Changes to the channel and point gravel bar adjacent to Structure 1 between October 2012 and March 2016. Note narrowing of the wetted channel and the encroachment of vegetation over the stabilising bar.

General findings

- The structures have remained intact over time and show no signs of displacement (Figure 27). The backfill has been removed in places especially at Structure 1.
- Vegetation has encroached on to the bar surfaces indicating favourable growing conditions probably aided by the paucity of high flows that can disrupt plant colonisation during the monitoring period (Figure 28). This matches observations from other sites and is unlikely to be related the presence of the structures.
- A large number of small fish (parr and fry?) were observed using the reach especially in the pool in between the two structures. It is not clear if structures have improved cover for the fish making the reach more attractive or if the pool - which reflects natural processes rather than the effect of the structures – offers particularly attractive habitat.

Morphological change

- Between August 2012 and October 2012 the greatest geomorphic changes were recorded over the 4 year period. This reflects the significant flood event that occurred on the 25th of September 2012 (Figure 29). Overall there was a net gain of sediment during this period. Notably, up to nearly 0.7 m of deposition occurred over existing bars and a new medial bar which developed close to Structure 1. Up to 4 m of riverbank was eroded (lateral direction) in the downstream portion of the reach. Vertical erosion of up to nearly 0.8 m of the bed was associated with Structure 1 indicating the flow deflection effect of the structure (Figure 29 and Figure 30). A considerable amount of the backfill was eroded during this event at Structure 1. In contrast change close to Structure 2 was less marked but bed scour possibly caused by the structure and some erosion of backfill occurred towards its downstream end.
- Between October 2012 and September 2014, geomorphic changes were minor reflecting the moderate flows during this period (Figure 29). Erosion of structure backfill continued during this period and overall there was a net loss of sediment.
- In the final period between September 2014 and March 2016, there was a net gain of sediment which has been deposited widely over the channel bed and bars (Figure 29). Much of this sediment gain is likely to be associated with the 5th of January 2016 flood. Scour of backfill, banks and stream bed adjacent to the structures was limited. Up to 2 m (lateral direction) of riverbank downstream of the structures was eroded during the period.
- Maximum bank erosion rates in the bends protected by structures were slightly lower than 3 out of 6 of the other unprotected bends during the first period (Figure 31). In the second period, rates were lower in the protected sections compared to all the unprotected bends where erosion reached over 2.5 m/year at one bend compared to less than 0.5 m/year at the bank protection structures. This tentatively suggests the structures were effective at satisfying their main aim of reducing riverbank erosion. This study however was limited by the short timeframe and limited number of surveyed eroding banks. Also differences in geometry and riverbank resistance – not considered in this analysis – could have influenced erosion rates.
- The removal of backfill and evidence of erosion of the riverbanks close to and behind the structures in some locations (especially Structure 1) means the long term effectiveness may have been compromised.

6.2.5. Guidance for future installation

- Riverbank erosion is a natural process in unconfined floodplains and a way in which rivers adjust to varying inputs of water and sediment. Consideration must be given towards whether such protection structures are needed especially in dynamic river environments where their function may be short-term (i.e. < 10 years).
- Tree planting and controlling grazing pressures are better potential solutions to address bank erosion problems by increasing the natural resistance of channel margins. These measures could be combined with carefully targeted wooden bank protection structures or log jams designed to deflect flow away from banks (e.g. Brooks et al., 2004), in key areas that require protection as an alternative to traditional rock armour or revetments.
- Consideration should be given to the strength of any backfill and turfs used to provide further bank reinforcement after structure installation; loose backfill doesn't stay in place in all settings and continued grazing prevents the development of natural vegetation that increases resistance.
- The location of the structures around a bend will affect their influence on current deflection and in turn erosion of areas beyond the bank that is being protected. The downstream end or exit from a meander is particularly sensitive area where river energy tends to be naturally focused (Bathurst, 1997).
- Structures can cause scour of the riverbed through deflection and create unnatural channel morphology (deep and narrow) by preventing the channel from adjusting laterally through bank erosion. This in turn could threaten the stability of the material into which the piles have been driven. By contributing sediment for onward transport, it may also offset the prevention of sediment input from eroding banks.

6.2.6. Further work

The geomorphic and structure condition monitoring needs to continue to gain a long term assessment of this measure. Further analysis of hydrology in relation to geomorphic changes by using the Kelsocleuch Burn flow record, would also be useful for understanding the rates and styles of geomorphic change observed.

