



HAL
open science

Geomorphological evolution and ecological response of the River Ehen to the reconnection of a headwater tributary

Baptiste Marteau

► **To cite this version:**

Baptiste Marteau. Geomorphological evolution and ecological response of the River Ehen to the reconnection of a headwater tributary. Geography. University of Aberdeen, 2017. English. NNT: . tel-04648699

HAL Id: tel-04648699

<https://hal.science/tel-04648699v1>

Submitted on 17 Jul 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

GEOMORPHOLOGICAL EVOLUTION AND ECOLOGICAL RESPONSE OF THE RIVER EHEN TO THE RECONNECTION OF A HEADWATER TRIBUTARY



Baptiste Marteau

MSc River Restoration & Management
(IMACOF) University of Tours, France

*A thesis presented for the degree of Doctor of Philosophy at the University of Aberdeen,
School of Geosciences*

Under the supervision of:

Prof. Chris Gibbins
Prof. Ramon J. Batalla
Dr. Damià Vericat

December 2017

Cover photos:

- *Top: Ben Gill and its confluence with the River Ehen, just downstream of Ennerdale Water – view from the fell (Photo: Baptiste Marteau, August 2016)*
- *Bottom left: A ‘young’ freshwater pearl mussel from the River Ehen (Photo: Baptiste Marteau, June 2015)*
- *Bottom centre: Larva of Ecdyonurus sp., collected from Croasdale Beck (Photo: Baptiste Marteau, May 2015)*
- *New deposition feature in the riffle, situated c. 100 m downstream from the confluence (Photo: Baptiste Marteau, May 2016)*

AUTHOR'S DECLARATION

I declare this thesis is the result of my own work and any contribution or information used from others has been explicitly cited. It is being submitted for the degree of Doctor of Philosophy in Geography at the University of Aberdeen and it has not been submitted for any other degree or examination in any other University or institution.

A handwritten signature in black ink, appearing to read 'Baptiste Marteau', with a long horizontal stroke extending to the right.

Baptiste Marteau

Aberdeen, December 2017

“A thing is right when it tends to preserve the integrity, stability, and beauty of the biotic community. It is wrong when it tends otherwise.”

Aldo Leopold, 1948

TABLE OF CONTENTS

Author’s declaration	ii
Table of contents	iv
Acknowledgments	x
Summary	xiii
Chapter 1. Introduction.....	2
1.1. Thesis outline.....	2
1.2. Background and rationale.....	2
1.3. The River Ehen.....	8
1.3.1. Catchment.....	8
1.3.2. Climate and hydrology.....	8
1.3.3. The freshwater pearl mussel in the Ehen.....	12
1.3.4. Restoring Sustainable Abstraction to Cumbrian rivers.....	13
1.4. Restoration Programme and efforts towards improving the river’s conditions.....	15
1.5. Aims, Objectives and structure of the thesis	18
1.6. Fieldwork design and overview of methods	21
1.6.1. Capturing geomorphic changes in Ben Gill	21
1.6.2. Monitoring the effects on fine sediments dynamics	21
1.6.3. Assessing geomorphic adjustments in the Ehen.....	21
1.6.4. Linking bed disturbance, invertebrate grazing and the abundance of biofilm ...	22
1.7. References	23
Chapter 2. Application of Structure-from-Motion photogrammetry to river restoration	31
2.1. Abstract.....	31
2.2. Introduction	32
2.3. Digital Photogrammetry: workflow and its application to river restoration.....	34
2.3.1. Study area and context.....	34

2.3.2.	Data acquisition	36
2.3.3.	Data processing.....	39
2.3.4.	Error analysis.....	42
2.4.	Evaluating geomorphic responses to river restoration: the case of Ben Gill and the River Ehen	43
2.4.1.	High resolution orthophotos.....	43
2.4.2.	Surface and roughness models.....	44
2.4.3.	Geomorphic change detection	48
2.4.4.	Sediment budget	52
2.5.	Discussion	52
2.5.1.	Application of the workflow to Ben Gill.....	52
2.5.2.	Wider relevance.....	55
2.6.	Concluding remarks.....	56
2.7.	List of abbreviations	56
2.8.	Reference list.....	58
Chapter 3.	The importance of a small ephemeral tributary for fine sediment dynamics in a main-stem river	63
3.1.	Abstract.....	63
3.2.	Introduction	64
3.3.	Study area	66
3.4.	Methods.....	68
3.4.1.	Rainfall and discharge.....	68
3.4.2.	Suspended sediment	69
3.5.	Results.....	70
3.5.1.	Hydrological context.....	70
3.5.2.	Variations in suspended sediment transport.....	72
3.5.3.	Contribution of the tributary to main-stem sediment loads.....	74

3.5.4.	Links between fine sediment dynamics and flow regime	76
3.6.	Discussion	77
3.6.1.	Context	77
3.6.2.	Sedimentary effects of the reconnection in the Ehen	78
3.6.3.	Implications	80
3.7.	Final remarks	82
3.8.	Reference list	83
Chapter 4.	Asynchronicity of fine sediment supply and its effects on transport and storage in a regulated river	88
4.1.	Abstract	88
4.3.	Introduction	90
4.4.	Material and methods	92
4.4.1.	Study area and context	92
4.5.	Data acquisition and monitoring	95
4.5.1.	Discharge and flow conditions	95
4.5.2.	Suspended sediment	95
4.5.3.	In-channel fine sediment storage	97
4.5.4.	Data processing and analysis	98
4.6.	Results	100
4.6.1.	Hydrological conditions	100
4.6.2.	Suspended sediment transport	103
4.6.3.	In-channel sediment storage	106
4.6.4.	Sediment budgets	114
4.7.	Discussion	115
4.7.1.	Flows and suspended sediment dynamics	115
4.7.2.	In-channel sediment storage	116
4.7.4.	Fluvial sediment budget and sources of material	119

4.7.5.	Management perspective	120
4.8.	Final remarks	121
4.9.	Reference list	123
Chapter 5.	Geomorphological adjustments in response to system-scale restoration	128
5.1.	Abstract.....	128
5.2.	Introduction	129
5.3.	Study context and area	131
5.4.	Materials and methods	134
5.4.1.	Hydrological context.....	134
5.4.2.	Coarse sediment supply	134
5.4.3.	Assessment of sedimentary changes in the Ehen.....	138
5.4.4.	Changes in bed topography	141
5.4.5.	Flow Hydraulics.....	143
5.4.1.	Data analysis	144
5.5.	Results.....	146
5.5.1.	Hydrological context.....	146
5.5.2.	Flow Hydraulics in the Ehen	147
5.5.3.	Bed material fluxes from Ben Gill	148
5.5.4.	Evolution of the confluence bar.....	150
5.5.5.	Changes in bed surface grain size distributions in the Ehen	154
5.5.6.	Particle mobility in the Ehen	158
5.5.7.	Reach-scale topographic changes at the River Ehen	165
5.6.	Discussion	166
5.6.1.	Context	166
5.6.1.	Key findings	167
5.6.2.	Methodological issues.....	174
5.7.	Final remarks	175

5.8. Reference list	177
Chapter 6. The ecological consequences of flow regulation in the Ehen: flow competence, bed disturbance and implications for the interaction between primary producers and grazers.....	184
6.1. Abstract.....	184
6.2. Introduction	185
6.3. Methods.....	187
6.3.1. Study area	187
6.3.2. Sampling design	189
6.3.3. Water chemistry	191
6.3.4. Bed disturbance.....	191
6.3.5. Macroinvertebrates.....	193
6.3.6. Benthic algal biomass	193
6.3.7. Data analysis	194
6.4. Results.....	196
6.4.1. Hydrology and stream power	196
6.4.2. Bed disturbance, GSDs and relationships with stream power	199
6.4.1. Water chemistry	200
6.4.2. Abundance and composition of the algal community.....	201
6.4.1. Macroinvertebrate assemblages and feeding groups.....	203
6.4.2. Correlations between invertebrate abundance and feeding groups, and between invertebrates and algae.....	205
6.4.3. Environmental controls on algae	207
6.5. Discussion	209
6.5.1. Environmental differences between the two rivers: effects of the regulation.	209
6.5.2. Ecological difference between the two rivers: also the effect of regulation? ..	211
6.5.3. What controls algal biomass and community composition in the River Ehen?	213
6.6. Final remarks	214

6.7. Reference list.....	216
Chapter 7. Synthesis and Conclusions	223
7.1. Context.....	223
7.2. General research approach	224
7.3. Main scientific findings	227
7.4. Appraisal of the success[es] (and failure[s]) of the restoration project	239
7.4.1. Implication of adjustments in channel morphology and processes for the freshwater pearl mussel.....	239
7.4.2. The restoration project	243
7.5. Beyond the restoration: functioning of the Ehen and other fluvial systems	248
7.6. The future of the freshwater pearl mussel in the Ehen	249
7.7. Conclusions.....	250
7.8. Reference list.....	252
Appendix.....	261

ACKNOWLEDGMENTS

This PhD thesis was financially supported by the Environment Agency and United Utilities, whose support is gratefully acknowledged.

I am forever grateful to my three supervisors for providing me the opportunity to do this PhD; Chris Gibbins, Ramon Batalla and Damià Vericat. First, thank you Chris, for your amazing support and guidance throughout the entire process, for always having your door open when I had questions and doubts, for your patience when trying to explain statistics, for your availability at any time of the day, week or year, for running down some remote Malaysian village at 5 in the morning looking for internet signal to answer my e-mails... Thank you, Ramon, for your amazing ability to make complicated things very clear and simple with just a pen and a white board, for the field-based lectures on fluvial geomorphology, turning stones and water into real stories, for your long replies to my 'always-too-long' e-mails, and for always making me feel welcome in Lleida... And Damià, thank you for always finding the right encouraging words, for patiently answering several times the same questions, for sharing your creativity and ideas to foster more and more discussions, for boosting everybody with your energy and enthusiasm, and for finding the time to break for a coffee (or a beer) despite your busy schedule... Thank you all for sharing your knowledge and enthusiasm for your fields. I feel lucky to have been part of this multidisciplinary team which allowed me to learn so many different things. I shall never forget these 3-hour skype calls which, I must admit, never quite ended as expected...

I would also like to thank all the past and present colleagues and friends of the Northern Rivers Institute. Special thanks to those who have shared an office with me; Jon Dick, Maria Blumstock and Claire Tunaley in my early days; Bernhard Scheliga, Luca Fabris, Bas Buddendorf, Aaron Neill for the longest part of the journey; and Thea Piovano and Katya Dimitrova who have embarked more recently... Thank you also to the other members of the group, Jean-Christophe Comte, Samson Oiro, Pertti Ala-Aho, Matthias Sprenger, Hailong Wang, Lucile Verrot, Sylvain Kuppel and Aaron Smith. Thank you also to Josie Geris, especially for taking on some administrative tasks. Thank you all for your company, your help with R and Matlab, or fieldwork equipment, the numerous cakes and coffees, and the great fun in and out of the office. And special thanks to the 'Friday lunch run' team; I hope you guys keep on running! I would also like to extend my gratitude to Audrey Innes. Thank you for your precious help on so many

occasions, for taking good care of us all in the group, for nice chats in the lab, and for your great sense of organisation. I don't know what the department would do without you!

Thank you also to the French interns, Justine, Claire, Emilie, and Léa for their help in the field during summers. I hope experiencing 'summer' on the west coast has not washed out your enthusiasm too much!

All these pages wouldn't have been written without the support from all the people from the Environment Agency and United Utilities; Grace Martin, Kat Liney, Helen Reid, and particularly Gail Butterill and Jane Atkins. Your involvement and dedication to this project, and to your job more generally, were the best fuel for motivation. Thank you also to Dan Atkins for his help with the invertebrate samples, Andy Newton for his help with the calibration of the turbidity-metres.

I owe the knowledge I have gained on the pearl mussel ecology to the many specialists I have met at meetings and during fieldwork. Thank you Ian Killeen and Evelyn Moorkens for all your explanations about the pearl mussel. Thank you also Mike Farrell, Diane O'Leary and Gavin Measures for taking me along on a mussel survey. Thank you also to the staff of the Freshwater Biological Association for their detailed tour of their Ark project facilities! Thank you also to Martyn Kelly, Maria Snell and Ben Surridge for accepting a collaborative work on the 'algal issue'. And of course, thank you David Green for driving all the way to the lakes on many occasions for just a few minutes of fun with a drone.

My sincere gratitude to Bill Arnott and all the team from the Cumbria County scout camp in Ennerdale Bridge. Thank you for letting me stay in the Bothy, and for being so accommodating with my last-minute requests and late arrivals during fieldwork. I cannot imagine what these years of work on the river would have been without your help.

I cannot forget the person who got me in Aberdeen in the first place, Benoît Demars. Thank you for your trust and confidence, for inviting me over to work with you at the James Hutton Institute for a while, for sharing your passion for ecology, and for providing me with a bed and a meal during my first weeks in Scotland. I wish you, Jo and the boys all the best for your new life overseas!

¡Moltes gràcies al grup de RIUS! Thank you everyone in Lleida for having me in your group for a few days, weeks or months: Gemma Piqué, Éfren Muñoz, Manel Llena and particularly Maria

Béjar. Thank you for accompanying me through this whole process, although most the time from (warm) Spain. It was a pleasure to “share the supervisors” with you! Thanks for hosting me during my visits to Lleida, and also for all these conferences we attended together!

I am also grateful to all the visitors we have had in Aberdeen, and especially my family, who had to put up with me talking about mussels, pebbles and beasties for hours... Thank you, Mum, Dad, and all my brothers and sister, for your support, help and encouragements, and for trying your best to decrypt my always too-long and too-complex explanation about ‘what it is that I do’. And many thanks, Germain, for your short-lectures on SQL and database management in R!

Finally, I am deeply indebted to Marion, for her patience and understanding when facing the too-frequent ‘*I might need a wee bit more time...*’. Thank you for sacrificing your Friday nights out to help me picking invertebrates in the lab, for coping with my last-minute fieldwork plans and proof-reading parts of this thesis. Your love and encouragements meant everything to me.

Ta!

SUMMARY

Freshwater ecosystems are amongst the most threatened in the world. They have been -and still are- altered by a wide range of human activities; from damming, dredging, mining and diversion, to water abstraction, pollution and over-exploitation of sediment and biota. Later recognition of the important ecosystem services provided by rivers, wetlands and floodplains, triggered a need for the restoration and rehabilitation of degraded freshwater systems. The protection and conservation of endangered species has been a particular focus of efforts.

The River Ehen, in Northwest England, is one such restoration initiative. The river is naturally regulated by a post-glacial lake, but its exploitation for water abstraction led to the construction of a weir and the diversion of a headwater tributary (several decades ago) that previously discharged just downstream from the lake outlet. Ben Gill is a first order ephemeral tributary whose diversion halted the natural transfer of water and sediments into the main-stem Ehen. This had an impact on the natural behaviour of the system and conditions in the river deteriorated. In the early 2010s, concerns were voiced about the consequences of habitat deterioration for the survival of the freshwater pearl mussel (*Margaritifera margaritifera* L.). This endangered species is present in high densities in the upper Ehen; in fact, the Ehen hosts the largest remaining population of England. In response to these concerns, the Environment Agency decided to review the water abstraction licence and restore natural sediment dynamics in the river by reconnecting the 'lost' tributary, Ben Gill.

The objective of the restoration is rather simple in its aim, but complex in its application: restore physical habitat to sustain the pearl mussel population. This thesis focuses on evaluating the changes to fluvial processes and resulting physical habitat in response to the restoration actions and assessing whether these were in line with what we know is suitable for pearl mussels. It sits on the back of preliminary efforts to characterise the pre-restoration conditions of the River Ehen.

The reconnection of Ben Gill is the centre-piece of this restoration, so it was crucial to monitor its evolution in order to assess the volumes and frequency of sediment delivery into the Ehen. Because the stream is ephemeral, it was possible to capture its topography under dry conditions, using Structure-from-Motion (SfM) photogrammetry. This technique is becoming common-place in fluvial geomorphology, but this thesis presents the first example of its application within a river restoration context. Aerial images were collected from a small UAV

and used to generate 3D models of the channel topography. Successive topographic models were then compared to determine the volumes of erosion and deposition within the channel and infer a minimum volume of export to the Ehen. Additionally, given the relatively small size of the channel (300 m long) and the possibility to install a dense network of ground control points (necessary to properly geo-reference SfM photogrammetry outputs), it was possible to test and determine the potential of using a camera with a fish-eye lens, often criticised as unsuitable for SfM photogrammetry. The results showed that SfM photogrammetry can be applied using a fish-eye camera, given appropriate calibration, assessment of errors and bespoke ground control point network. Model accuracy was consistent over time and the quality high enough to accurately capture the geomorphic evolution of the channel. Confidence in the results was improved by the unexpectedly large scale of the changes observed. These changes meant that large volumes of sediment were exported from Ben Gill and deposited in the Ehen from the early days of the opening of the channel.