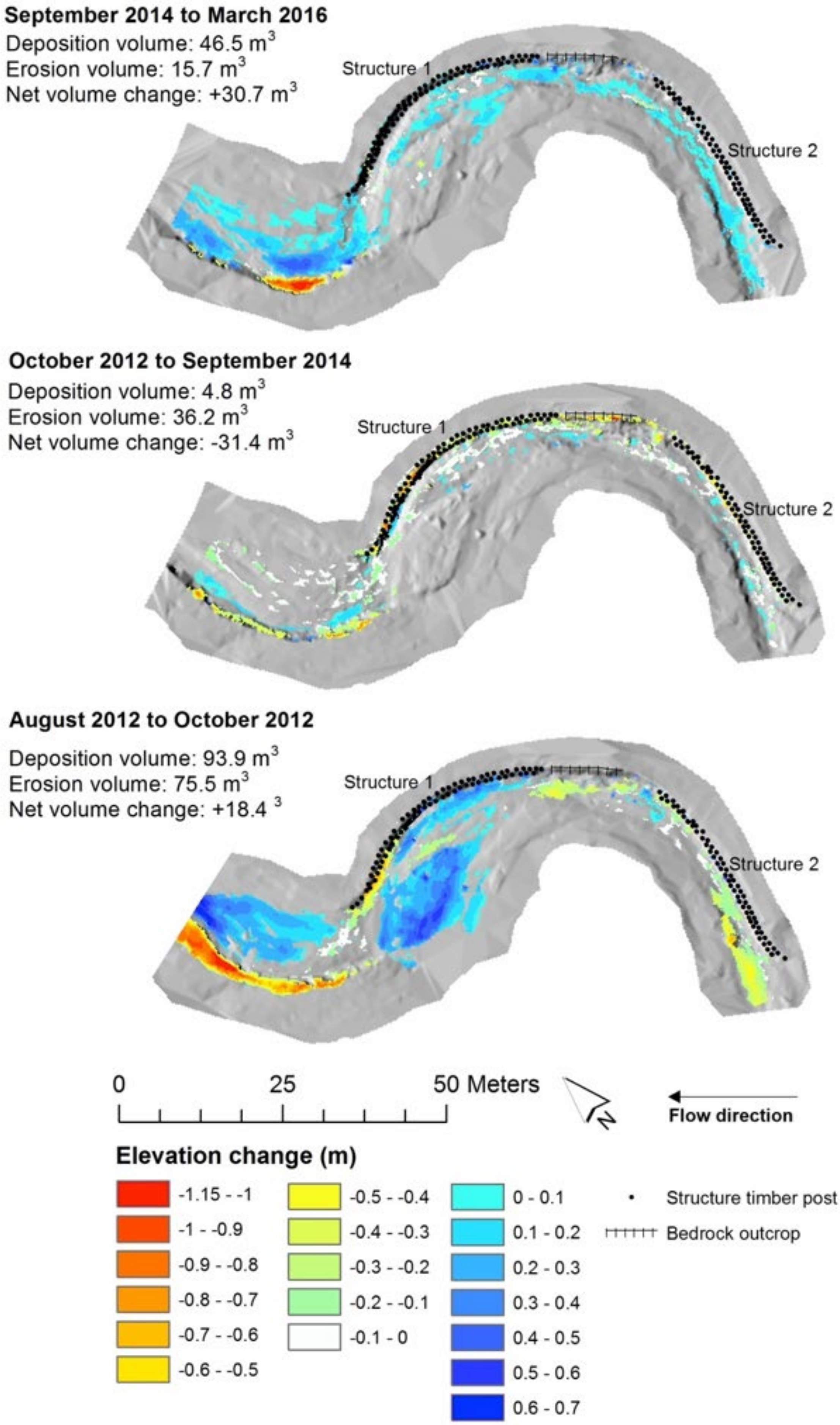


Figure 29: Topography and sediment volume changes at the Kelsocleuch bank protection structure monitoring site for three periods between August 2012 and March 2016. Underlying hillshade topography maps dated to the first survey of each period.

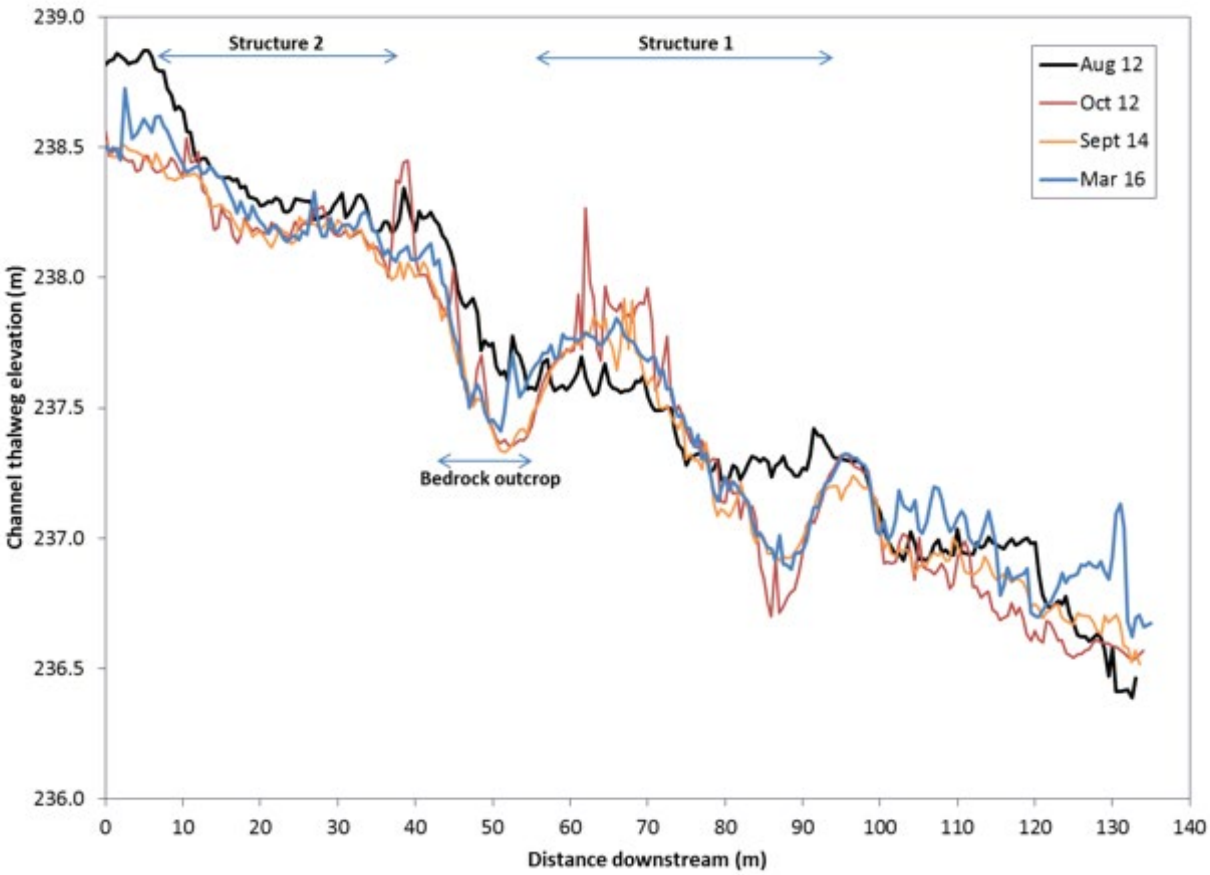


Figure 30: Channel elevation profile along the deepest part of the riverbed (thalweg) adjacent to the log structures between August 2012 and March 2016.