As part of monitoring related to the reconnection, the Environment Agency installed a series of turbidity meters in the Ehen which, after empirical field-based calibration, provided time-series of suspended sediment concentrations. It was thus possible to assess the changes in the dynamics of suspended sediments in relation to the reactivation of its headwater sub-catchment. By comparing 2 years prior to and 2 years following the reconnection, it was possible to characterise the role played by this small, ephemeral but highly dynamic tributary in driving suspended sediment dynamics in the regulated Ehen. On average, the suspended sediment load increased by 65% following the reconnection (i.e. for an increase in catchment size of 1.2%), with most transport occurring through short but intense flow events. This was of particular interest from a geomorphic process perspective, since most studies of ephemeral streams are concentrated in arid or Mediterranean regions; little is known about their relative influence in temperate climate regions. A significant finding from a management perspective is that the increased suspended sediment loads in the Ehen –if left unchecked– may threaten mussels and counter other positive changes resulting from the reconnection.

Although mussels can cope with short-lived high suspended sediment events, they are highly vulnerable to the deposition and accumulation of fines on the riverbed. This is particularly true for the juveniles that live buried in the top layer sediment for the first few years of their life. Thus, in-channel fine sediment storage was monitored for over 2 years in the Ehen to assess the effects that the increased suspended sediment loads had on mussel habitat. Analysis of the

timing of flows in the Ehen compared to those in Ben Gill revealed that in-channel storage was controlled by the degree of synchronicity between the two streams. High deposition occurred when Ben Gill was connected but flows did not spill over the weir, while the removal of fines was only observed for very high discharges in the Ehen. As with suspended sediment loads, the storage of fines in the riverbed increased following the reconnection.

The geomorphic adjustments in the Ehen in response to the newly restored delivery of coarse sediment from Ben Gill was assessed by looking at changes in grain size distribution, surface particle mobility and cross-sectional topography. A large fraction of the material exported from Ben Gill accumulated at the confluence, forming downstream a continuously growing depositional bar. Using the same SfM photogrammetry technique used for Ben Gill, the growth and role of the depositional bar as a transient storage were assessed. It appears, at least in the first two years following the reconnection, only a relatively small fraction of material deposited on the bar is actually re-mobilised and conveyed downstream in the Ehen; most deposits remain on the bar which consequently has kept growing in size. Nevertheless, topographic surveys have confirmed visual observations of deposition in the first 300 m downstream from the confluence, notably a new lateral bar on the true right bank. Other areas have been subject to erosion. Grain size distribution has also changed in the most active morphological units, with an overall trend towards a fining of the bed texture. Surface particle mobility has increased since the reconnection, but still remains rather limited despite the occurrence of very high flows during the period of this study. Nevertheless, this increase in mobility is significant in the two most active morphological units and, along with the observed changes in topography, bode well for a continued improvement of conditions in the future.

The hydraulic and geomorphic changes observed in the Ehen as a result of flow regulation and the diversion of Ben Gill are thought to have facilitated excessive growth of algae on the river bed. To investigate this, a 13-month study of the factors potentially influencing algal growth, including the abundance of grazing invertebrates, was undertaken. Monthly surveys were undertaken at two sites in the Ehen and two in Croasdale Beck, an unregulated tributary of the Ehen. This work emphasised the different temporal dynamics of algal growth in the Ehen compared to Croasdale. Algal abundance, represented using total chlorophyll-*a*, varied according to the magnitude of bed disturbance in the period preceding sampling dates. Invertebrate communities differed between the Ehen and Croasdale, largely reflecting changes in the abundance of different functional feeding groups. Generalised Estimating Equations

suggested some of the variation in total algal abundance (chlorophyll-*a*) could be accounted for by grazer abundance. However, ordination-based analysis of the composition of the algal community suggested more complex interactions, with environmental controls (flow hydraulics, nutrients, bed stability) more important than simply grazing pressure.

The reconnection of Ben Gill to its main-stem Ehen is a unique example of non-invasive catchment-scale restoration initiative of an upland river. In this sense, it differs from some rehabilitation projects whose actions are limited to things such as artificial gravel augmentation, the installation of deflectors or other in-channel features, or in some cases the 'landscape gardening' of a target reach. The focus of the Ehen project is on restoring fluvial processes which, in turn, will help achieve the objective of improving physical habitat for the pearl mussel. Although proper assessment of the response of the pearl mussel population to the restoration will require more time and investigation, the primary goal of the reconnection has been achieved; the natural delivery of coarse sediments has been reactivated and material is being conveyed downstream the upper Ehen, creating new geomorphic features and increasing habitat diversity. As is the case with any restoration or rehabilitation project, there has been uncertainty and unpredictability as to how the tributary might behave and how the river might respond. The primary and most worrying manifestation has been the marked increase in fine sediment loads. Given the sensitivity of the focal species, these high loads have been a cause for concern for the government agencies and conservation groups involved in the project. This has raised interesting questions about the possible need for intervention, though for the moment the decision has been made to simply monitor how the situation evolves. This and all other elements of the reconnection have ensured that the restoration of the Ehen has been an invaluable learning experience from a management perspective, and especially regarding the role of monitoring to help assess river response and the achievement of target objectives.

CHAPTER 1.

INTRODUCTION



*Ennerdale Water, before the reconnection of Ben Gill.
Photo: Baptiste Marteau, August 2014.*

CHAPTER 1. INTRODUCTION

1.1. THESIS OUTLINE

This thesis presents the work and summarises the scientific findings of the PhD research in 7 chapters. Chapter 1 provides an introduction to the geographic and historic context of this study, and develops the scientific rationale behind the project. Chapters 2 to 5 are the main ‘results’ chapters and form the core of the thesis. They are formatted as scientific publications and can thus be read more or less independently. Chapters 2 and 3 are already published (Marteau et al. 2016, 2017), and chapter 4 is currently under review. Chapters 5 and 6 will be submitted in the near future. Finally, Chapter 7 discusses and synthesises the main findings of the work and concludes with proposals for further research and sustainable catchment management in the Ehen. The reader is referred to section 1.5 for the specific aim and objectives of the thesis and chapters.

1.2. BACKGROUND AND RATIONALE

It is widely accepted that, given the widespread alteration of natural systems, conservation measures alone will not support ecosystem functions and services (Hilderbrand et al. 2005). The majority of rivers are managed to suit human activities, such as water abstraction (for agriculture, commercial use or public supply), recreation, flood control, gravel mining and energy production, between many others (Kondolf 1997; Millenium Ecosystem Assessment 2005). These alterations threaten the provision of natural services from fluvial ecosystems, not only related to water quality and quantity but also non-extractive benefits such as self-purification, flood-plain expansion, or cultural services (Petts 2007; Costanza 2012). Given the limits of conservation, our dependence on healthy ecosystems has made the need for restoration unavoidable.

The hydromorphological degradation of rivers compromises their ecological integrity (Petts 2007; Friberg et al. 2009). The response of river channels to human alterations is complex in its scale and temporality (Petts 1980) and not entirely predictable from universal principles (Grant 2012). For instance, a long period may elapse before a river channel reaches any sort of equilibrium following the construction of a dam (i.e . relaxation period, as per Petts and Gurnell 2005). This slow rate of environmental responses needs also be considered when efforts are made to restore river systems.

Early examples of river restoration arose in relation to water quality (see references of pioneer studies in Ormerod 2004), such as organic pollution, eutrophication and release of toxic substances (Jähnig et al. 2011). In the 1980s and 1990s, the interest shifted towards a broader focus on ecosystem restoration, considering ecological, hydrological and morphological conditions (Ormerod 2004; Dufour and Piégay 2009). Restoration was long based on the principle of returning to a static pre-disturbance state, but in the mid-90s, different definitions of ‘restoration’ emerged from the increasing interest of scientists for the subject (Dufour and Piégay 2009). The term ‘restoration’ remained attached to the concept of a return to pre-existing state, free from human disturbance and alteration, along with its pre-disturbance biotic and abiotic functionalities (Aronson et al. 1993; Wohl et al. 2005; Brierley and Fryirs 2008). However, some authors recognised the futility, in some cases, of attempting to re-establish a reference state (Stanford et al. 1996; Hilderbrand et al. 2005; Palmer et al. 2005). Indeed, many human changes to aquatic ecosystems are irreversible or only partially reversible (Jungwirth et al. 2002). Under such circumstances, efforts to manage or change a river from a degraded state to an improved state, with higher functionalities and ecosystem services, should be targeted; this was termed ‘rehabilitation’ (Brierley and Fryirs 2008). It is generally acknowledged that rehabilitation may be subject to high uncertainties and with time-limited benefits (Brooks et al. 2006; Wheaton et al. 2010a) since there may be little opportunities to remove all the causes of degradation (Hendry et al. 2003; Wohl 2005). Under prevailing conditions, efforts for the rehabilitation of rivers may actually entail the creation of a ‘new’ state (Brierley and Fryirs 2005).

The terminology used to characterise a project and its objectives is important to ensure common understanding between the different actors (Dufour and Piégay 2009) and to prevent the misuse and appropriation of the vocabulary for other means. Indeed, the term ‘restoration’ has gained a political and marketing value over time, so that projects involving a continued degradation and human use of a river are sometimes labelled as ‘restoration projects’. This is the case for instance of riverbank stabilisation (Gillilan et al. 2005) and other constructions of waterfront protective and recreative infrastructures (Palmer et al. 2005). Similarly, the definition of the success of a project is very much dependent on how success is assessed. When no ecological objectives are defined *a priori*, it is likely that a project will be considered successful if it is implemented as designed (Alexander and Allan 2007; Jähnig et al. 2011).

River restoration and rehabilitation are intrinsically subject to uncertainty (Wheaton et al. 2008) which sometimes fails to be recognised (Hilderbrand et al. 2005). Difficulties may arise in defining

objectives of rehabilitation due to the complex and non-linear trajectories that characterise natural fluvial systems (Petts 1980; Ward et al. 2001; Dufour and Piégay 2009). In these conditions, evaluating the success of river restoration is also challenging. A project should be primarily judged on its 'ecological' success, i.e. hydrological, geomorphological and biological conditions (Palmer et al. 2005). However, it is also important to consider other aspects of the value of a rehabilitation project, and in particular the social dimension (Morandi et al. 2014). Palmer et al. (2005) argue that the success of a restoration project should be evaluated not only from the 'ecological benefits' but also from a 'stakeholder' (i.e. aesthetics, costs, achievement of objectives) and 'learning experience' (i.e. education, scientific and technical experience) point of view (Alexander and Allan 2007).

The definition of objectives is important to assess the potential success of a project (Bradshaw 1996; Boon 1998; England et al. 2008). However, these objectives need to build on an accurate understanding of the system and its processes. Poor appraisal of broader scale interactions is the reason for the failure of many rehabilitation projects (Roni et al. 2008). This was referred to as 'The myth of the cookbook' by Hilderbrand et al. (2005); a successful rehabilitation experience cannot necessarily be applied elsewhere as similar-looking systems may exhibit considerable differences in variables that regulate slow processes (e.g. carbon storage, sediment production). Mistargeted or overambitious objectives can be prevented by making the best use of local knowledge. Although they may be non-specialists, staff from local government agencies develop considerable knowledge of their systems which is highly valuable in the decision-making process (Kelly 2014).

Another issue preventing the accurate evaluation of success or failure of river restoration is the lack of pre-restoration monitoring (Jungwirth et al. 2002; Bernhardt et al. 2005; Palmer et al. 2005; Bernhardt and Palmer 2011; Friberg et al. 2011; Pander and Geist 2013) and of systematic and objective assessments of completed projects (Kondolf et al. 2007). Pre-restoration evaluation is essential when defining project objectives, and can lead to the application of effective restoration measures and actions (Bernhardt and Palmer 2011; Pander and Geist 2013). Although post-restoration monitoring has begun to receive more attention, evaluation of pre-restoration conditions remains limited (Wohl 2005). The improvement of restoration practices requires a better understanding of rivers' responses to restoration actions, which can gain valuable insight from both pre- and post-restoration evaluation (Alexander and Allan 2007). The development of

guidelines for the implementation of restoration actions (e.g. Bernhardt et al. 2007; Pander and Geist 2013; Langhans et al. 2014) represents a move in the right direction.

It is in this context that the need for a shift from “reference-based” to “objective-based” rehabilitation actions has been advocated (Dufour and Piégay 2009). These objectives vary depending on the context and priorities. Some may focus on societal needs (flood defence, clean water, recreation, landscape), others more on natural processes or on the protection of identified rare or threatened species (Wohl et al. 2005; Newson and Large 2006; Gilvear et al. 2012). In Europe, these are supported by the Water Framework Directive (WFD, European Union 2000) which sets targets for the improvements in the quality of surface waters towards a ‘potential’ or ‘good ecological status’. As a consequence, an increasing number of projects are driven by the need to meet WFD targets and by the financial support that the European Union may provide (Jähnig et al. 2011; Gilvear et al. 2012; Pander and Geist 2013). The WFD holds a particular emphasis on the protection and conservation of rare and threatened species (through the Habitat Directive), which was translated in some countries into a rise in restoration or rehabilitation projects targeting specific species and their habitat (e.g. Scotland; Gilvear et al. 2012).

Freshwater ecosystems represent only a fraction of the Earth’s surface, yet they are important hotspots for biodiversity (Strayer and Dudgeon 2010). At the same time, they may well be the most endangered ecosystems in the world (Dudgeon et al. 2006; Gleick et al. 2009). Among all freshwater species, invertebrates suffer from the highest extinction rates (Strayer 2006). Threats to aquatic biodiversity can be listed within 5 categories: over-exploitation, water pollution, habitat degradation, flow modification and invasions by exotic species (see review by Geist 2011); all of which are exacerbated by the landscape position of these systems as ‘receivers’ (Dudgeon et al. 2006). As an example, Geist (2011) suggests that freshwater mussels, with an estimated extinction rate of 2-7% per century, would rank amongst the highest extinction rates of all taxonomic groups.

Filter-feeding bivalves, such as the freshwater pearl mussel (*Margaritifera margaritifera* L. 1758) are particularly sensitive to habitat alteration and water quality degradation because of their sensitivity to organic matter, pollution and acidification (Bauer 1988; Dunca et al. 2011), the complexity of their life cycle (Skinner et al. 2003), their specific habitat requirements (Hastie et al. 2000; Quinlan et al. 2015b) and their slow reaction to changes (Denic and Geist 2017). The species is threatened throughout its entire Holarctic range (Skinner et al. 2003) and is estimated to be present across only 5% of its original range (Mollusc Specialist Group 1996). In rivers where populations have survived, decreases in abundance of 90% have been reported (e.g. Bauer 1988).

It is now protected under the Directive Habitat and classified as 'Endangered' by the UICN (Mollusc Specialist Group 1996).

Reasons for the decline of populations throughout the species range are not solely linked to human alteration of living conditions. For centuries, mussels were poached and killed for their valuable pearls; this was found to be the main cause of decline in many rivers in Scotland (Cosgrove et al. 2000; Hastie 2011). Additionally, the threats faced by its salmonid hosts (Atlantic salmon *Salmo Salar* L. and Brown trout *Salmo trutta* L.) are also affecting the probability of successful mussel recruitment (Hastie and Cosgrove 2001; Hastie 2011). Nevertheless, amongst the 5 categories of threats to freshwater biota, loss of physical habitat has been flagged as the major issue (Geist and Auerswald 2007; Degerman et al. 2009; Cooksley et al. 2012). This is exacerbated by the fact that the pearl mussel's hosts share common habitat requirements and are thus threatened similarly by river degradation (Geist 2010; Taeubert and Geist 2017).

Suitable freshwater pearl mussel habitat must meet two rather contrasting requirements: a certain degree of bed stability (Purser 1985; e.g. by the presence of boulders; Beasley and Roberts 1999) to prevent both adults and juveniles from being swept away (Skinner et al. 2003), but also a clear and unclogged matrix of coarse sand to fine gravel that provides permanent oxygen supply (Hastie et al. 2000; Geist and Auerswald 2007; Gumpinger et al. 2015). However, the precise point on the continuum between stability and instability of the bed (some of which is necessary to ensure the prevention of compaction) that represents optimum conditions has yet to be established (Quinlan et al. 2015b). Mussels are also sensitive to excessive volumes of fine sediment and especially its organic content (Beasley and Roberts 1999; Hastie et al. 2000; Moorkens 2000; Geist and Auerswald 2007; Tarr 2008; Österling et al. 2010) although the lack of consistency in the methods used to evaluate the tolerance of mussel to fine sediments has made the definition of accurate thresholds impossible (Quinlan et al. 2015b). Despite incomplete knowledge, given the risks of seeing the species disappearing, measures to improve habitat and bolster population recruitment have been undertaken widely across Europe.

Ziuganov et al. (1994) identified 4 methods for the conservation of pearl mussels: (1) passive protection of remaining populations (creation of protected territories); (2) acclimatisation of mussels in new water bodies by introducing adult specimens; (3) semiartificial reproduction by intensive infestation of fish with glochidia under natural conditions; and (4) artificial pearl mussel culture. Cosgrove et al. (2016) also stressed the need to support stronger protective legal actions to stop pearl fishing. There is an increasing number of initiatives and programmes of captive

breeding, aimed at rearing juveniles for a later release in their original habitat (Thomas et al. 2010; Gum et al. 2011; Lavictoire et al. 2016). Catchment-wide and reach-scale initiatives also exist throughout Europe, to protect and preserve existing populations (e.g. Scandinavia; Oulasvirta et al. 2017; UK; Pearls in Peril 2017). These primarily consist in extensive surveys of the remaining populations (e.g. Degerman et al. 2009; Oulasvirta et al. 2017), management plans to limit water pollution, maintenance of riverbanks to prevent further degradation of habitat (e.g. bank fencing to promote riparian vegetation; Hastie 2005; plantation of trees, bank reinforcement; Pearls in Peril 2017), silt-trapping to limit clogging of gravel (Vandré 2005) and, in some Scandinavian countries, the liming of freshwater bodies to counteract water acidification (see references in Degerman et al. 2013). Some actions were directly related to the manipulation of individuals, such as the re-introduction of healthy individuals to sections with suitable habitat (Hastie 2005; Degerman et al. 2009) or the active infection of host fish (on banks, by placing fish in buckets full of glochidia) and their direct release in their river of origin (Degerman et al. 2009; O’Leary et al. 2017). However, to date, there are few examples of attempts to ‘actively’ restore physical habitat.

Based on the assumption that large clasts can stabilise a matrix of finer gravel, boulders have been added to the River Nötån (Sweden) as part of a LIFE project (Degerman et al. 2009). To foster juvenile recruitment by recreating suitable habitats, gravel has been added to potentially suitable reaches (Henrikson 2005; Henrikson and Alexanderson 2012). Degerman et al. (2009) also provide ‘guidelines’ as to how recreate spawning grounds that could benefit both the pearl mussel and its host. However, no results could yet be reported because of the slow growth rates of young mussels and the difficulty to observe them *in-situ* before they reach the age of *c.* 10 years (Henrikson and Alexanderson 2012). Given the level of threat faced by the species and the time needed to properly assess whether recruitment is improving, it has been advocated that rehabilitation and restoration efforts can be primarily assessed on the basis of habitat conditions (Quinlan et al. 2015b).

It is within this context that the work undertaken in the River Ehen is presented here. Actions were taken to restore the upper River Ehen, with the underlying objective of improving habitat conditions for the pearl mussel population. Because this study only spans *c.* 3 years, no attempt was made to directly measure potential benefits of the restoration project for pearl mussel recruitment; this is being undertaken in parallel by Ian Killeen as part of long term monitoring on the Ehen (e.g. Killeen and Oliver, 1997). Instead, this project focussed on the physical processes

responsible for the creation of mussel habitat, and how these have been affected by the recent management actions undertaken in the Ehen.

1.3. THE RIVER EHEN

1.3.1. Catchment

The River Ehen is located in North-West England, in the county of Cumbria, on the western side of the Lake District National Park (Figure 1.1). The river and its tributaries drain a total catchment of 155.8 km², from the Western Fells (highest point: Great Gable, 899 m.a.s.l.) to the west coast of Cumbria, where it debouches into the Irish Sea. The upper part of the catchment is formed by the River Liza, which flows through a steep-sided valley to Ennerdale Water. The geology there is mainly composed of Igneous Tuff of the Borrowdale formation, with granitic intrusions in places. The Ehen then flows south-westwards from the lake to the sea through the villages of Ennerdale Bridge, Cleator Moor, Egremont and Braystones for a distance of 27 km. The lower part of the catchment is composed of argillaceous rocks of the Skiddaw group, separated from the coast by a belt of Sherwood sandstones. The Ehen finally joins with the River Calder near Sellafield where they form a common estuary.

Ennerdale Water is a natural glacial lake that plays an important role in the hydrology and sedimentary activity of the river. It is located c. 5 km upstream from the village of Ennerdale Bridge. Upstream from the lake, the River Liza collects water and sediment from first-order headwater streams, delivering significant quantities of sediment into Ennerdale Water (Brown et al. 2008). The lake acts as a natural sediment trap which prevents sediment mobilisation. Downstream from the lake outlet, the River Ehen suffers from limited sediment availability with a very stable riverbed (Quinlan et al. 2015a). The lake and its associated usage also affect the hydrology of the river and dampen the catchment's response to rainfall (Gibbins et al. 2004). More details on these are given in subsequent chapters.

1.3.2. Climate and hydrology

Although Ennerdale Water is a natural lake, a concrete weir was built at its outlet to heighten water levels and increase its storage to secure water supply for the area. The original weir was constructed in 1864 and made of wooden planks. It was later replaced by a concrete and masonry, 1.3-m high structure (in 1902) equipped with a fish-pass on its true right bank (Plate 1.1). The

relative impact of the weir on the river's hydrology is difficult to assess since there is no record of discharge prior to its construction. However, Moir et al. (2003) compared the hydrological regime of the Ehen to that of the adjacent unregulated River Calder. Both rivers have virtually identical catchment areas (Ehen 44.2 km² and Calder 44.8 km² at their respective gauging stations). Although the Ehen shows a higher long-term mean discharge (1974-2003, 2.48 m³ s⁻¹) than the Calder (1.84 m³ s⁻¹), peak discharges were consistently higher in the latter river. The authors argued that the regulation has some effects on the higher range of flows, although it is not possible to disentangle the relative effects of water abstraction, water retention by the weir, natural regulation by the lake and the diversion of Ben Gill. Regulation also affects the low flow percentiles in the Ehen, due to the release of a minimum compensation flow (see section 1.3.4.).



Plate 1.1. Outlet of Ennerdale Water, with the weir and fish-pass (left hand-side). When lake levels are low, the weir does not overflow and compensation flows are released through the fish-pass (Photo: Baptiste Marteau).

Introduction

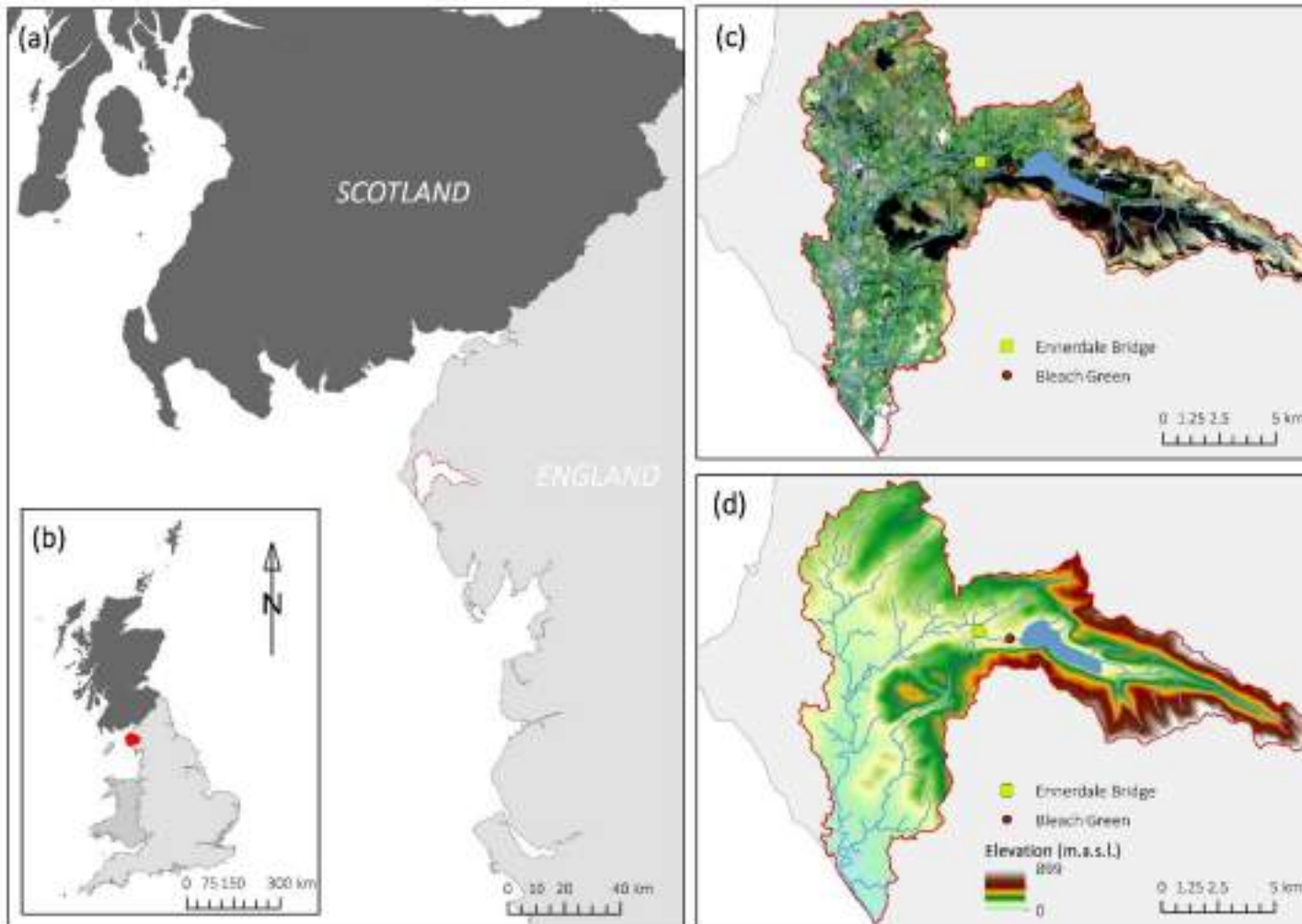


Figure 1.1. The Ehen catchment. (a) and (b): location of the catchment within the United Kingdom. (c) satellite photograph of the Ehen catchment, showing the contrast between the upper part (steep slope, mountainous and forested) and the lower part (lowland farmlands and more urban areas towards the coast). (d) digital elevation model of the Ehen catchment showing altitude.

Records of daily mean discharge in the Ehen exist from Bleach Green gauging station, located approximately 500 m downstream from the lake outlet. Despite some missing data and the inherent variability, annual discharge shows a significant increasing ($r^2 = 0.42$, $n = 43$, $p < 0.01$) over time (Figure 1.2a). Such trends have been observed in annual precipitation in the UK since 1960 (Jenkins et al. 2009) and particularly in the NW England, where winter precipitation tend to arrive in more extreme events now than in the past (Jones et al. 2013).

Additionally, in 2012 the minimum compensation flow was increased in the Ehen (see details in section 1.3.4) in response to the threats posed by long-lasting dry spells on the mussel population.

Generally, flows in the Ehen are typical for the North-West of England, with lower flows in late spring and summer and higher flows in the winter, with occasional rainstorms in late summer (Figure 1.2b).

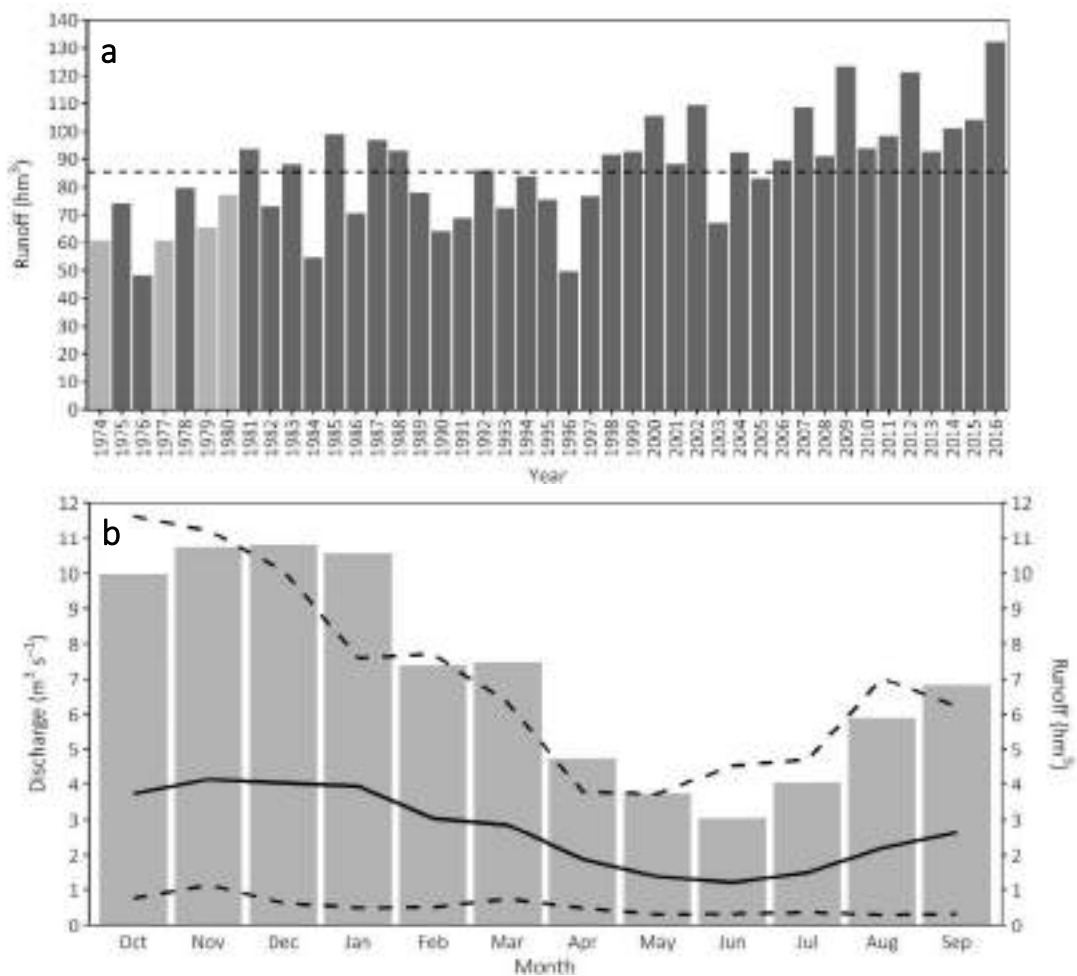


Figure 1.2. (a) Mean annual runoff (dashed line is long-term average) and (b) Mean monthly discharge (solid line), with maximum and minimum mean monthly discharge (dashed lines) and mean monthly runoff (bars). Data for the River Ehen, recorded at Bleach Green gauging station for the period 1974-2016. Light grey bars in (a) represent years where 1, 2 or 3 month(s) of record are missing.

1.3.3. The freshwater pearl mussel in the Ehen

The River Ehen is home to the largest remaining population of the freshwater pearl mussel (*Margaritifera margaritifera* L. 1758) in England. The population has been under close scrutiny over the last 25 years, with numerous projects monitoring the health and distribution of the population as well as assessing habitat suitability in the river (Killeen and Oliver 1997; Killeen 2006; Killeen and Moorkens 2013; O’Leary 2013 and references therein). The first surveys (1996) found the mussels to be present in high numbers and with signs of recruitment, despite a distribution limited to the upper c. 4 km of the river. However, surveys carried out 10 years later helped stress the poor condition of the population. Although the population was still rather large, juveniles less than 4 years old were rare (Killeen 2010). The age of the entire cohort observed 10 years earlier had shifted, with very limited mussel recruitment since the previous survey. More recently, the river’s population was estimated around 550,000 individuals but was found to still be threatened by poor recruitment and the lack of juveniles (Killeen and Moorkens 2013). The conditions in the river were not considered favourable, resulting in *‘an ageing of the population which would inevitably lead to extinction unless the trend was reversed’* (Killeen 2010).

The complex life cycle of the freshwater pearl mussel requires a parasitic stage on a host fish. Once released by the females in the water, the larvae, called ‘glochidia’, need to attach to the gills of a salmonid fish (i.e. a salmon or a trout) for a few months, with a preference for fry (Hastie and Young 2003). This constrains the recruitment of young mussels to rivers with the presence (and health) of fish populations, and the concordance in time and space of both species. Early work by Gibbins et al. (2004) showed evidence from fishery surveys that the juvenile salmonid densities in the Ehen were below the optimum required for mussel recruitment. More recently, O’Leary (2013) summarised in her report the complexity of the situation for the main host in the River Ehen, the Atlantic salmon (*Salmo salar*). Surveys of ‘estimated egg deposition’ showed no significant concern for the population *‘for now or in five years’ time’*, although the author stressed the uncertainties around the methods and the spatial resolution of these studies (O’Leary 2013). Alternatively, juvenile electrofishing surveys were used to improve the understanding of the spatial distribution of the salmonid population in the river. While many areas of the catchment support healthy and numerous population of salmonids, it appears that the upper reach of the Ehen, downstream of Ennerdale Water, is in extremely poor conditions (O’Leary 2013). Unfortunately, this section of the river sustains a

large proportion of the mussel population. Thus, efforts to restore a healthy population of mussels will only be successful if combined with the improvement of conditions for salmon.

As a result of the presence of the endangered pearl mussel, and the threat caused by the relatively unstable conditions of its main host, 13.5 km of the River Ehen (approximately 23.3 ha), from Ennerdale Water to the confluence of the River Keekle, were designated in 2005 as Specific Area of Conservation (SAC), under Annexe II of the European Habitat Directive (Freshwater pearl mussel as primary reason, Atlantic salmon as qualifying feature, JNCC 2011). The mussel population was already the subject of a Site of Special Scientific Interest (SSSI) protection since 1997, under the Wildlife and Countryside Act 1981. Both protection schemes are designed to aid conservation and management of the river and its threatened wildlife.