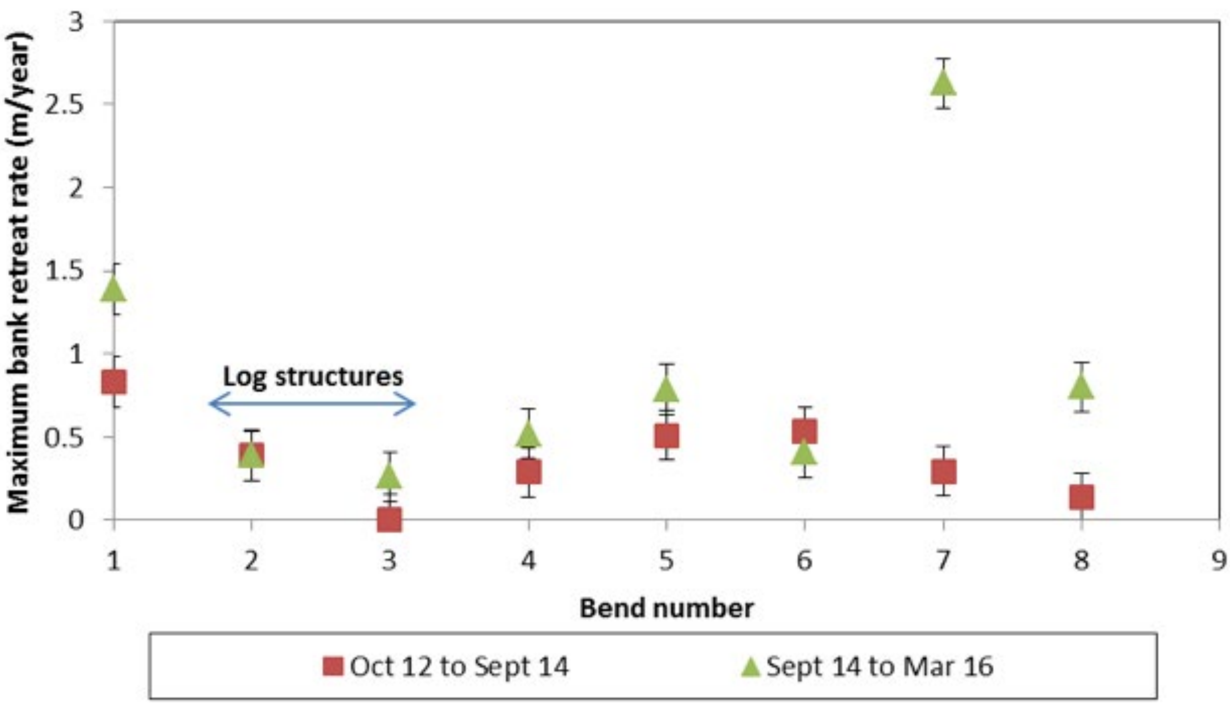


Figure 31: Maximum bank erosion rates at channel bends adjacent to and upstream or downstream of the bank protection log structures. Bend numbers in an upstream ascending order. 0.15 m error bars indicate uncertainty of erosion rates due to assumed potential survey point error for recording the location of eroding bank edges.

6.3 Elm Sike flow restrictors

Figure 32: (A) Location of the Elm Sike study site. (B) Distribution of flow restrictors (S1 to S16) and water level sensors at the Elm Sike study site. Aerial photo dated to 2007 (Copyright Getmapping plc.).

6.3.1. Introduction and site description

The Elm Sike is a second order tributary (mean channel gradient of 0.16 m/m) of the Kelsocleuch Burn (Figure 32(A)) which drains the western slopes of Cock Law (Figure 32(B)). The steep catchment (mean slope of 23°) drains a total catchment area of 0.33 km^2. Typical of other small headwaters in the Bowmont valley, the catchment is treeless (rough moorland) and used for sheep grazing. Large areas of the hillslopes are covered by bracken and in recent years the local farmer has been attempting to remove it. An alluvial fan has developed on the lowest section of the Elm Sike before the confluence with the Kelsocleuch Burn where sediment naturally accumulates (Figure 33). On account of the grazing pressures and mobile nature of the sediment, signs of river (banks and bed) and hillslope erosion are common (Figure 34). Channel head cuts (also known as knickpoints) occur along the upper Elm Sike indicating significant channel erosion in response to flood events (Figure 34(B)) and may represent a major source of coarse sediment supply to the study site.

The experimental monitoring site is centered on the lower end of the Elm Sike (Figure 32(B)), a steep section of channel (0.089 m/m) with limited pockets of floodplain and adjacent hillslopes covered by bracken. The streambed is comprised of a poorly sorted mixture of sand, gravel and cobbles (median sediment size: 49.8 mm, surveyed in June 2016). The site was chosen by Tweed Forum following consultation with the local farmer who was willing to set aside this low value land for tree planting and flow restrictor measures (Figure 35). In early 2013, the fenced enclosure was established to protect trees planted in summer 2013 from grazing. The fenced area encloses an area of 0.29 ha within which the flow restrictors have been emplaced in the channel.

Figure 33: (A) Outlet of the Elm Sike in April 2013 before the flow restrictors were installed but with the fenced enclosure established. Note the large build up of coarse sediment in an alluvial fan between the fences. (B) The approximate same view in February 2016 after dredging of the channel in Autumn 2013 and following several flows sufficient to move coarse sediment and re-shape the channel (including 5th and 27th of January 2016 floods).

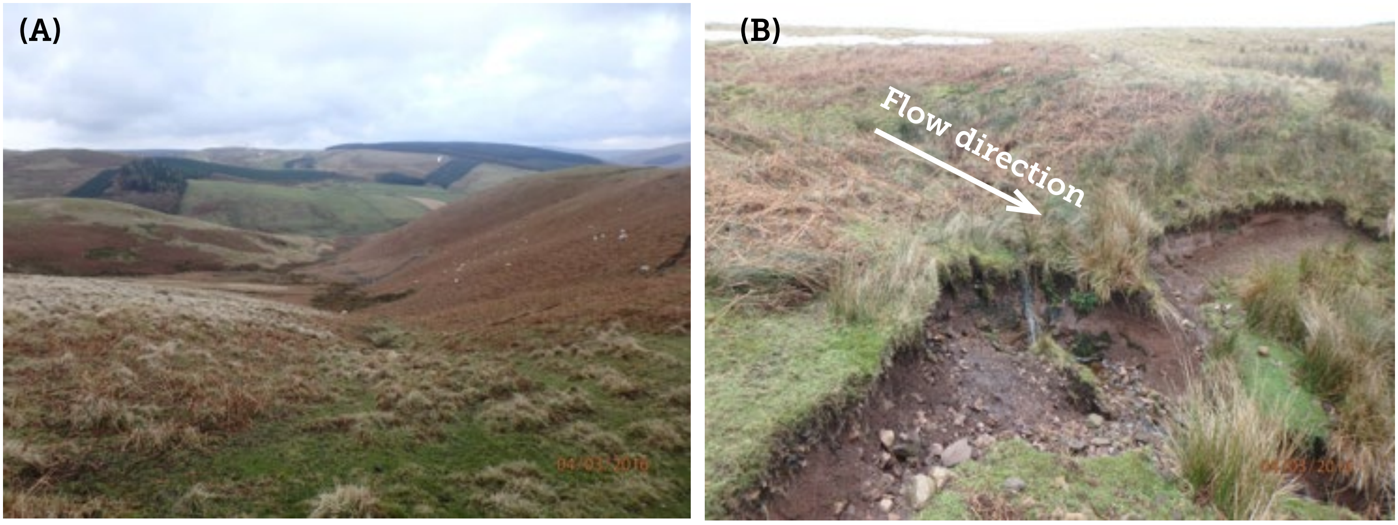


Figure 34: (A) View of the Elm Sike catchment taken from Cock Law in March 2016. (B) A channel headcut on the upper Elm Sike in March 2016. Note the sudden difference in channel width and depth at the small waterfall created by scour.

Initially ten flow restrictors were built by a local contractor in September 2013 (S1 to S10). In February 2014, seven new structures were added to the upper part of the enclosed section of channel (S10 to S16) and the lowest structure (S1) was widened (by using material taken from the original structure S2) to increase its damming effect. The aim of the restrictors is to slow down the flow of water during floods by creating backwater effects to encourage temporary water storage and by increasing flow resistance (this type of measure is classified as a leaky barrier in the SEPA NFM Handbook and the Environment Agency Working with Natural Processes evidence directory). It is an engineered structure that aims to mimic the properties of naturally occurring in-channel wood. Engineering is essential in order to securely fix the structure and prevent washout. A second aim is to trap coarse sediment and delay its movement further downstream.

Each flow restrictor consists of two horizontal timbers securely attached to posts embedded into the banks (Figure 35). During construction, a gap of at least 0.3 m between the lowest timber and the streambed was made due to concerns about fish passage. Branches were added to the structures to the increase the roughness effect. The adjacent tree planting was designed to help bind the hillslopes to reduce sediment input to the channel, reduce runoff, increase shading, improve biodiversity and in the future, to act as a source of naturally occurring wood to the channel.

Figure 35: Flow restrictor S1 in the foreground photographed in February 2014 with structures S2 to S8 in the background. Note the gap (minimum of 0.3 m) below the timbers to facilitate fish passage.

6.3.2 Aims of monitoring

1. To assess the effectiveness of peak flow attenuation and delay functions of the flow restrictors.
2. To assess the sediment and debris trapping effectiveness of the flow restrictors.
3. To help inform guidance on the optimal design and placement characteristics of these structures.

6.3.3. Methods

Channel water level monitoring

Since October 2013, channel water levels (stage) have been monitored at 5 minute intervals at sites R2 and R3 with pressure transducers (Figure 32(B)). The instruments were installed to:

1. Understand the hydrological response of the Elm Sike;
2. Using R3 gain an understanding of water storage and release characteristics at the scale of an individual structure;
3. Understand the potential peak flow attenuation and delay effects of multiple structures; 4. Relate the frequency and magnitude of flows to the geomorphic changes observed.

In July 2015 another pressure transducer was added upstream (R1); this allows a comparison of peak flow transit times between the treated (i.e. reach with the flow restrictors) and untreated (unaltered section of channel upstream of the fenced enclosure) sections of channel to improve assessment of the hydrological effects of the structures. Due to the mobile riverbed sediments, the channel geometry has been continually changing meaning that the local datum for the flow stage measurements been reset on multiple occasions (especially at R3). This in part has precluded the development of reliable stage-discharge relationships to continuously monitor discharge. However the measurement of channel water level still provides useful information on the hydrology of the stream and potential effect of the structures.

Assessing morphological change

Morphological changes created by erosion and deposition have been monitored by using repeated annual topographical surveys of the stream bed and banks. The structure dimensions were also measured at the start of the monitoring period to give information on the location, orientation and geometry of the structures. This understanding can be used to assess the relationship between the structure characteristics and the hydraulic and geomorphic effects including the trapping of sediment. A Leica GeoSystems GPS 1200 dGPS rover and a GPS 500 base station were used to conduct the surveys (survey point accuracy of ca. ±0.02 in plan and ± 0.03 m in elevation). The morphological changes and sediment volumes eroded and deposited were analysed using ArcGIS Version 10.1 and the GCD software to reduce uncertainty in the results (see Addy and Wilkinson, 2016 for more details).

Tracer surveys

Between September 2014 and March 2016, sediment tracers have been monitored to gain an insight into the coarse sediment dynamics of the lower Elm Sike and the potential trapping effect of the flow restrictor structures. Tracers ranging in size from fine gravel to small cobbles, were installed in three clusters: at the R2 water level monitoring station, at structure S16 and structure S6. Loss of tracers through hydraulic transport to hidden areas (e.g. undercut banks and where obscured by vegetation), burial or movement beyond the study site during floods has limited the value of this experiment.

Photography

An automatic time lapse camera located in the lower part of the treated reach records photos every hour to give visual evidence of the hydraulic impacts of the structures (centered on structure S1). The camera has been in operation since May 2014. Conventional photographs have also been taken during topographical surveys to further assess the effects of the structures and their condition (e.g. structural modification and trapping debris).

Flow modelling

The one-dimensional flow model HEC-RAS was used to model the hydraulic and hydrological impacts of the flow restrictor structures to make initial predictions on their ability to satisfy their main aim. Due to the difficulty of modeling steep streams and lack of robust model calibration, the results should be treated with caution.

6.3.4. Results

General findings

- All structures have remained intact over the monitoring period and have not moved.
- Throughout the monitoring period there has been free passage potential for fish underneath the structures until January 2016 when sediment was deposited closing the gap between the structure and stream bed in some cases (S5 and S7).
- Debris trapping has been limited reflecting the limited availability of transportable large organic debris and much of the brash added during construction has been transported away or decomposed.

Hydrological and hydraulic effects of structures

- Figure 36 highlights water level data from the monitoring period that has not been corrected with respect to changing bed datums. Appendix A5 explains the issues surrounding monitoring water level at the site in more detail. The 2015/2016 winter was associated with several large flows; most notable were the 21st of December, 5th of January and 27th of January of flow events which exceeded bankfull level.
- Due to the short duration of monitoring, bed scour altering bed datums at water level sensor stations and the limited number of high flow events, work is still ongoing to determine how the flow restrictors slow the progression of high flows.
- Preliminary 1D flow modelling results suggest that the current design and location of structures have no effect on peak water discharge or the speed at which the peak was generated (for simulated 1, 2, 5 and 10 year return flood events). Modification of the structures to increase the channel blockage effect and their hydraulic roughness did not reduce peak discharge but did delay the movement of the peak slightly for 1 year return period floods.
- Based on time lapse photography (Figure 37) and inference from geomorphic responses (Figure 38) and high flow trashlines, the hydraulic influence of most of the structures is likely to have been limited so far. This reflects their blockage of the channel cross section only during high flows (i.e. approximately bankfull or greater) which reduces the likelihood of backwater effects. It may also reflect the steep nature of the channel meaning that hydraulic interference is limited.