Freshwater pearl mussels are found throughout the River Ehen SAC (Killeen 2006). The population was reported to be different in the lower part of the river, i.e. downstream from Ennerdale Bridge, likely as a result of differences in water chemistry. Killeen and Oliver (1997) hypothesised that this was linked to the difference in geology: the higher calcium content of the bedrock downstream from Ennerdale Bridge is reflected in the water chemistry and may allow the mussels to grow faster, at the cost of a smaller shell and shorter life expectancy. Nevertheless, adult mussels are regularly found in breeding conditions in the river, with electrofishing surveys showing signs of glochidia encystment on salmon fry (Environment Agency 2014). The lack of recruitment despite the presence of encysted fries points towards the conclusion that juvenile mussels, once they drop off their host, struggle to find suitable conditions to develop, and so cannot reach adulthood.

1.3.4. Restoring Sustainable Abstraction to Cumbrian rivers

A number of surface water bodies in the North-West of England are subject to water abstraction. The abstraction of water is controlled by a licensing system which was first introduced by the Water Resource Act 1963 and is administered by the Environment Agency (Environment Agency 2002). It was subsequently amended and consolidated into newer legislation with the Water Resource Act 1991, the Environment Act 1995 and the Water Act 2003 (Environment Agency 2016). However, the publication by the UK Government in 1999 of a series of decisions in *'Taking Water Responsibly'* highlighted the need for changes in the abstraction licensing system, in particular with regards to the European Water Framework Directive (2000). This was enacted by the launching of the Restoring Sustainable Abstraction

(RSA) Programme whose aims are to identify over-abstraction in rivers and wetland sites, characterise the impacts associated with abstraction and implement solutions (Environment Agency 2001).

The River Ehen is part of a regional RSA project for the North-West region of England, which targets sites that are experiencing or could experience environmental damage as a result of water abstraction. The earliest references to abstraction of water in the upper Ehen date back to 1849, when a 1-ft (c. 0.3 m) high wooden weir was installed at the outlet of the lake to compensate for abstracting water towards local mill owners (Alvarez-Codesal and Sweeting 2015). Increasing demand from local authorities for water later led to the construction of the concrete weir in 1902, slightly higher (2-ft, c. 0.6 m) which probably coincided with larger volumes of water abstracted from the lake. The current masonry weir was constructed in 1995 as a replacement of the 1902 structure. It is 1.3-m high and 60-m wide, and is equipped with a fish-pass on its right bank which was designed in 1972 (Alvarez-Codesal and Sweeting 2015). This fish-pass allows for the release of the compensation flow when lake levels drop below weir crest.

The definition of minimum compensation flows and Hands-off Flows (HoFs) was the focus of the RSA programme for the rivers that were found to be impacted by water abstraction. The need for a change in the abstraction license from Ennerdale Water came to light during the drought of 2010. At this time, flows remained at the minimum compensation flow of $0.37 \text{ m}^3 \text{ s}^{-1}$ for a prolonged period of time. These conditions can force adult mussels to stand out of the riverbed where they would normally live partly buried, in search for higher flow velocities and more oxygen, with the less fit individuals dying of stress (Killeen and Moorkens 2013). As a result, minimum compensation flow was increased in 2012, as part of the Review of Consents process under the Habitats and Species Regulations 2010. It is currently set at $0.92 \text{ m}^3 \text{ s}^{-1}$, sometimes phased down to $0.69 \text{ m}^3 \text{ s}^{-1}$ depending on lake level (Environment Agency 2014). While the increased compensation flow is considered favourable to the fauna and flora of the river, it creates more rapid and frequent drawdowns in the lake. When lake levels fall below the gravitational water feed into the fish-pass, water needs to be pumped from the lake into the fish-pass in order to deliver the minimum flow required (Cascade 2013).

Following recent work undertaken by the Environment Agency on different possible scenarios to protect the pearl mussel population, it was decided to replace the current fish-pass, which was found to be not efficient for fish passage (Environment Agency 2013) and to show limited

flexibility to deliver the minimum compensation flow at high drawdowns (Cascade 2013). Moreover, the abstraction licence from Ennerdale Water will be revoked by 2024, and there are plans to remove the weir within the next twenty years. However, this part of the project remains conditioned by the provision of additional sources of water (e.g. boreholes, increase abstraction in other local reservoirs) and further consideration and assessment of potential impacts for the mussel population (Environment Agency 2013).

1.4. RESTORATION PROGRAMME AND EFFORTS TOWARDS IMPROVING THE RIVER'S CONDITIONS

The River Ehen is the focus of a major rehabilitation project, designed to conserve its important pearl mussel population. Initial efforts were undertaken by the Forestry Commission, in the upper part of the River Liza (upstream from Ennerdale lake) to stop the forestry activity which could enhance siltation, nutrient enrichment and acidification of the river (O'Leary 2013). The area was felled then allowed to regenerate as a mix of open habitats and native woodland (Killeen 2010).

Several actions were undertaken across the Ehen to manage bank vegetation (tree maintenance and fencing), limit direct access of cattle to the river and prevent bank erosion (Killeen 2010; O'Leary 2013). The reconnection of Ben Gill fits within this rehabilitation project and represents the largest and most ambitious action. A detailed description of the work in presented is Chapter 2, but a summary is given below.

The upper Ehen, which hosts *c.* 90% of the entire mussel population of the river (Killeen 2010), was described by Quinlan et al. (2015a) as sub-optimum for pearl mussels due to high compaction and low particle mobility. The lack of suitable habitat was also reported by Killeen (2006) and Killeen and Moorkens (2013), especially for juveniles, as a combined effect of absence of loose fine gravel, severe hyporheic anoxic conditions and a potentially hampering high density of algae. The causes of this habitat degradation were quickly related to the flow regulation and work undertaken in the past to improve the storage capacity of the reservoir.

Ennerdale Lake is an important source for the local supply of drinking and industrial water. Water abstraction began in the Ehen in 1850, near Ennerdale Bridge, but was later moved to the lake in 1864 (Alvarez-Codesal and Sweeting 2015). Then, the decision was made in the 1970s to divert a headwater tributary -Ben Gill- towards the lake to further increase storage

and permit greater abstraction. The diversion involved the water from Ben Gill being redirected to the lake via an underground culvert. The lower part of the channel was filled in and *terrestrialised* over time to become grassland. The upper part of the stream would still deliver sediment which was retained by a metal grid at the culvert entrance. This sediment was removed on a regular basis and used locally as building material.

Given the importance of mussels and poor habitat conditions in the river, the decision was made to reconnect Ben Gill to the Ehen, with the aim of re-naturalising the hydrological regime of the river and increasing the sediment supply, to help reinstate more natural (dynamic) fluvial processes (Ben Gill was considered a potentially important source of sediment by Brown et al. 2008). The work began in summer 2014. The diversion culvert was disabled and the entrance grid removed. Then, a new 300-m long section of channel was engineered through the old alluvial fan to reconnect the functional upper part of Ben Gill to the Ehen. The confluence between the two is c. 15 m downstream from the weir (Plate 1.2). The new channel was designed to convey an estimated 100-year flood. It was constructed 5 m wide and 0.5 m deep on average, with a generally semi-circular shape (United Utilities 2012). Bed surface was lined with cobble-size material and some larger clasts along the banks. Because of the sensitivity of mussels to fine sediment, the site was carefully surrounded with silt traps to prevent surface run-off of fines during all the engineering work. Additionally, just prior to its final opening the bed was thoroughly washed, section by section, to prevent the first flush delivery of fine sediment. The wash water was stored in temporary off channel settlement tanks; settled fine material was removed from site and the remaining clean water was pumped back into the lake. The final few metres at bottom end were excavated and opened to connect to the Ehen on 3 October 2014 (Figure 1.3.).

Thus, the core of this study is focussed on the newly reconnected Ben Gill channel, and the upper part of the River Ehen, directly downstream from the lake outlet (Figure 1.3) and relies on previous pre-reconnection monitoring efforts (see Quinlan (2014) for full details).



Plate 1.2. View from the fell of Ben Gill alluvial fan during the construction work of the new channel, summer 2014 (Photo: Baptiste Marteau).

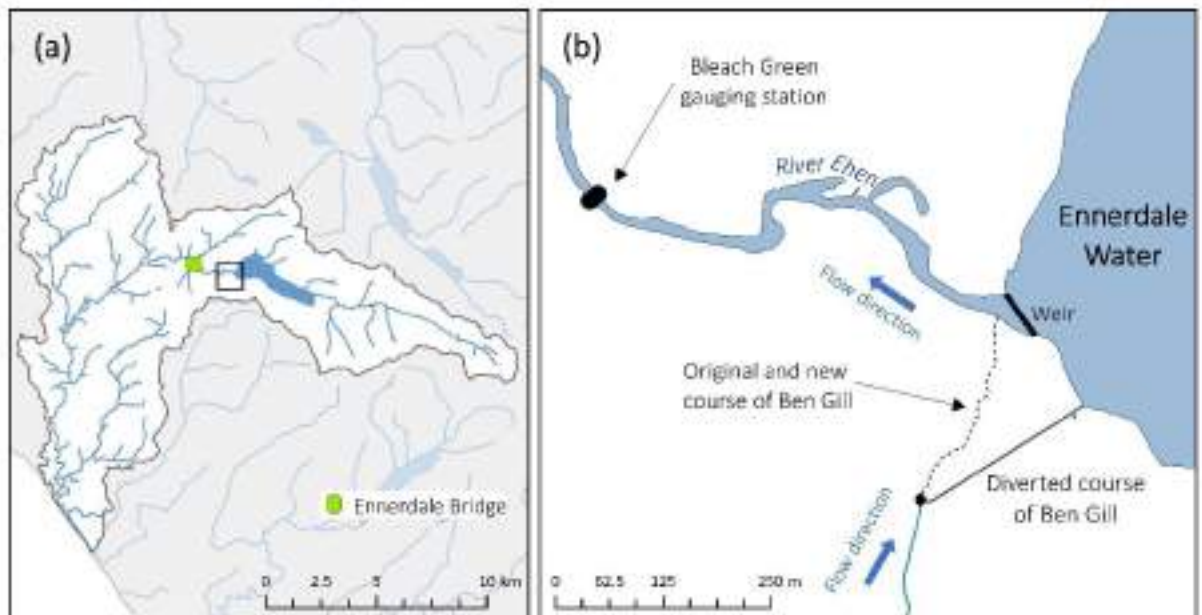


Figure 1.3. (a) Location of the study site within the Ehen catchment. (b) Original, diverted and new course of Ben Gill, from the old diversion point to its confluence with the Ehen.

The framework of this restoration project is, in itself, somewhat unusual. Although the engineering was physically limited to the re-creation of the lowermost section of Ben Gill (c. 300m), in practice it involved the reconnection of its entire sub-catchment to the main-stem Ehen. This means that renewed transfer of water, sediments and energy is related to catchment-scale (re)connectivity rather than simply the restoration of a section of stream.

One of the risks associated with the post-restoration monitoring of geomorphological river restoration is the failure to capture relevant and/or significant changes on the system of interest. This risk is increased when monitoring is implemented 'early' after the restoration work. The choice of the monitoring programme is driven by the characteristics of the system and the issues at stake. The need for early and intense monitoring in the Ehen was defined by the sensitivity of the focal species to changes in habitat, and particularly fine sediment dynamics.

1.5. AIMS, OBJECTIVES AND STRUCTURE OF THE THESIS

The work undertaken in for this thesis sits on the basis of a strong preliminary research. In addition to the intensive monitoring of the mussel population funded by the Environment Agency and United Utilities, a series of geomorphological, hydrochemical and ecological assessments, as well as hydraulic modelling studies, were carried out over the years (Moir et al. 2003; Gibbins et al. 2004, 2005; Brown et al. 2008). Other studies were undertaken on several aspects of conditions of the river by commercial consultancies, with the aim of understanding near-bed velocity, habitat suitability for pearl mussels and salmon, and the suitability of different compensation flow scenarios.

The cornerstone of this thesis, however, is the work carried out by Emma Quinlan over the course of her PhD (Quinlan 2014). The focus of Quinlan's work was to understand the processes and conditions in the river in order to establish a baseline against which the river's response to the reconnection of Ben Gill could be assessed. This work formed an invaluable dataset of what is recognised as frequently missing in river restoration projects, i.e. a monitoring of pre-restoration conditions to evaluate the changes associated with the restoration actions and the potential success or failure of these actions.

The overall aim of the research conducted for this PhD was to assess the impacts of the Ben Gill reconnection on the geomorphology, sedimentary conditions and the ecology of the River

Ehen. In order to do so, the research was designed with the following specific objectives and associated chapters (see Figure 1.4 for an overview of all chapters, objectives and papers delivered through this PhD):

1. Monitor the **morphological evolution** of the newly created Ben Gill channel and establish its sediment budget (Chapter 2 & 5);
2. Assess the **sedimentary effects** of the reconnection and the consequences of this new sediment supply on suspended sediment dynamics in the Ehen (Chapter 3);
3. Analyse the relationship between **flows** in the Ehen and those in Ben Gill and understand how this relationship controls **in-channel storage** patterns in the River Ehen (Chapter 4);
4. Assess the topographic and **geomorphic changes** in the River Ehen as a result of the reconnection and understand the processes occurring (Chapter 5);
5. Assess the potential implication of these changes for the **ecology** of the Ehen (Chapter 6).

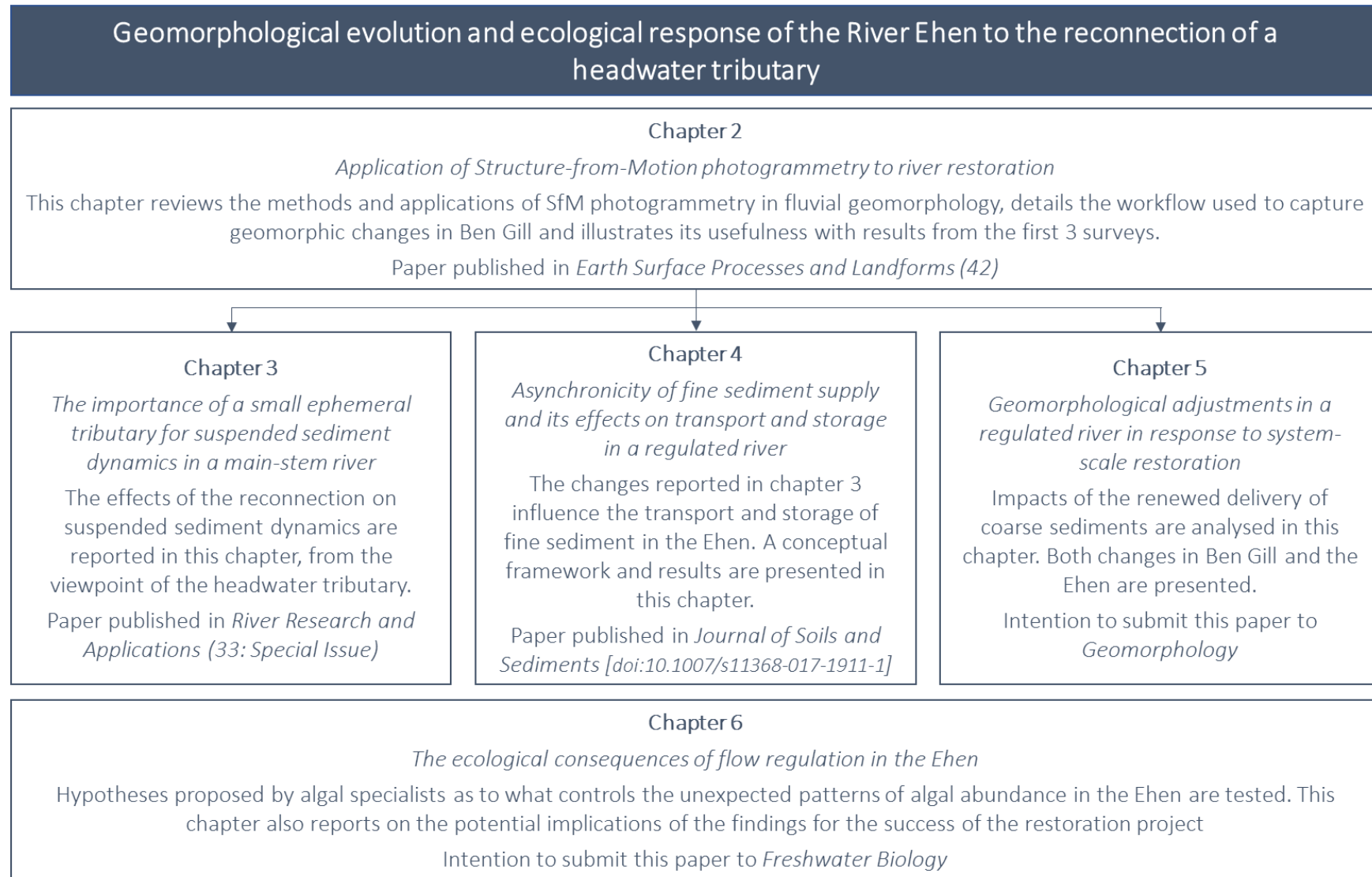


Figure 1.4. Structure of the thesis with the different chapters, associated objectives and journals where papers have been published or will be submitted.