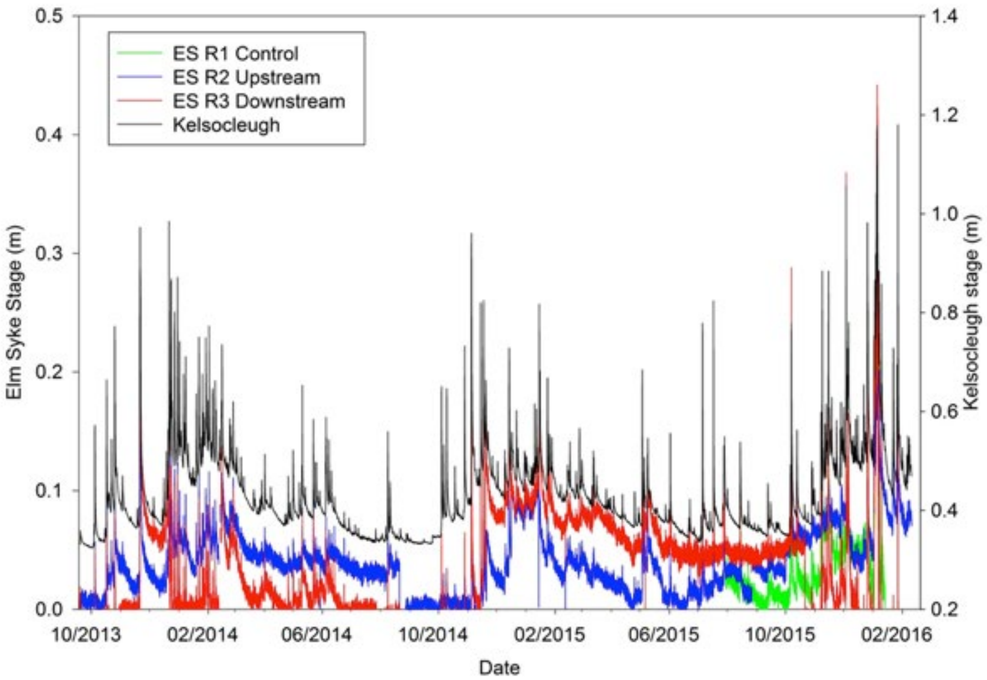


Figure 36: Complete flow level record for the Kelsocleuch Burn and the Elm Sike (R1 to R3) for the Elm Sike monitoring period.

Figure 37: Selected time lapse photographs of structure S1 in the foreground with other lower structures visible in the background during different flow conditions.

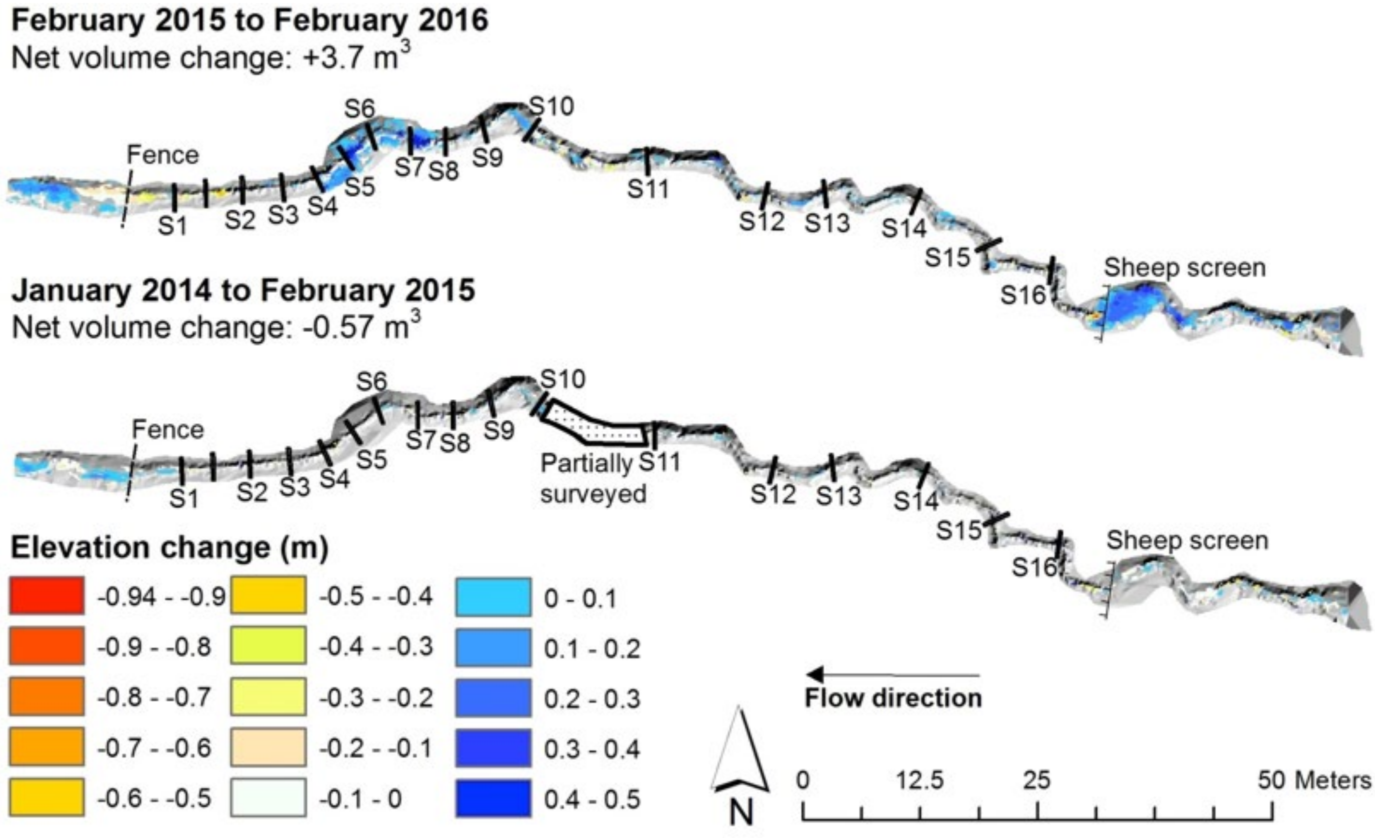


Figure 38: Distribution of elevation change during the two comparison periods between January 2014 and February 2016. Underlying hillshade topography maps dated to the first survey of each period are shown for context.

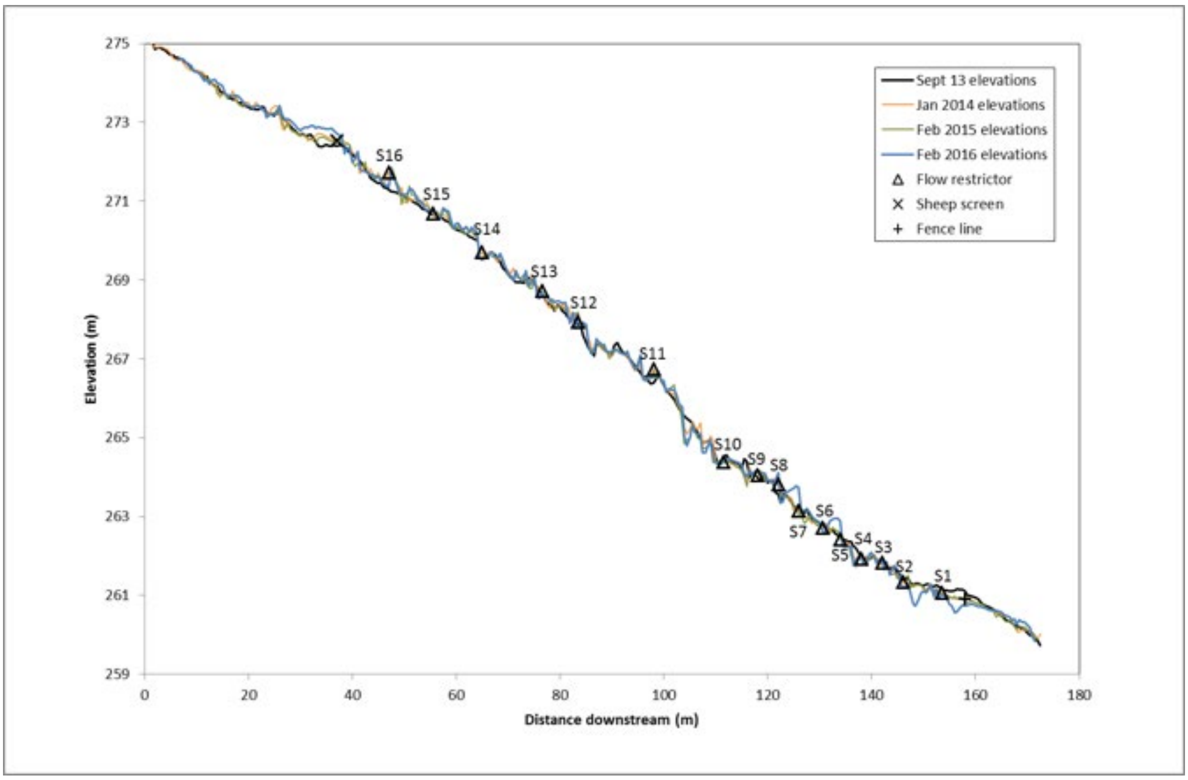


Figure 39: Channel (centerline of channel) elevation profiles for different survey dates.

Figure 40: Selected range of geomorphic responses observed during the February 2016 survey (following several high flows in December 2015 and January 2016). Refer to Figure 38 for the locations of these sites. (A) Vertical scour of up to 0.35 m below a flow restrictor. (B) Deposition of 0.85 m^3 of material upstream of a flow restrictor (C) Scour of up to 0.1 m underneath a flow restrictor and trapping of debris. (D) Deposition of 2.9 m^3 of sediment upstream of the sheep screen at the upper end of the fenced enclosure.

- During the 2014 to 2015 period, morphological change was limited reflecting the moderate flows (Figure 38). Over the entire reach, the overall response was erosional with approximately 0.57 m^3 (some uncertainty due to small area not surveyed in January 2014; Figure 38) of sediment lost from the reach.
- In contrast during the 2015 to 2016 period, the reach gained sediment with a total net gain of 3.7 m^3 (Figure 38). This is related to several flows during December 2015 and January 2016 that transported sediment into the reach from upstream and internal (i.e. within the monitored reach) sources.
- Establishing the degree to which the net sediment gain at the reach scale can be attributed to the presence of the structures is difficult. To some extent the channel especially the lower gradient sections of the modified alluvial fan and just upstream of the fenced enclosure, are likely to be naturally functioning as sediment sinks.
- At the scale of individual structures for the 2015 to 2016 period, flow restrictors S4-S7 have induced significant upstream sediment deposition (Figure 38, Figure 39 and Figure 40(B)). The deposition observed behind the structures S5 and S7 is analogous to the sediment trapping effect of check dams used to control channel gradient and bedload transport in steep streams.
- The degree of erosion created by the hydraulic influence of the structures (i.e. acceleration of scouring flow underneath the logs) is difficult to ascertain but vertical erosion of up to 0.6 m has occurred downstream close to S1-S3. Erosion of up to 0.2 m is associated with S10-S13 and S15-S16 (Figure 39 and Figure 40(C)).
- The upstream sheep screen has collected the greatest volume of sediment (2.9 m3; Figure 40(D)). This could reflect both the significant effect of the structure and the greater upstream sediment supply that has been intercepted by the structure before the downstream flow restrictors within the fenced enclosure capture it.
- Between the September 2014 and March 2016, gravel (2-64 mm) and cobble (64 – 256 mm) sized tracers were transported downstream along the bed due to several flows that exceeded the entrainment thresholds of particles that occur within the reach (See Appendix A6 for more details). No transported particles were found in association with the presence of structures suggesting their trapping influence was limited. However it is likely that several tracers were lost and buried by high flows in December 2015 or January 2016 within the upstream sediment deposits associated with S4-S7.

6.3.5 Further work

Continuation of geomorphic, hydrological and structure condition monitoring of the flow restrictors is needed to give a long term assessment of effectiveness. Further analysis of water level data is needed to determine if the structures delay the passage of flood waves and reduce peak flow magnitude. Additional analysis is also needed to relate the styles and rates of geomorphic changes to the locations and dimension of the structures.

6.3.6 Guidance for future installation

- Placement in streams that are less steep with wider pockets of floodplain (ideally that is hydraulically rough, e.g. through tree planting to enhance temporary storage and slow the flow) would improve effectiveness.
- Structures, if designed to block a greater proportion of the channel, would be more effective at attenuating flows and trapping sediment. However, consideration of the potential effects on fish movement needs to be given.
- Awareness of the stability of the stream bed in relation to the potential flow deflection and scour effect of installing flow restrictors is required if there are concerns about these geomorphic effects.
- The distance between structures should be large enough to ensure ponded water does not intersect another structure (i.e. ensuring storage is maximized).
- Consideration should also be given to the requirements of fish to ensure passage past the structures.