1.6. FIELDWORK DESIGN AND OVERVIEW OF METHODS

Details of the materials and methods are presented in each of the result chapters. A brief overview is given here to illustrate and summarise the overall approach and structure of the data collection programme.

1.6.1. Capturing geomorphic changes in Ben Gill

The use of Structure-from-Motion (SfM) in fluvial geomorphology is not novel, but its application to river restoration was not yet found in the literature. The use of a distorted lens (i.e. fish-eye), regularly reported as not suitable for the application of SfM, was tested and analysed. The acquisition of high resolution topography data required careful calibration and assessment of errors but proved to be helpful to capture and characterise the geomorphic activity of the newly reconnected channel.

1.6.2. Monitoring the effects on fine sediments dynamics

Because the freshwater pearl mussel is sensitive to fine sediments, the Environment Agency installed a series of turbidity meters along the first 4 km downstream from the reconnection. After empirical calibration, turbidity readings were used to infer suspended sediment concentrations.

The fate of fine material coming from Ben Gill was assessed using the turbidity data and by looking at the deposition and removal of fines from the riverbed of the main-stem Ehen. In-channel sediment storage was sampled using the cylinder technique in each of the three dominant morphological units of the study reach (plane bed, riffle and pool). Samples collected over the c. 2 years of the study allowed assessment of volumes of storage, but also the organic fraction and the particle size, both of which are regularly cited as relevant for the survival of the pearl mussel.

1.6.3. Assessing geomorphic adjustments in the Ehen

The aim of the reconnection was to help reinstate suitable physical habitat for the pearl mussel, so it was important to capture signs of morphological adjustments in the Ehen. To do so, bed texture (grain size distribution from pebble counts), bed particle mobility (painted tracers) and topographic changes (cross-sectional surveys) were monitored regularly over the course of the

study. Baseline data from Emma Quinlan's PhD proved to be crucial in the understanding of geomorphic changes. Comparison between pre- and post-reconnection conditions helped determine the influence of the restoration and frame hypotheses about the future changes in the Ehen.

1.6.4. Linking bed disturbance, invertebrate grazing and the abundance of biofilm

The Environment Agency raised concerns about the high abundance of biofilm covering the bed of the Ehen (assumed to be related to flow regulation and associated bed stability) and the potential implications of this for pearl mussels. Algae were also found growing directly on mussels. A group of algae specialists was asked to monitor patterns in biofilm abundance and the findings led the authors to formulate hypotheses about the main factors controlling the mass of biofilms. These hypotheses formed the basis of the final thesis chapter. The abundance of biofilm was monitored during a year at 4 sites -2 in the Ehen and 2 in a neighbouring 'control' stream (Croasdale Beck) along with several environmental controls. These controls included discharge and flow hydraulics, water chemistry (pH, dissolved oxygen, temperature, nutrients, conductivity and alkalinity), bed stability (using painted tracers) and the abundance of grazing macroinvertebrates. The chapter allows exploration of how a number of factors influenced by flow regulation (bed stability, flow hydraulics, and the abundance of algae and benthic invertebrates) interact with each other to alter the result of trophic interactions.

1.7. REFERENCES

- Alexander GG, Allan JD (2007). Ecological success in stream restoration: Case studies from the midwestern United States. *Environmental Management* 40:245–255
- Alvarez-Codesal S, Sweeting RA (2015). Historic changes in the Upper River Ehen Catchment. A Report for United Utilities. FBA unpublished report (S/0016/W)
- Aronson J, Floret C, Le Floc’h E, Ovalle C, Pontanier R (1993). Restoration and Rehabilitation of Degraded Ecosystems in Arid and Semi-Arid Lands. I. A View from the South. *Restoration Ecology* 1:8–17
- Bauer G (1988). Threats to the freshwater pearl mussel *Margaritifera margaritifera* L. in Central Europe. *Biological Conservation* 45:239–253
- Beasley CR, Roberts D (1999). Towards a strategy for the conservation of the freshwater pearl mussel *Margaritifera margaritifera* in County Donegal, Ireland. *Biological Conservation* 89:275–284
- Bernhardt ES, Likens GE, Hall RO, Buso DC, Fisher SG, Burton TM, Meyer JL, Mcdowell WH, Mayer MS, Bowden WB, Findlay SEG, Macneale KH, Stelzer RS, Lowe WH (2005). Can’t See the Forest for the Stream? In-stream Processing and Terrestrial Nitrogen Exports. *BioScience* 55:219
- Bernhardt ES, Palmer MA (2011). River restoration : the fuzzy logic of repairing reaches to reverse catchment scale degradation. *Ecological Applications* 21:1926–1931
- Bernhardt ES, Sudduth EB, Palmer MA, Allan JD, Meyer JL, Alexander G, Follastad-Shah J, Hassett B, Jenkinson R, Lave R, Rumps J, Pagano L (2007). Restoring rivers one reach at a time: Results from a survey of U.S. river restoration practitioners. *Restoration Ecology* 15:482–493
- Boon PJ (1998). River restoration in five dimensions. *Aquatic Conservation: Marine and Freshwater Ecosystems* 8:257–264
- Bradshaw AD (1996). Underlying principles of restoration. *Canadian Journal of Fisheries and Aquatic Sciences* 53:3–9
- Brierley GJ, Fryirs KA (2008). River Futures - An integrative scientific approach to river repair. Island Press
- Brierley GJ, Fryirs KA (2005). Geomorphology and River Management: Applications of the River Styles Framework. Blackwell Publishing Ltd.
- Brooks AP, Howell T, Abbe TB, Arthington AH (2006). Confronting hysteresis: Wood based river rehabilitation in highly altered riverine landscapes of south-eastern Australia. *Geomorphology* 79:395–422
- Brown D, Butterill G, Bayliss B (2008). Ben Ghyll Geomorphology report. Environment Agency, Version 2.0, Penrith, Cumbria
- Cascade (2013). Ben Gill Realignment - Habitats Regulations Assessment and Ecological Impact Assessment - Project No. CC535 - Final report.
- Cooksley SL, Brewer MJ, Donnelly D, Spezia L, Tree A (2012). Impacts of artificial structures on

- the freshwater pearl mussel *Margaritifera margaritifera* in the River Dee, Scotland. *Aquatic Conservation: Marine and Freshwater Ecosystems* 22:318–330
- Cosgrove P, Watt J, Hastie L, Sime I, Shields D, Cosgrove C, Brown L, Isherwood I, Bao M (2016). The status of the freshwater pearl mussel *Margaritifera margaritifera* in Scotland: extent of change since 1990s, threats and management implications. *Biodiversity and Conservation* 25:2093–2112
- Cosgrove PJ, Young MR, Hastie LC, Gaywood M, Boon PJ (2000). The status of the freshwater pearl mussel *Margaritifera margaritifera* Linn. in Scotland. *Aquatic Conservation: Marine and Freshwater Ecosystems* 10:197–208
- Costanza R (2012). Ecosystem health and ecological engineering. *Ecological Engineering* 45:24–29
- Degerman E, Alexanderson S, Bergengren J, Henrikson L, Johansson B-E, Larsen BM, Söderberg H (2009). Restoration of freshwater pearl mussel streams. *WWF Sweden, Solna*
- Degerman E, Andersson K, Söderberg H, Norrgrann O, Henrikson L, Angelstam P, Törnblom J (2013). Predicting population status of freshwater pearl mussel (*Margaritifera margaritifera*, L.) in central Sweden using instream and riparian zone land-use data. *Aquatic Conservation: Marine and Freshwater Ecosystems* 23:332–342
- Denic M, Geist J (2017). The freshwater pearl mussel *Margaritifera margaritifera* in Bavaria, Germany—Population status, conservation efforts and challenges. *Biology Bulletin* 44:61–66
- Dudgeon D, Arthington AH, Gessner MO, Kawabata Z-I, Knowler DJ, Lévêque C, Naiman RJ, Prieur-Richard A-H, Soto D, Stiassny MLJ, Sullivan C a (2006). Freshwater biodiversity: importance, threats, status and conservation challenges. *Biological reviews of the Cambridge Philosophical Society* 81:163–82
- Dufour S, Piégay H (2009). From the myth of a lost paradise to targeted river restoration: forget natural references and focus on human benefits. *River Research and Applications* 25:568–591
- Dunca E, Söderberg H, Norrgrann O (2011). Shell growth and age determination in the freshwater pearl mussel *Margaritifera margaritifera* in Sweden: natural versus limed streams. In: Thielen F (ed) *Rearing of unionid mussels (with special emphasis on the Freshwater Pearl Mussel Margaritifera margaritifera)*. Ferrantia 64, Musée national d'histoire naturelle, Luxembourg, pp 48–58
- England J, Skinner KS, Carter MG (2008). Monitoring, river restoration and the Water Framework Directive. *Water and Environment Journal* 22:227–234
- Environment Agency (2014). Restoring Sustainable Abstraction / Heavily Modified Water Body Monitoring Programme - 2010 to 2015. *Environment Agency, Bristol*
- Environment Agency (2002). Managing Water Abstraction - The Catchment Abstraction Management Strategy process. *Environment Agency, Bristol*
- Environment Agency (2016). Managing Water Abstraction. *Environment Agency Publications, Bristol*
- Environment Agency (2001). Restoring Sustainable Abstraction - Technical Guidance. *Water*

Resources - Restoring Sustainable Abstraction Programme, Bristol

- Environment Agency (2013). River Ehen SAC: SAC Site Action Plan Addendum, Ennerdale abstraction licence No. 277400.008. *Habitat Directive Review of Consents - Water Resources*
- European Union (2000). Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. *Official Journal of the European Communities* L237:1–73
- Friberg N, Bonada N, Bradley DC, Dunbar MJ, Edwards FK, Grey J, Hayes RB, Hildrew AG, Lamouroux N, Trimmer M, Woodward G (2011). Biomonitoring of Human Impacts in Freshwater Ecosystems: The Good, the Bad and the Ugly. *Advances in Ecological Research* 44:1–68
- Friberg N, Sandin L, Pedersen ML (2009). Assessing the effects of hydromorphological degradation on macroinvertebrate indicators in rivers: examples, constraints, and outlook. *Integrated Environmental Assessment and Management* 5:86–96
- Geist J (2011). Integrative freshwater ecology and biodiversity conservation. *Ecological Indicators* 11:1507–1516
- Geist J (2010). Strategies for the conservation of endangered freshwater pearl mussels (*Margaritifera margaritifera* L.): a synthesis of Conservation Genetics and Ecology. *Hydrobiologia* 644:69–88
- Geist J, Auerswald K (2007). Physicochemical stream bed characteristics and recruitment of the freshwater pearl mussel (*Margaritifera margaritifera*). *Freshwater Biology* 52:2299–2316
- Gibbins C, Young M, Hastie L, Soulsby C, Pokrajac D, Campbell L (2004). River Ehen Freshwater Pearl Mussel Project: Final Report, Contract No. JB128. University of Aberdeen: 44p.
- Gibbins CN, Pokrajac D, Campbell L (2005). Hydraulic modelling of River Ehen sites. Project report for English Nature - Contract JB 218. University of Aberdeen: 10p.
- Gillilan S, Boyd K, Hoitsma T, Kauffman M (2005). Challenges in developing and implementing ecological standards for geomorphic river restoration projects: A practitioner's response to Palmer et al. (2005). *Journal of Applied Ecology* 42:223–227
- Gilvear DJ, Casas-Mulet R, Spray CJ (2012). Trends and issues in delivery of integrated catchment scale river restoration: lessons learned from a national river restoration survey within Scotland. *River Research and Applications* 28:234–246
- Gleick PH, Allen L, Christian-Smith J, Cohen MJ, Cooley H, Heberger M, Morrison J, Palaniappan M, Schulte P (2009). The World's Water - The Biennial Report on Freshwater Resources, Volume 7. Island Press
- Grant GE (2012). The Geomorphic Response of Gravel-bed Rivers to Dams: Perspectives and Prospects. In: Church MA, Biron PM, Roy AG (eds) *Gravel-bed Rivers: Processes, Tools, Environments*. John Wiley & Sons, Ltd, Chichester, UK, pp 165–181
- Gum B, Lange M, Geist J (2011). A critical reflection on the success of rearing and culturing juvenile freshwater mussels with a focus on the endangered freshwater pearl mussel (*Margaritifera margaritifera* L.). *Aquatic Conservation: Marine and Freshwater Ecosystems* 21:743–751

- Gumpinger C, Hauer C, Scheder C (2015). The current status and future challenges for the preservation and conservation of freshwater pearl mussel habitats. *Limnologica - Ecology and Management of Inland Waters* 50:1–3
- Hastie LC (2011). Are Scottish freshwater pearl mussel populations recruiting normally? *Toxicological & Environmental Chemistry* 93:1748–1763
- Hastie LC (2005). Restoration of Freshwater Pearl Mussel Populations in Scotland. In: Vandr  R, Schmidt C (eds) *Proceedings of the Workshop "Pearl Mussel Conservation and River Restoration."* Bezirk Oberfranken & Anglerverband S dsachsen Mulde/Elster e.V., Bad Elster, Germany, pp 11–14
- Hastie LC, Boon PJ, Young MR (2000). Physical microhabitat requirements of freshwater pearl mussels, *Margaritifera margaritifera* (L.). *Hydrobiologia* 429:59–71
- Hastie LC, Cosgrove PJ (2001). The decline of migratory salmonid stocks: a new threat to pearl mussels in Scotland. *Freshwater Forum* 15:85–96
- Hastie LC, Young MR (2003). Timing of spawning and glochidial release in Scottish freshwater pearl mussel (*Margaritifera margaritifera*) populations. *Freshwater Biology* 48:2107–2117
- Hendry K, Cragg-Hine D, O’Grady M, Sambrook H, Stephen A (2003). Management of habitat for rehabilitation and enhancement of salmonid stocks. *Fisheries Research* 62:171–192
- Henrikson L (2005). The Freshwater Pearl Mussel *Margaritifera margaritifera* and its habitats in Sweden - a LIFE project. In: Vandr  R, Schmidt C (eds) *Proceedings of the Workshop "Pearl Mussel Conservation and River Restoration."* Bezirk Oberfranken & Anglerverband S dsachsen Mulde/Elster e.V., Bad Elster, Germany, pp 15–20
- Henrikson L, Alexanderson S (2012). The EU LIFE project "The freshwater pearl mussel and its habitats in Sweden." In: Henrikson L, Arvidsson BL,  sterling ME (eds) *Aquatic Conservation with Focus on Margaritifera margaritifera - Proceedings of the International Conference.* Karlstad University Studies, Sundsvall, Sweden, pp 5–10
- Hilderbrand RH, Watts AC, Randle AM (2005). The myths of restoration ecology. *Ecology and Society* 10:1–19
- J hnig SC, Lorenz AW, Hering D, Antons C, Sundermann A, Jedicke E, Haase P (2011). River restoration success: A question of perception. *Ecological Applications* 21:2007–2015
- Jenkins GJ, Perry MC, Prior MJ (2009). The climate of the UK and recent trends. Met Office Hadley Centre, Exeter, UK
- JNCC (2011). Special Area of Conservation - River Ehen. <http://jncc.defra.gov.uk/protectedsites/sacselection/sac.asp?EUCode=UK0030057>. Accessed 11 Dec 2016
- Jones MR, Fowler HJ, Kilsby CG, Blenkinsop S (2013). An assessment of changes in seasonal and annual extreme rainfall in the UK between 1961 and 2009. *International Journal of Climatology* 33:1178–1194
- Jungwirth M, Muhar S, Schmutz S (2002). Re-establishing and assessing ecological integrity in riverine landscapes. *Freshwater Biology* 47:867–887
- Kelly M (2014). Simplicity is the ultimate sophistication: Building capacity to meet the challenges of the Water Framework Directive. *Ecological Indicators* 36:519–523