7 Conclusions and guidance

Hydrology

Key findings

The Bowmont Water is a responsive (flashy) upland catchment; at the catchment outlet of Yetholm Mains (87 km^2) the average lag time of peak flows following rainfall events is under 7 hours. This is owing to the topography, landuse, soils, geology and climate of the catchment (i.e. in areas the soils are thin, rainfall is often intense, land is heavily grazed and slopes are steep; all of which can increase the risk of flooding; see Wilkinson et al. (2013)). Based on a review of a 20 year record (1995 to 2015), the wettest months in the catchment occur from July through to January with the remainder of the year experiencing less rainfall and long periods of low flows. September is the most common month for extreme events (recording the 1st, 5th and 6th largest rainfall events in the last 20 years). The wettest month in the record was September 2008 with a total of 334 mm. However, the variability in monthly totals between years is large. There is no indication in the data to show yearly rainfall trends are increasing or decreasing.

Between 2011 and 2016, the wettest year was September 2012 with four out of five of wettest months occurring in this year. The wettest month was January 2016 (303 mm of rainfall) and the second wettest was December 2012 with a total of 225 mm of rainfall. There have been fourteen flow events (based on assessment of Yetholm Mains stage record) that have approached or exceeded bankfull discharge with the September 2012 and January 2016 floods standing out as the largest events.

Implications for NFM

Measures should be appropriate in terms of location, scale and type given the hydrology of the Bowmont Water. The effectiveness of measures should be considered in space (i.e. where in the catchment and which scales) and time (i.e. some measures will take longer to have an impact on flood peak attenuation). At present tree planting has been on a very small scale (< 1% of the catchment area) and the trees are at a young age. This will not translate into a detectable reduction of peak flows at the catchment outlet. However, long term detection of hydrological response to tree planting in the Calroust catchment may by possible given the larger proportion of catchment area covered relative to other catchments (10.3%; Table 1).

Other measures so far installed (ELJs, flow restrictors, bank protection measures and a hedgerow) are also unlikely to affect peak flows at the catchment scale. Managing run-off at its source on high slopes and in valley floor pathway zones by altering land use to forest cover is likely to be the most effective means of attenuating flows but current land use restricts the potential for this.

Given the dominance of grazing land use, the best way to increase forest cover is by liaison with farmers to identify less productive areas coupled with appropriate financial incentives. Although good progress has been made, the last 5 years have shown that encouraging and incentivizing farmers to give up land for trees is challenging.

River geomorphology

Key findings

The Bowmont Water is well known as a highly active wandering gravel bed river. Over the 4 year monitoring period, the channel has alternated between long periods of stability due to extended low flows and sudden large changes in response to floods. Quiescent phases have led to channel area shrinkage as vegetation has rapidly colonised margins and gravel bar deposits. Floods have widened channels, created avulsions (sudden changes of channel course) and caused sediment build up in the wandering channel environments characteristic of the Bowmont mainstem.

In all three regular monitoring reaches (Elm Sike, Kelsocleuch Burn and Swindon Haugh), a net gain of sediment has occurred over the four years which may in part reflect the measures installed with the exception of the Kelsocluech Burn site. However the natural controls (sediment supply, valley slope and width) are likely to be more important; the sites investigated appear to be operating as sediment sinks. More widely, the sudden changes to channel cross section recorded at nearly all the flow level monitoring stations over the four year monitoring period show how changeable the morphology is at all scales of river.

Previously, the relatively high dynamism of the Bowmont Water and the young age of the floodplain have been identified (McEwen, 1985). However, detailed understanding of coarse sediment dynamics is poor in the Bowmont catchment. Riverbank and floodplain sediments are readily eroded given their poorly consolidated nature and the lack of mature riparian vegetation that provides natural reinforcement. Coarse sediments lining the riverbed tend to be poorly sorted and contain a large proportion of sand that may lower the threshold for gravel transport (Church and Ferguson, 2015). Combined with the weak riverbanks, these factors may make river morphology particularly sensitive to change.

The distinctive nature and transport of coarse sediment in the Bowmont catchment may partly reflect the underlying geology. Previous work has shown the importance of lithology in determining sediment supply rates and river morphology (Mueller and Pitlick, 2013); softer volcanic rocks like the andesite found in the Bowmont catchment, tend to break down into finer particles than other more resistant rock types like granite. Further investigation and comparison with other rivers would help to shed light on the thresholds, rates and styles of river change in the Bowmont.

Implications for NFM and coarse sediment management

The sensitive nature of the riverbed and banks means that any measures installed within the river corridor are susceptible to scour and washout or being bypassed due to channel course change. This means that measures like log jams, novel bank protection engineering or measures untested here, like bunds or ponds, are liable to damage. Careful placement of installations is needed to ensure their effectiveness whilst at the same time accepting that regular monitoring and maintenance are required.

The dynamic nature of the Bowmont Water and its tributaries means that sediment management measures like dredging are unlikely to be effective either for controlling sediment movement or flood risk. The re-alignment of the Swindon Haugh reach in 2010 was followed by rapid regrowth of gravel bars and change of channel course in the September 2012 flood. This shows that such efforts are unlikely to be beneficial for reducing local flood risk, confining water along one route or reducing the onward movement of sediment as sediment stores are quickly replenished by sources from upstream.

Wherever possible, less productive areas that coincide with sediment input and dynamic zones, should be considered for tree planting with appropriate species and livestock exclusion to reduce coarse sediment input and stabilise riverbanks (Orr and Carling, 2006; Lane et al., 2008).

Effectiveness of wooden structures

Key findings

Over the monitoring period, the structure effectiveness and stability have varied. Significant sediment deposition (> 0.3 m) was associated only with a limited number of bar apex ELJs structures (5 out of 45 structures), with deposition restricted to Swindon Haugh and mostly in response to the September 2012 flood event. This partly reflects the placement locations and the small size of the structures which together limited their effectiveness (on floodplains and on stabilising gravel bars away from the deeper areas of river channel). Trees planted within the bar apex ELJ structures to improve sediment capture and stabilisation had a poor survival rate (14 of 45) owing to poor growing conditions (livestock grazing pressure, displacement by floods or soil condition).

The lower rate of bank erosion at Kelsocleuch bank protection ELJ reach tentatively suggests the structures were effective at reducing riverbank erosion although recently observed removal of backfill and bank vegetation suggests their effectiveness may have been lost. The greater lateral resistance created by one of the structures has led to significant toe scour and the formation of a deep channel.

The hydraulic and sediment capture effects of the Elm Sike flow restrictor structures were minor due to their limited channel blockage. Blockage of flow occurred only during high flows (i.e. approximately bankfull or greater) and together with the steep, confined nature of the channel, reduced the likelihood of backwater effects and flow attenuation. This combined with the lack of physical blockage of bedload fluxes (i.e. there is a gap under each structure allowing onward movement of sediment), limited sediment capture effectiveness.