- Killeen I (2006). The Freshwater Pearl Mussel, in the River Ehen Cumbria. Report on the 2006 Survey. Malacological Services, Dublin
- Killeen I, Moorkens E (2013). Environmental Monitoring of the River Ehen freshwater pearl mussel population 2012: A report to United Utilities. Malacological Services, Dublin
- Killeen I, Oliver G (1997). The Freshwater Pearl Mussel (*Margaritifera margaritifera* [L. 1758]) in the River Ehen. Part 1. Report on 1996 Survey. Department of Zoology, National Museum of Wales, Cardiff: 24p.
- Killeen IJ (2010). Conservation and restoration of a freshwater pearl mussel (*Margaritifera margaritifera*) population in Northern England. In: *Aquatic Conservation with Focus on Margaritifera margaritifera. Proceedings of the International Conference in Sundsvall, Sweden, 12-14 August 2009*. pp 69–80
- Kondolf GM (1997). Hungry Water: Effects of Dams and Gravel Mining on River Channels. *Environmental Management* 21:533–551
- Kondolf GM, Anderson S, Lave R, Pagano L, Merenlender A, Bernhardt ES (2007). Two decades of river restoration in California: What can we learn? *Restoration Ecology* 15:516–523
- Langhans SD, Hermoso V, Linke S, Bunn SE, Possingham HP (2014). Cost-effective river rehabilitation planning: optimizing for morphological benefits at large spatial scales. *Journal of Environmental Management* 132:296–303
- Lavictoire L, Moorkens E, Ramsey AD, Sinclair W, Sweeting RA (2016). Effects of substrate size and cleaning regime on growth and survival of captive-bred juvenile freshwater pearl mussels, *Margaritifera margaritifera* (Linnaeus, 1758). *Hydrobiologia* 766:89–102
- Marteau B, Batalla RJ, Vericat D, Gibbins CN (2017). The importance of a small ephemeral tributary for suspended sediment dynamics in a main-stem river. *River Research and Applications* 1–15
- Marteau B, Vericat D, Gibbins C, Batalla RJ, Green DR (2016). Application of Structure-from-Motion photogrammetry to river restoration. *Earth Surface Processes and Landforms* 42:503–515
- Millenium Ecosystem Assessment (2005). Freshwater Ecosystem Services. In: Chopra K, Leemans R, Kumar P, Simons H (eds) *Ecosystems and Human Well-being: Policy Responses*. Island Press, Washington, USA, pp 213–255
- Moir HJ, Gibbins CN, Soulsby C (2003). River Ehen Pearl Mussel Project: Fluvial Audit. University of Aberdeen: 26p.
- Mollusc Specialist Group (1996). *Margaritifera margaritifera*. In: IUCN Red List Threat. Species 1996 e.T12799A3382532.
- Moorkens EA (2000). Conservation management of the freshwater pearl mussel *Margaritifera margaritifera*, Part 2: Water quality requirements. Irish Wildl. Manuals 9: 44p.
- Morandi B, Piégay H, Lamouroux N, Vaudor L (2014). How is success or failure in river restoration projects evaluated? Feedback from French restoration projects. *Journal of Environmental Management* 137:178–188
- Newson MD, Large ARG (2006). “Natural” rivers, “hydromorphological quality” and river restoration: a challenging new agenda for applied fluvial geomorphology. *Earth Surface*

Processes and Landforms 31:1606–1624

- O’Leary D (2013). Pearls in Peril LIFE+ GB - Action A3: Conservation Actions for the Freshwater Pearl Mussel in the River Ehen, Cumbria. Report LIFE 11 NAT/UK/383. West Cumbria River Trust, UK: 45p.
- O’Leary D, Webley J, Sime I (2017). Securing the future of the Freshwater Pearl Mussel. *British Wildlife* 28:421–425
- Ormerod SJ (2004). A golden age of river restoration science? *Aquatic Conservation: Marine and Freshwater Ecosystems* 14:543–549
- Österling ME, Arvidsson BL, Greenberg LA (2010). Habitat degradation and the decline of the threatened mussel *Margaritifera margaritifera*: influence of turbidity and sedimentation on the mussel and its host. *Journal of Applied Ecology* 47:759–768
- Oulasvirta P, Leinikki J, Syväranta J (2017). Freshwater pearl mussel in Finland—current status and future prospects. *Biology Bulletin* 44:81–91
- Palmer MA, Bernhardt ES, Allan JD, Lake PS, Alexander G, Brooks S, Carr J, Clayton S, Dahm CN, Follstad Shah J, Galat DL, Loss SG, Goodwin P, Hart DD, Hassett B, Jenkinson R, Kondolf GM, Lave R, Meyer JL, O’Donnell TK, Pagano L, Sudduth E (2005). Standards for ecologically successful river restoration. *Journal of Applied Ecology* 42:208–217
- Pander J, Geist J (2013). Ecological indicators for stream restoration success. *Ecological Indicators* 30:106–118
- Pearls in Peril (2017). Pearls in Peril. <http://www.pearlsinperil.org.uk/>. Accessed 5 Jun 2017
- Petts GE (2007). Hydroecology: The Scientific Basis for Water Resources Management and River Regulation. In: *Hydroecology and Ecohydrology*. John Wiley & Sons Ltd., pp 225–252
- Petts GE (1980). Long-term consequences of upstream impoundment. *Environmental Conservation* 7:325–332
- Petts GE, Gurnell AM (2005). Dams and geomorphology: Research progress and future directions. *Geomorphology* 71:27–47
- Purser GJ (1985). Factors affecting the distribution of the freshwater pearl mussel *Margaritifera margaritifera* (L.) in Britain. University of Aberdeen
- Quinlan E (2014). Ecogeomorphological dynamics of the River Ehen prior to its restoration. PhD thesis, University of Aberdeen, Scotland
- Quinlan E, Gibbins CN, Batalla RJ, Vericat D (2015a). Impacts of Small Scale Flow Regulation on Sediment Dynamics in an Ecologically Important Upland River. *Environmental Management* 55:671–686
- Quinlan E, Gibbins CN, Malcolm I, Batalla RJ, Vericat D, Hastie L (2015b). A review of the physical habitat requirements and research priorities needed to underpin conservation of the endangered freshwater pearl mussel *Margaritifera margaritifera*. *Aquatic Conservation: Marine and Freshwater Ecosystems* 124:107–124
- Roni P, Hanson K, Beechie T (2008). Global Review of the Physical and Biological Effectiveness of Stream Habitat Rehabilitation Techniques. *North American Journal of Fisheries Management* 28:856–890

- Skinner A, Young M, Hastie L (2003). Ecology of the Freshwater Pearl Mussel. *Conserving Natura 2000 Rivers Ecology Series No 2*, English Nature, Peterborough
- Stanford JA, Ward J V., Liss WJ, Frissell CA, Williams RN, Lichatowich JA, Coutant CC (1996). A General Protocol for Restoration of Regulated Rivers. *Regulated Rivers: Research & Management* 12:391–413
- Strayer DL (2006). Challenges for freshwater invertebrate conservation. *Journal of the North American Benthological Society* 25:271–287
- Strayer DL, Dudgeon D (2010). Freshwater biodiversity conservation: recent progress and future challenges. *Journal of the North American Benthological Society* 29:344–358
- Taubert J-E, Geist J (2017). The relationship between the freshwater pearl mussel (*Margaritifera margaritifera*) and its hosts. *Biology Bulletin* 44:67–73
- Tarr EC (2008). The population structure and habitat requirements of the freshwater pearl mussel, *Margaritifera margaritifera*, in Scotland. PhD thesis, University of Aberdeen, Scotland
- Thomas GR, Taylor J, Garcia de Leaniz C (2010). Captive breeding of the endangered freshwater pearl mussel *Margaritifera margaritifera*. *Endangered Species Research* 12:1–9
- United Utilities (2012). Hydrodynamic and Sediment Transport Modelling Report - Project Name: Ennerdale and Ben Gill - Project No: 80020012.
- Vandré R (2005). Field Trip: Measures of Habitat Restoration and Species Conservation Measures of the LIFE-Nature Project and Monitoring Results. In: Vandré R, Schmidt C (eds) *Proceedings of the Workshop "Pearl Mussel Conservation and River Restoration."* Bezirk Oberfranken & Anglerverband Südsachsen Mulde/Elster e.V., Bad Elster, Germany, pp 6–10
- Ward JV, Tockner K, Uehlinger U, Malard F (2001). Understanding Natural Patterns and Processes in River Corridors as the Basis for Effective River Restoration. *Regulated Rivers: Research & Management* 17:311–323
- Wheaton JM, Brasington J, Darby SE, Merz J, Pasternack GB, Sear D, Vericat D (2010). Linking geomorphic changes to salmonid habitat at a scale relevant to fish. *River Research and Applications* 26:469–486
- Wheaton JM, Darby SE, Sear DA (2008). The Scope of Uncertainties in River Restoration. In: Darby SE, Sear DA (eds) *River Restoration: Managing the Uncertainty in Restoring Physical Habitat*. John Wiley & Sons, Ltd., pp 21–39
- Wohl E (2005). Compromised rivers: Understanding historical human impacts on rivers in the context of restoration. *Ecology and Society* 10:1–16
- Wohl E, Angermeier PL, Bledsoe B, Kondolf GM, MacDonnell L, Merritt DM, Palmer MA, Poff NL, Tarboton D (2005). River restoration. *Water Resources Research* 41:1–12
- Ziuganov V, Zotin A, Nezhlin L, Tretiakov V (1994). The freshwater pearl mussels and their relationships with salmonid fish, Vniro Publ. Moscow

CHAPTER 2.

APPLICATION OF STRUCTURE-FROM-MOTION PHOTOGRAMMETRY TO RIVER RESTORATION

Baptiste Marteau, Damià Vericat, Chris Gibbins, Ramon J. Batalla and David R. Green.



*Outlet of Ennerdale Water during the engineering work undertaken to reconnect Ben Gill to the River Ehen.
Photo: SUAVE Air Photos, September 2014.*

Paper published in the journal *Earth Surface Processes and Landforms* (42): 503-515 [2017]

CHAPTER 2. APPLICATION OF STRUCTURE-FROM-MOTION PHOTOGRAMMETRY TO RIVER RESTORATION

2.1. ABSTRACT

Structure-from-Motion (SfM) photogrammetry is now used widely to study a range of earth surface processes and landforms, and is fast becoming a core tool in fluvial geomorphology. SfM photogrammetry allows extraction of topographic information and orthophotos from aerial imagery. However, one field where it is not yet widely used is that of river restoration. The characterisation of physical habitat conditions pre- and post-restoration is critical for assessing project success, and SfM can be used easily and effectively for this purpose. In this paper we outline a workflow model for the application of SfM photogrammetry to collect topographic data, develop surface models and assess geomorphic change resulting from river restoration actions. We illustrate the application of the model to a river restoration project in the NW of England, to show how SfM techniques have been used to assess whether the project is achieving its geomorphic objectives. We outline the details of each stage of the workflow, which extend from preliminary decision-making related to the establishment of a ground control network, through fish-eye lens camera testing and calibration, to final image analysis for the creation of facies maps, the extraction of point clouds, and the development of Digital Elevation Models (DEMs) and channel roughness maps. The workflow enabled us to confidently identify geomorphic changes occurring in the river channel over time, as well as assess spatial variation in erosion and aggradation. Critical to the assessment of change was the high number of ground control points and the application of a minimum level of detection threshold used to assess uncertainties in the topographic models. We suggest that these two things are especially important for river restoration applications.

Key words: Structure-from-Motion, Photogrammetry, River Restoration, UAV, High Resolution Topography, Digital Elevation Models, Geomorphic Change.

2.2. INTRODUCTION

Developments in surveying techniques (e.g. terrestrial and airborne LiDAR) alongside the availability of improved data-processing tools (e.g. GIS and remote sensing software, open source geostatistical toolkits) have brought geomorphological science into a new era (see recent reviews by Bangen et al. 2014 and Smith et al. 2015). This new era is changing not only the way in which we can characterise landscapes but also how we understand the processes which shape them. The new era is particularly evident in fluvial geomorphology, where the application of newly evolving surveying and processing tools has been seen as heralding-in the High Resolution Topography (HRT) revolution (as described recently by Vericat et al. 2017). This revolution is greatly improving our ability to assess geomorphic change in river channels, whether in the context of human impacts or natural fluvial dynamics.

HRT was defined by Passalacqua et al. (2015) as topographic surveys at a minimum of the metre resolution. In fluvial geomorphology, HRT is most commonly used for: (i) landscape characterisation (e.g. topography, roughness; Heritage and Milan 2009; Brasington et al. 2012; Tamminga et al. 2014; Woodget et al. 2014), and/or (ii) monitoring topographic changes (e.g. quantification of the volume of sediments mobilised; Lane et al. 2003). Several commonly used technologies allow the collection of HRT data (Passalacqua et al. 2015), but increasing use is now being made of digital photogrammetry via Structure-from-Motion (SfM) and Multi View Stereo (MVS) techniques (hereafter together referred to as SfM, James and Robson 2012). One of the advantages of SfM over other HRT acquisition methods is the collection of topographic information and orthophotos at multiple spatial scales (from the microhabitat or patch scale (m^2) to the scale of river reaches (tens, hundreds or even thousands of metres in length; Dietrich 2016)), and with a resolution appropriate for many applications (Wheaton et al. 2010a, b; Tamminga et al. 2014). While the basic concepts are similar, SfM differs from traditional photogrammetry in the fact that little expertise is required, image processing and camera calibration can be fully automated and relatively few control points are required (James and Robson 2012). SfM creates a light 3D point cloud from automatically aligned overlapping images, while the MVS algorithms then allow for the generation of a high-density 3D point cloud (detailed in James and Robson 2012; Micheletti et al. 2015; Smith et al. 2015). The rapid improvement in Unmanned Aerial Vehicle (UAV) platforms is facilitating the acquisition of high quality aerial imagery from which SfM can be applied to obtain orthophotos and point clouds (e.g. Javernick et al. 2014; Woodget et al. 2014; Smith and Vericat 2015).

The acquisition of HRT data is now commonplace, and as a result the HRT revolution has changed the nature of the problem faced by geomorphologists. Historically the problem was one of being able to collect sufficient data to adequately capture the landscape characteristics or processes of interest, whereas now the problem is one of how best to process and use the mass of high resolution data that it is possible to collect (Vericat et al. 2017). In short, HRT data do not necessarily mean that research questions or hypotheses can be properly addressed (Lane and Chandler 2003); rather, the point is that they have to be seen simply as part of the toolkit which helps us to better understand earth surface processes (Tarolli 2014). An equally critical part of the toolkit is a framework or workflow that allows data to be collected and used correctly to address the research question(s) at hand. Key stages include the establishment of an appropriate Ground Control Point (GCP) network (Westoby et al. 2012) and appropriate camera calibration (Micusík and Pajdla 2006). Assessment of error, at various stages, is also important (Passalacqua et al. 2015) and for this some experimentation is often necessary. Thus, greater engagement with each stage of the process is extremely important (Smith et al. 2015).

The last decade has seen a significant rise of interest in the theory and practice of river restoration (Smith et al. 2014a). River restoration extends from localised actions such as gravel augmentation to broader ecosystem restoration such as the connection of river and floodplain areas through channel and flow re-naturalisation (Boon 1998). Lamouroux et al. (2015) highlighted the need for science-based tools to reliably predict the ecological responses to such restoration. These tools rely partly on the correct characterisation of physical habitat conditions prior to the commencement of restoration and the tracking of habitat changes that occur over time in response to the restoration. However, such characterisation, which is now possible through the acquisition of HRT data, has been argued to be missing in many restoration monitoring projects (Olden et al. 2014; Lamouroux et al. 2015). The emergence of UAVs and the application of SfM to UAV imagery can potentially help resolve this issue: i.e. repeat topographic survey data allow assessment of the geomorphic 'success' of restoration projects and, in turn, whether such physical habitat changes may lead to improved Ecological Status (as defined in Europe by Water Framework Directive criteria, European Union 2000).

This paper addresses the question of how we can best use HRT data and SfM techniques to assess geomorphic changes occurring in response to river restoration. The paper presents a detailed workflow model of how HRT data can be obtained effectively and how they can be used to aid assessment of geomorphic change. We first provide some basic information on HRT

acquisition and applications. Then we present the workflow model designed to acquire and assess HRT information by means of SfM photogrammetry applied to UAV-based imagery; it builds upon existing generic workflows (e.g. Westoby et al. 2012) to improve confidence in output from consumer grade cameras and UAV platforms. As part of the presentation of this workflow we discuss the various issues that need to be considered at each stage, and cite key papers that provide greater details of specific methods or analyses. We then use a case study (Ben Gill, NW England) to show examples of analyses and outputs from each stage of the workflow. Finally, we summarise and discuss the insights provided by HRT data and SfM photogrammetry in the river restoration case study, and outline the broader relevance of the workflow model.

2.3. DIGITAL PHOTOGRAMMETRY: WORKFLOW AND ITS APPLICATION TO RIVER RESTORATION

2.3.1. Study area and context

The River Ehen (NW England, Figure 2.1) supports an internationally important population of the endangered mussel *Margaritifera margaritifera* (L.). As part of a programme of measures to improve habitat conditions in the Ehen for mussels, restoration work on one of its tributaries (Ben Gill) commenced in 2014. Ben Gill is a small (0.54 km²), high gradient (slope 25%) first order stream. Although it is not gauged, previous estimates suggest that it flows for approximately 23% of the time (Quinlan et al. 2015a). In the 1970s Ben Gill was disconnected from the Ehen and diverted to Ennerdale Lake (see Figure 2.1B) to help increase lake storage and meet abstraction requirements in the region. The disconnection diverted the lower section of Ben Gill, such that rather than following its original course to the Ehen, water fell through a grill and was conveyed via an underground culvert to the lake. The original channel in the lower section has progressively terrestrialised in the 40 years since the diversion, becoming largely indistinguishable from the surrounding rough pasture land. Sediments delivered from the upper section, which accumulated around the grill, have been removed periodically and used locally as building material. However, concerns over how this diversion might be limiting sediment supply to and flows in the Ehen (and hence impacting the suitability of conditions for mussels) prompted plans to reconnect it.