The stability of all types of wooden in-channel structures is an important consideration as displacement could partially block channels or bridges leading to increased local flood risk and damage to infrastructure. The risk of complete blockage was lessened due to the small scale of the timbers used in the structures but should be considered. Over the last 5 years the stability of the majority of structures was good during testing flood conditions (but smaller than the 2008 and 2009 floods). However the loss of some bar apex log jams (5 out of 45), complete displacement of four bank protection structures at the Irish Bridge near Calroust and the timber palisade structure near Clifton during the September 2012 flood showed the vulnerability of wooden installations if not properly designed and constructed.

Implications for NFM and coarse sediment management

ELJ and other wooden structures can be useful for dealing with coarse sediment problems (e.g. Brooks et al., 2004), creating habitat (e.g. Langford et al., 2012) and attenuating flows (Thomas and Nisbet, 2012). Using these structures in dynamic river environments like the Bowmont will always pose risks of failure to meet such management objectives. Failure is possible if structures are displaced or damaged by floods and bypassed by channel movement. Even if structural stability is maintained, if the placement is inappropriate to capture sediment, structures can fail in terms of function as demonstrated by ELJs placed in floodplain areas which captured very minor amounts of sediment. The model-based ELJ stability and function design approach outlined by Brooks et al., (2006) should in future be used to inform future construction (especially in mainstem settings like the Bowmont Water) – to optimise structure stability and effectiveness. Care should also be taken in order to allow migratory fish to safely pass in-channel structures (none of the features in the Bowmont pose a barrier to fish).

ELJs and other wooden structures should not be used in isolation as they tend to deal with symptoms of a problem (e.g. high rates of sediment transport related to high catchment runoff and extensive eroding riverbank sediment sources). Carefully designed and placed wooden structures should be included in a suite of measures (e.g. improved land management and targeted tree planting of sediment source zones) that tackle runoff and sediment problems directly.

Recommendations for future construction using the structure designs monitored are as follows:

Bar apex ELJS: Place structures in area of sediment transport (i.e. avoid placing on floodplains where their function is lost) and increase the density (i.e. make the structures more complex and less porous) and size of the structures relative to river size if possible to increase their hydraulic and geomorphic effects.

Kelsocleuch riverbank protection ELJ: Consider first if a riverbank needs to be protected with such a structure. Riverbank erosion is an expected and natural process that allows rivers to accommodate water and sediment inputs. If riverbank protection is needed, tree planting and soft bank protection measures may be more effective and sustainable. If structural reinforcement is needed, ensure that backfill is put back into place properly and ideally manage grazing pressures so that vegetation can grow and reinforce the bank further. Also, consider instead structures that are designed to deflect flow away from riverbanks which may be more effective.

Elm Sike flow restrictors: These types of structures may capture sediment and attenuate flow more effectively in less steep channels with wide floodplains. Increasing the degree of channel blockage would increase their hydraulic interference which could translate into delayed time to peak and discharge attenuation. Sediment capture effectiveness may also improve. However consideration needs to be given towards maintaining fish passage.

Monitoring of wooden structures

Monitoring of the three different structure designs should continue in the Bowmont catchment as knowledge on the long term effectiveness of in-channel wooden structures – needed to inform design and placement strategies in the future – is still limited. Specifically, knowledge of structure durability (in relation to wood decay or displacement) and associated geomorphic and hydraulic effects over 10 years or beyond is limited in a UK context. In the Bowmont catchment, responses are mainly driven by the frequency of floods; monitoring over the next 5 years increases the chances detecting the individual and cumulative effects of multiple floods.

References

Abbe TB and Montgomery DR. 1996. Large woody debris jams, channel hydraulics and habitat formation in large rivers. Regulated Rivers: Research & Management 12: 201–221.

Addy, S., and Wilkinson, M. (2016). An assessment of engineered log jam structures in response to a flood event in an upland gravel-bed river. Earth Surface Processes and Landforms 41(12, 1658-1670.

Bathurst, J. 1997. Environmental river flow hydraulics. *Applied Fluvial Geomorphology for River Engineering and Management, edited by CR Thorne, RD Hey, and MD Newson,* 69-93.

Brooks AP, Gehrke PC, Jansen JD, Abbe TB. 2004. Experimental reintroduction of woody debris on the Williams River, NSW: geomorphic and ecological responses. River Research and Applications 20: 513–536. DOI:10.1002/rra.764.

Brooks AP, Abbe T, Cohen T, Marsh N, Mika S, Boulton A, Broderick T, Borg D, Rutherfurd I. 2006. Design Guideline for the Reintroduction of Wood into Australian Streams. Canberra: Land & Water Australia.

Church, M. and R. Ferguson (2015). Morphodynamics: Rivers beyond steady state. Water Resources Research 51(4): 1883-1897.

Langford T, Langford J. and Hawkins S. 2012. Conflicting effects of woody debris on stream fish populations: implications for management. Freshwater Biology 57: 1096–1111.

MNV Consulting. (2010) Bowmont-Glen catchment initative, Report to the Tweed Forum.

McEwen, L. J. 1985. River channel planform changes in upland Scotland with specific reference to climatic fluctuations and land use changes over the last 250 years, unpublished PhD thesis, University of St. Andrews.

Mueller, E. R. and J. Pitlick (2013). Sediment supply and channel morphology in mountain river systems: 1. Relative importance of lithology, topography, and climate. Journal of Geophysical Research: Earth Surface 118(4): 2325-2342.

Oughton E., Passmore D.andDilley L. 2009. Cheviots Flood Impact Study. Centre for Rural Economy. Newcastle University.

Quinn, P.F., O'Donnel, G.M., Nicholson, A.R., Wilkinson, M.E, Owen, G., Jonczyk, J., Barber, N.J., Hardwick, M. and Davies G. (2013) Potential Use of Runoff Attenuation Features in Small Rural Catchments for Flood Mitigation. *Belford catchment report*. Newcastle University

SEPA (2016). Natural Flood Management Handbook.

Tipping R. Bowmont: An Environmental History of the Bowmont Valley and the Northern Cheviot Hills, 10,000 BC - AD 2000. Edinburgh: Society of Antiquaries of Scotland, 2010.

Werritty A, Leys KF. 2001 The sensitivity of Scottish rivers and upland valley floors to recent environmental change. Catena 42, 251-273.

Wilkinson, M.E., Quinn, P.F., Hewett, C.J.M., 2013. The floods and agriculture riskmatrix: a decision support tool for effectively communicating flood risk from farmed landscapes. Int. J. River Basin Manage. 11 (3), 237–252.