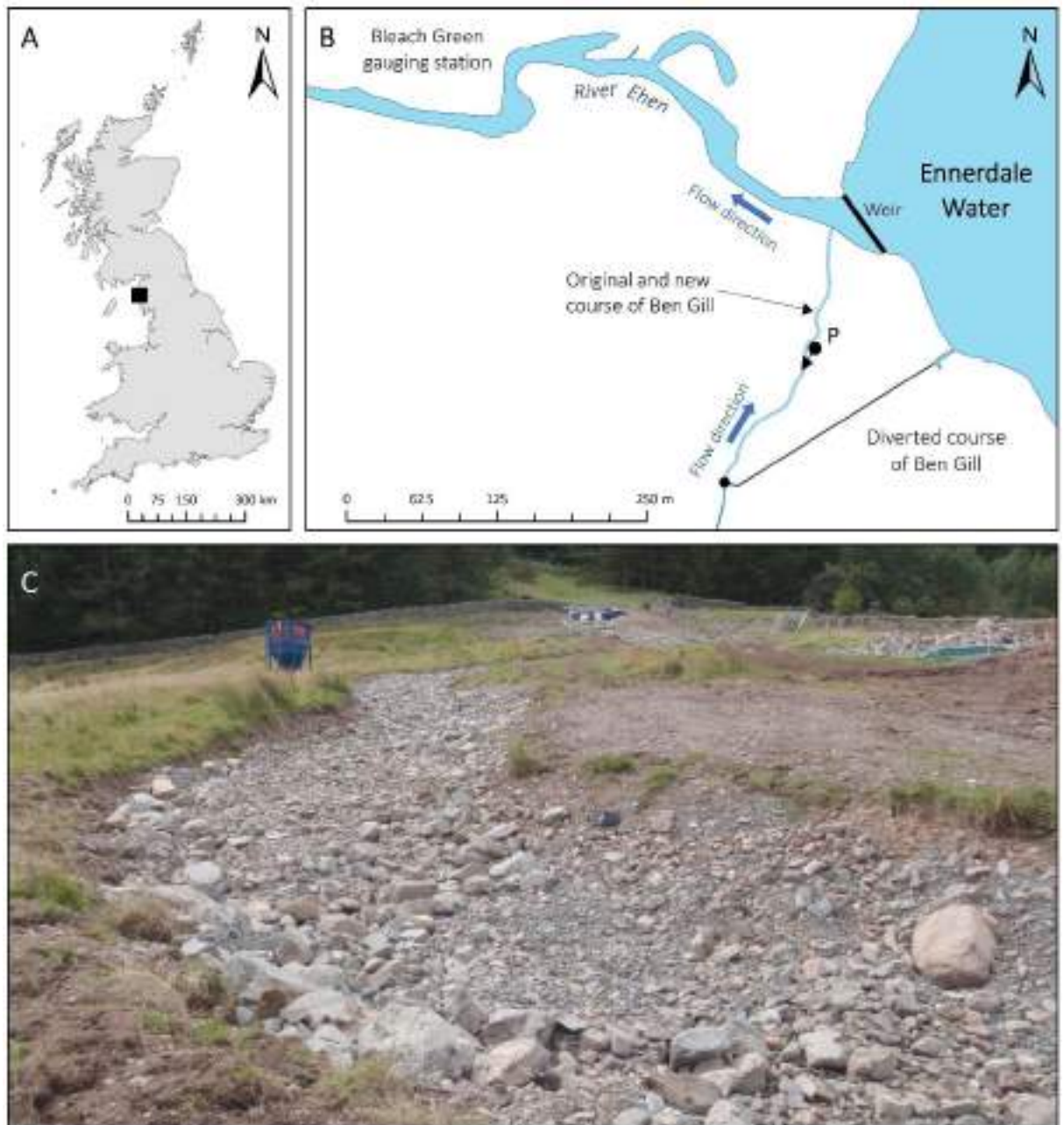


Figure 2.1. (A) Location of the study site (River Ehen, Lake District, NW England); (B) Original and new course of Ben Gill, from the old diversion to its confluence with the Ehen (point “P” shows position and direction of photograph in C); (C) Photograph of the newly created Ben Gill channel before reconnection (credit: EA Penrith).

During the summer of 2014, a new channel was engineered for the lower section of Ben Gill, following its original (pre-diversion) course. The channel was designed to convey a 1 in 100-year flood, plus a 20% increment to accommodate potential increases in discharge related to climate change. It was constructed 5 m wide and 0.5 m deep (mean values), with a generally semi-circular cross sectional shape (Figure 2.1C) (United Utilities 2012). This new lower section of channel is approximately 300 m long and has an average gradient of 9.4%. Once dug, the channel was lined with cobble-size material (sizes between 20 and 250 mm *b* axis), with larger

boulders along the sides (up to 750 mm b axis). The new channel was reconnected on October 3rd, 2014, at which point water and sediments from Ben Gill were again able to enter the main River Ehen (Figure 2.1B). Our objective was to monitor geomorphic changes in Ben Gill, in order to quantify how much sediment would be delivered to the Ehen as a result of the reconnection and the evolution of the engineered channel. Figure 2.2 shows the timeline of the study while Figure 2.3 presents the workflow model designed to provide a framework to assess geomorphic changes in Ben Gill.

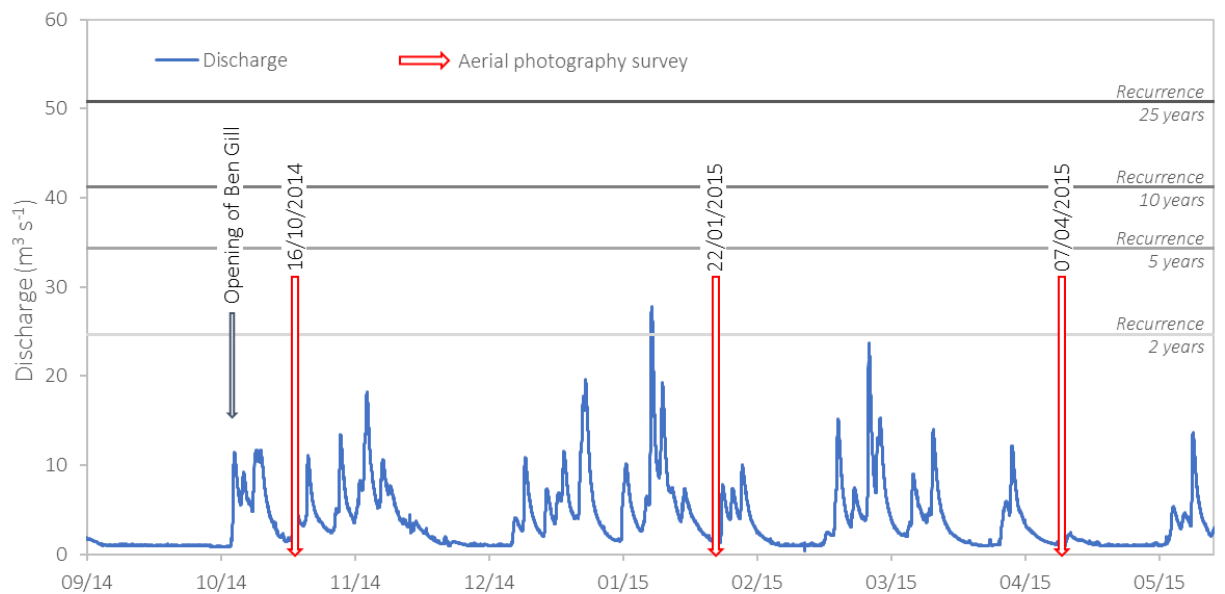


Figure 2.2. Timing of the aerial photography surveys in relation to discharge measured at the River Ehen Bleach Green gauging station, approximately 550 m downstream from the confluence of Ben Gill and the Ehen.

2.3.2. Data acquisition

The spatial coverage and resolution of image capture in photogrammetric studies should be chosen to match research objectives. In fluvial applications, the areas covered are frequently in the order of km^2 , with variable flying altitudes (e.g. Javernick et al. 2014 [600m]; Tamminga et al. 2014 [100m]; Dietrich 2016 [200m]). While the resolution achieved in such large spatial area studies can be remarkable, a much higher resolution can be expected when the same technology is applied to a much smaller area with a low flying altitude (e.g. in the case of Ben Gill, covering 300 m channel length at <20 m altitude). Low altitude flights also have the advantage that, in the UK, they are below those needed for Civil Aviation Authority permissions (121.92 m, Civil Aviation Authority 2015).

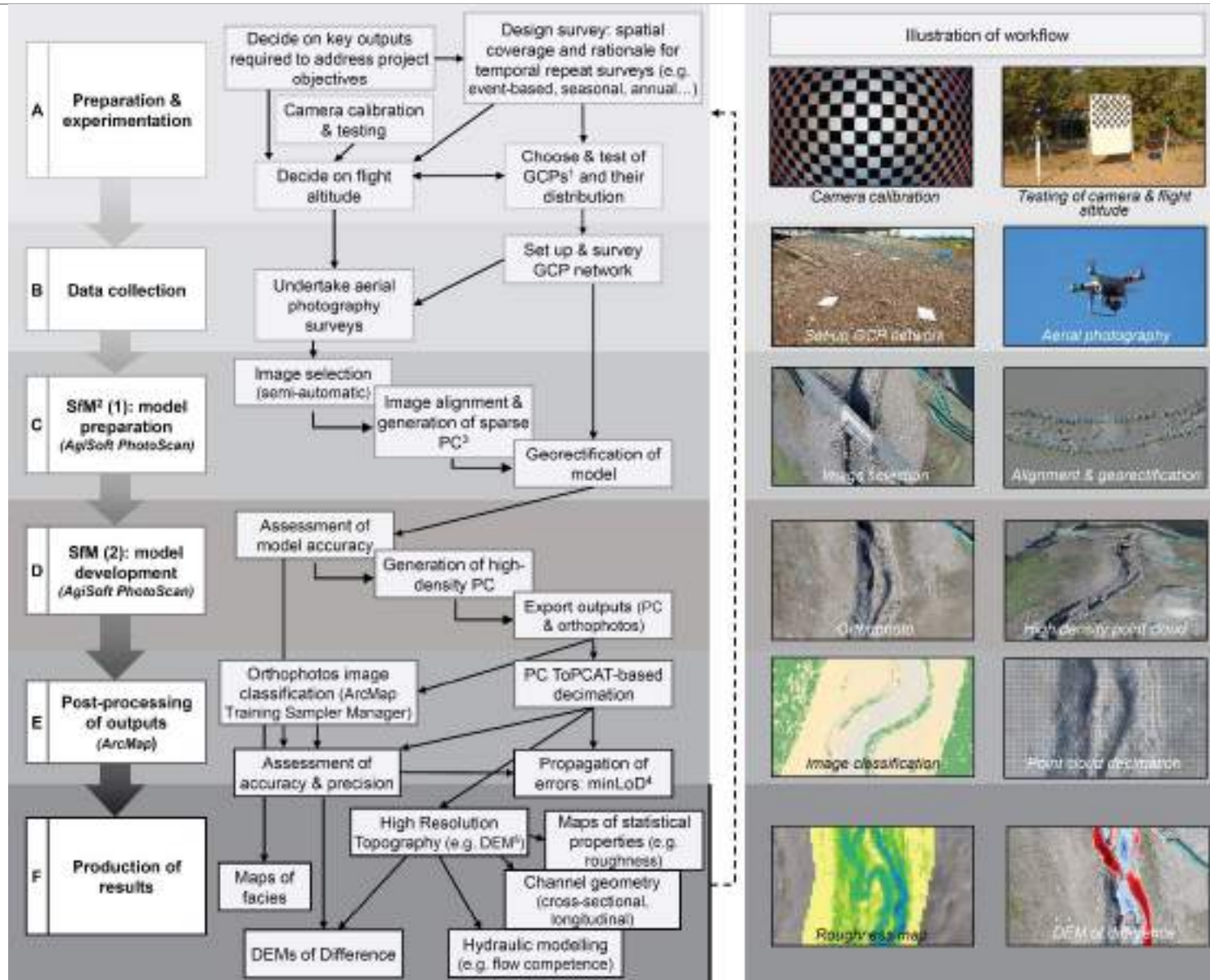


Figure 2.3. Schematic to illustrate the general workflow presented in this paper, including: (A) Preparation & experimentation, (B) Data collection, (C) Structure-from-Motion photogrammetry process preparation and (D) development, (E) Post-processing of outputs and (F) Production of results. Timeline runs through from A to F. Note that the abbreviations mean: ¹Ground Control Points, ²Structure-from-Motion Photogrammetry, ³Point Cloud, ⁴minimum Level of Detection, ⁵Digital Elevation Model.

The fact that Ben Gill is an intermittent stream means that for most of the time the channel bed is exposed, enabling the collection of HRT data for its whole area. This avoids errors related to water surface reflection in submerged areas (as discussed by Tamminga et al. 2014; Woodget et al. 2014). Aerial images for the channel were collected using a 12 megapixel GoPro Hero 3+ Black Edition (Woodman Labs, Inc., USA). GoPro cameras are used increasingly for photogrammetry but the use of fisheye lenses (as present in the GoPro) has been criticised (e.g. James and Robson 2012). We therefore undertook a series of camera tests prior to data collection (Figure 2.3); these tests were also designed to determine appropriate Ground Control Point (GCP) markers. First, we evaluated different shapes, sizes and colours of GCP markers, to assess visibility and ease of picking out their centre points at multiple distances (i.e. at potential flight altitudes). Second, camera calibration parameters were obtained using AgiSoft Lens (AgiSoft LLC 2015a; AgiSoft LLC, Russia). These parameters included the k_3 and k_4 distortion coefficients, which are advised when using fish-eye lenses for SfM (PhotoModeler 2013). Third, once calibrated, an experiment was designed to test for the ability of the camera to capture details at different distances and to evaluate the errors associated with different flight altitudes. This experiment was conducted outdoors. Two A0 sized posters with attached coloured semi-spheres (of known sizes, from 1 to 10 cm diameter) were each glued to a board. Pictures were taken at multiple distances from the boards (5 m, then from 10 to 50 m at 10 m increments) to represent different flight altitudes. A local survey control network was set up by means of 4 targets installed around the field where the experiment was conducted, and markers placed on each corner of each board. A Leica TCRP1201 Total Station (Leica Geosystems Inc.) was set up using the local control network and used to survey the position and shape of each of the painted semi-spheres. Additionally, 100 random points were surveyed on the flat surface of each of the boards. The point clouds obtained from the GoPro photographs taken at different distances from the boards were compared with the points surveyed by the Total Station. The results indicated that Root Mean Square Errors (RMSE) of the residuals of the elevations ranged from 0.015 to 0.192 m. Residuals were lowest at 5 m from the boards (RMSE= 0.015), and were consistent at 10 and 20 m (RMSE of 0.040 and 0.030 m respectively). At distances greater than 30 m from the boards, residuals were of the same magnitude as the size of the semi-spheres. Thus, the optimal flight altitude for this camera, given the RMSE values, was determined to be around 20 m. This altitude guarantees a sufficiently large image footprint and, given the camera's lens, minimal error for characterising channel properties (e.g. roughness).

Once flight altitude and camera tests were completed, 196 A3-sized white GCPs, marked with a black cross in the centre, were installed around the channel. GCPs are necessary to register all data to the same coordinate system. They are also the most common way to infer positional uncertainty in SfM (Passalacqua et al. 2015) and, when distributed appropriately, can help with correction of the so-called ‘dome effect’ (which results from the use of exclusively vertical imagery; Smith and Vericat, 2015). Of the 196 GCPs, 178 were spread regularly in four parallel lines (two along each side of the channel), while the remaining 18 were scattered randomly at meanders to better capture channel planform where it was more complex. The same GCPs were used for all flights (i.e. we had a fixed control network) and were re-surveyed frequently to make sure none had moved. The total area studied covers approximately 0.06 km², with the GCPs therefore giving an average density of 3300 per km² (i.e. 33 GCPs per hectare) This is a very high density compared to other studies (e.g. Woodget et al. 2014; 5.7 to 7.6 per hectare). All GCPs were surveyed using a Leica Viva GNSS (Leica Geosystems Inc.) differential rtk-GPS. The quality of the coordinates (3D quality) oscillated between 0.009 and 0.024 m.

Periodic UAV surveys were undertaken following the reconnection of the Ben Gill channel (Figure 2.2), timed to capture changes following high flow events. The camera was mounted on a DJI Phantom I UAV. Images were captured vertically, thanks to the Zenmuse H3 2D gimbal camera mount holding the GoPro. The time-lapse function of the camera allowed for image capture at 1 second intervals, with around 1100 images acquired per survey. The UAV was controlled manually on each survey. Test flights indicated that flying at 20 m altitude along 3 lines (both banks, then along the channel centreline) yielded necessary image overlap. As the channel was open and accessible along its full length, altitude and flight lines were controlled easily by walking alongside the UAV. Here we present data and outputs from 3 surveys to illustrate application of the workflow.

2.3.3. Data processing

2.3.3.1. Digital Photogrammetry: set up and application

Aerial images were post-processed using Agisoft PhotoScan Professional (Agisoft LLC 2015b); the main steps are schematically represented in Figure 2.3. The number of images selected for each model was limited to a maximum of 500, in order to provide good overlap without over-extending the computing time required for processing. A first set of images was discarded using the ‘Estimated Image Quality’ from PhotoScan, which uses sharpness values to define quality

(0 = blurred, 1 = very sharp). The standard approach is to discard images with sharpness values less than 0.5. However, we adopted a value of 0.85 which meant that only the very sharpest images were retained. Additional images were then discarded on the basis of 4 criteria: (i) over-exposure to light, (ii) graininess due to high ISO values, (iii) objects (e.g. legs of the UAV) hiding features of interest, and (iv) very high overlap between images (e.g. when the UAV was static). The final selected images were then aligned in AgiSoft using the calibration parameters acquired during the 'preparation and experimentation' phase. The centre points of the GCPs were identified and adjusted manually on the images for more accurate positioning. The coordinates of the GCPs were used to georeference the sparse point cloud. The MVS algorithm implemented in the software allowed creation of the final dense point cloud. AgiSoft provides the errors (in three dimensions) of the GCPs used for the registration. These registration errors provide a first indication of the quality of the point cloud, although strictly speaking they only represent the error associated with the transformation (rotation, translation and scaling) of the point clouds. We therefore used some of the GCPs as Check Point (ChP) markers to assess the accuracy of the point cloud.

2.3.3.2. Processing point clouds

The steps reported above allowed the creation of very high-density point clouds (>20 million observations) which represented large and computationally demanding files. To reduce the processing constraints, the raw point clouds were decimated using the Topography Point Cloud Analysis Toolkit (ToPCAT) (Brasington et al. 2012). ToPCAT is now available within the Geomorphic Change Detection ArcMap extension (see <http://gcd6help.joewheaton.org/>) and has been used by several authors (e.g. Brasington et al. 2012; Storz-Peretz and Laronne 2013; Williams et al. 2014; Smith and Vericat 2015). The point cloud decimation procedure followed the approach set out by these authors, and allows the creation of gridded topographic information, including statistical parameters for each cell.

Point cloud decimation was executed at two different resolutions. A 0.05 m resolution model was created and used to obtain the DEMs, which were then used to assess geomorphic changes. This resolution was chosen to be in agreement with the errors of the surveys (see 'Error analysis' section below). The minimum elevation within each cell was the statistical parameter used as ground elevation. These values were gridded using the *Topo to Raster* tool in ArcMap 10.3 (Esri[®] Inc., USA). The choice of interpolation method is important when the

density and distribution of data points are poor (Chaplot et al. 2006; Weng 2006). In our case a formal interpolation was not required as the average point density per cell was high (up to 35). To complement the 0.05 m resolution model, a 0.25 m decimation was undertaken and used to generate sub-grid statistics that were used to characterise channel roughness. Among the statistics produced were the standard deviations of the detrended elevations within each cell. This statistic is being used increasingly as a metric of roughness across the Earth Sciences (Smith 2014); it is particularly useful as it represents how variable the micro-topography is in each cell, as a function of particle size variability and bedforms. For Ben Gill, the 0.25 m model was used to develop roughness maps. Roughness values are influenced by the size of the grid cells: if the grid is too small, all observations within a cell may fall on the same particle, while if the grid is too large, the deviation of the elevations will not be just determined by the size of the particles, but will be influenced by bedforms or by abrupt topographic changes (e.g. at banks). Thus, the selection of the grid cell size in this type of analysis is fundamental. For Ben Gill, grid cell size was determined based on the sediments used to line the new channel (maximum 250 mm *b* axis).

2.3.3.3. Analysing geomorphic change

Although direct comparison of point clouds is possible (Lague et al. 2013), the most commonly used approach to monitor geomorphic change is to compare two successive DEMs through the production of DEMs of Difference (DoDs). DoDs have been applied widely in fluvial geomorphology to estimate bed material transport rates (Ashmore and Church 1998; Church 2006; Vericat et al. 2017), as well as to analyse channel changes (Lane et al. 2003; Brasington et al. 2003; Wheaton et al. 2013) and to help parameterise hydraulic models (e.g. Williams et al. 2013). For Ben Gill, DoDs were used to assess the magnitude and spatial patterns of geomorphic change as well as to establish sediment budgets (Lane et al. 2003; Brasington et al. 2003; Wheaton et al. 2010b). In this paper we present DoDs produced from 3 flights, which we use to assess changes occurring over two periods within the first 6 months of the reconnection. The quality of the DEMs determines the level of confidence that can be placed on assessment of change, and is discussed in the 'Error analysis' section.

2.3.3.4. Obtaining orthophotos

High resolution orthophotos (0.025 m cell) of the survey area were exported from AgiSoft PhotoScan. Although these can be used for a variety of purposes (e.g. Vericat et al. 2009;

Tamminga et al. 2014), we used them to classify and quantify substrate cover in Ben Gill, distinguishing between features of interest (substrate) and non-interest (vegetation, fences, a footbridge etc.). Sediments in these orthophotos (referred to henceforth as facies maps) were classified as coarse (gravel to boulder sized material) or very fine material (sand and clay material). The 'Image Classification' tool (ArcMap 10.3) was used to run a Maximum Likelihood Classification of the orthophotos. Classified images were used to help interpret assessments of change. Note that direct field-based validation of the classification was not undertaken.

2.3.4. Error analysis

Based on some of the general principles reported by Wheaton et al. (2010b), the next key step in the workflow was to assess uncertainties in the DoDs. Uncertainty in the comparison of topographic models has been analysed critically by Brasington et al. (2000) and Lane et al. (2003). More recently, Wheaton et al. (2010) questioned the possibility of distinguishing real geomorphic change from noise when two DEMs are compared through DoDs. They developed different methods to account for uncertainty in DoDs, from simple to more complex ones. AgiSoft PhotoScan provides information on the error associated with the registration process. Additionally, it is possible to produce an estimation of the quality of the point cloud by using some of the GCPs as ChPs. For Ben Gill, differences between the real coordinates of the ChPs and their estimated coordinates (provided automatically by the software) was used as an indication of the 'measurement quality'. One third ($n = 64$) of the GCPs were used as ChPs, while the remainder ($n = 129$) were used as markers (i.e. for the registration of the point cloud). A bootstrapping resampling technique was implemented within AgiSoft to randomly select ChPs and calculate the errors (residuals) for all GCPs. After 1000 resamplings, (i) the standard deviation of these residuals was defined as the measurement uncertainty (or precision), while (ii) the mean of the residuals was considered as the accuracy.

Once the measurement of uncertainty of each model is assessed, a minimum Level of Detection threshold (minLoD) can be calculated. This minLoD allows what is considered as real topographic change to be distinguished from inherent noise (Fuller et al. 2003). There are different methods to propagate the errors and identify the minLoD, ranging from a simple uniform distribution of the estimated DEM error to more complex statistical calculations of spatially distributed errors (see Brasington et al. 2000; Lane et al. 2003; Wheaton et al. 2010b; Milan et al. 2011). The conventional uniform approach can be sufficient for low topographic

complexity environments, but tends to be overly-conservative compared to the spatially distributed approach (Milan et al. 2011). A more sophisticated statistical model of DEM surface error propagation (Lane et al. 2003; Brasington et al. 2003; Wheaton et al. 2010b) that helps detect lower magnitude geomorphic changes (erosion and/or deposition) was used for Ben Gill. This involves calculation of the spatial distribution of *t*-scores (Lane et al. 2003) using:

$$t = \frac{Z_2 - Z_1}{\sqrt{(\varepsilon_{DEM_1})^2 + (\varepsilon_{DEM_2})^2}}$$

with Z_2 and Z_1 being the elevation in a given cell of the most recent and oldest DEM respectively, and ε_{DEM_2} and ε_{DEM_1} their respective error terms (in our case the standard deviation of the ChP residuals).

In this approach, each cell is attributed a *t*-score. Change observed in each cell is estimated to be true or false, based on the chosen minimum threshold of *t*-score (e.g. 1.28 for 80% Confidence Interval [CI], 1.96 for 95% CI). Therefore, by rearranging the above equation (Brasington et al. 2003), a minLoD can be calculated as:

$$minLoD = t \sqrt{(\varepsilon_{DEM_1})^2 + (\varepsilon_{DEM_2})^2}$$

Consequently, when the difference in elevation ($Z_2 - Z_1$) in a given cell is smaller than the minLoD, the change is considered uncertain at the chosen confidence interval (*t*). This does not mean that no change occurred in the cell, but simply that the estimated changes are subject to such uncertainty that it is unwise to use them.

2.4. EVALUATING GEOMORPHIC RESPONSES TO RIVER RESTORATION: THE CASE OF BEN GILL AND THE RIVER EHEN

2.4.1. High resolution orthophotos

Table 2.1 shows the main parameters for each of the three flights, with an example orthophoto presented in Figure 2.4A. Data for this orthophoto were acquired in April 2015; the registration error during post-processing was 0.039 m. It was exported at 0.025 m resolution and used for classification of vegetation, gravel and fine sediment (Figure 2.4B).

Table 2.1. Main parameters for each flight performed and the average point density of the point clouds obtained. Note that the pixel resolution is the optimum established by the software according to image quality.

Model	Number of images	Average flight altitude <i>m</i>	Average pixel resolution <i>cm²/pix</i>	Average point density <i>p/m²</i>
October 2014	500	13.1	0.0556	1790
January 2015	361	15.6	0.0729	1370
April 2015	475	12.4	0.0454	2210

Image classification can be of great use for critically reviewing geomorphic changes inferred from DoDs. For example, vegetation may be wrongly interpreted as geomorphic change due to seasonal patterns of growth and decay. Vegetation was not a major issue in Ben Gill because it was more or less absent from the active channel (Figure 2.4B). Areas determined as fine sediments were very flat and had low roughness values. Thus, geomorphic changes appearing in such areas are very likely to be real ones. Conversely, areas identified as being composed of coarser material had different values of roughness and, potentially, the uncertainty surrounding estimates of topographic change monitored in these areas will be greater.

2.4.2. Surface and roughness models

Table 2.1 presents the average point density of the three Ben Gill point clouds, while Table 2.2 shows the registration errors and the uncertainty and accuracy of each one. On average, point clouds had more than 1000 points/m². Values for registration errors and model uncertainty were very similar and never exceeded 0.06 m. These results indicate that the workflow allowed the collection of high density and accurate HRT data for the Ben Gill channel. Figure 2.4C shows an example of one of the DEMs.

An example of using the detrended standard deviation of elevations as an indicator of bed roughness is shown in Figure 2.5. As is evident in the Figure, the banks of the channel are formed by relatively rough (i.e. coarse) sediments while finer sediments are present mostly in the bed of the channel. Roughness values for the flat parts of the channel are in agreement with sediment sizes observed in the field. However, as Figure 2.1C shows, the convex parts of the bends were covered with relatively fine material, something which is not evident solely from the roughness values. The overestimation of roughness in these convex areas may be

attributed to the size of the grid for which roughness was calculated (0.25 m) in relation to the sharpness of the bank. A similar effect is observed with the presence of bedforms in river channel beds. If the grid of the cell used to calculate the sub-grid statistics using ToPCAT is larger than the bank line (or the bedform if the case), the detrending procedure does not only provide the variability of the elevations mainly attributed to the particles, but also the variation attributed to the bank slope (or to the bedform). A simple way to overcome the problem is to clip these zones out from the analyses (using the orthophoto classification data); alternatively, the grid resolution in these zones could be changed. These solutions require some additional work, but their products are advantageous as they allow the production of continuous maps of roughness which can be very valuable for the assessment of habitat conditions, their evolution over time, and for the parametrisation of hydraulic models, all of which are extremely useful in restoration applications.

Table 2.2. Registration errors and model precision and accuracy of the October 2014, January 2015 and April 2015 point clouds.

Model	Registration error* (m)				Model precision ** (m)				Model accuracy*** (m)			
	x	y	z	3D	x	y	z	3D	x	y	z	3D
October 2014	0.031	0.030	0.021	0.050	0.031	0.031	0.022	0.025	0.025	0.024	0.014	0.044
January 2015	0.028	0.048	0.020	0.060	0.032	0.049	0.020	0.030	0.028	0.039	0.015	0.056
April 2015	0.030	0.019	0.011	0.039	0.031	0.020	0.012	0.017	0.025	0.016	0.009	0.035

*Errors of the Ground Control Points (GCP) after georeferencing the point cloud.

**Precision assessed as the standard deviation of the Check Point (ChP) residuals.

***Accuracy estimated as the mean value of the ChP residuals.

Three close-ups are presented as part of Figure 2.5 to illustrate different features in the new channel. Figure 2.5A shows contrasting roughness around an erosional area in the downstream section of the channel. While the main layer of clay is flat and constant, abrupt lines of coarse sediment are observed. Figure 2.5B shows a rather uniform section (except for the margins) in the middle section of the channel. Although the roughness values here are generally similar, several facies can be observed; this is in agreement with visual observation of the orthophotos. Finally, in 5C a more complex and heterogeneous distribution of roughness is shown for an upstream section of the channel. The heterogeneity is related mainly to the large boulders which were placed here at the time of channel construction.

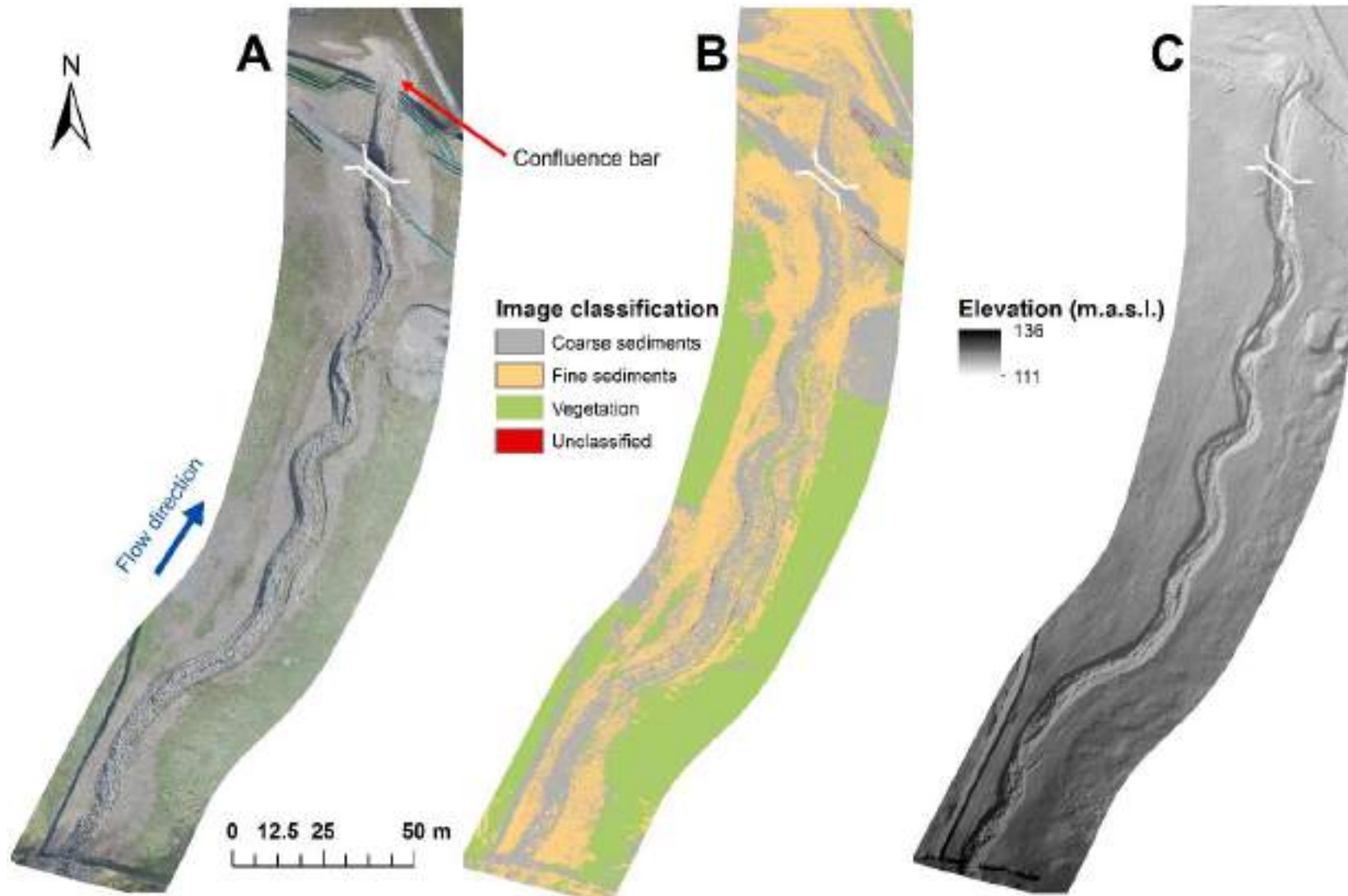


Figure 2.4. Illustration of some workflow outputs: (A) An example of high resolution orthophoto (0.025m resolution) produced from the mosaic of individual images, (B) Result of the image classification process of the orthophotos, and (C) Digital Elevation Model (0.05 m resolution). All relate to images taken in April 2015. *Note that "Unclassified" in B refers to obstructing features that were not classified as sediments or vegetation (e.g. fences).

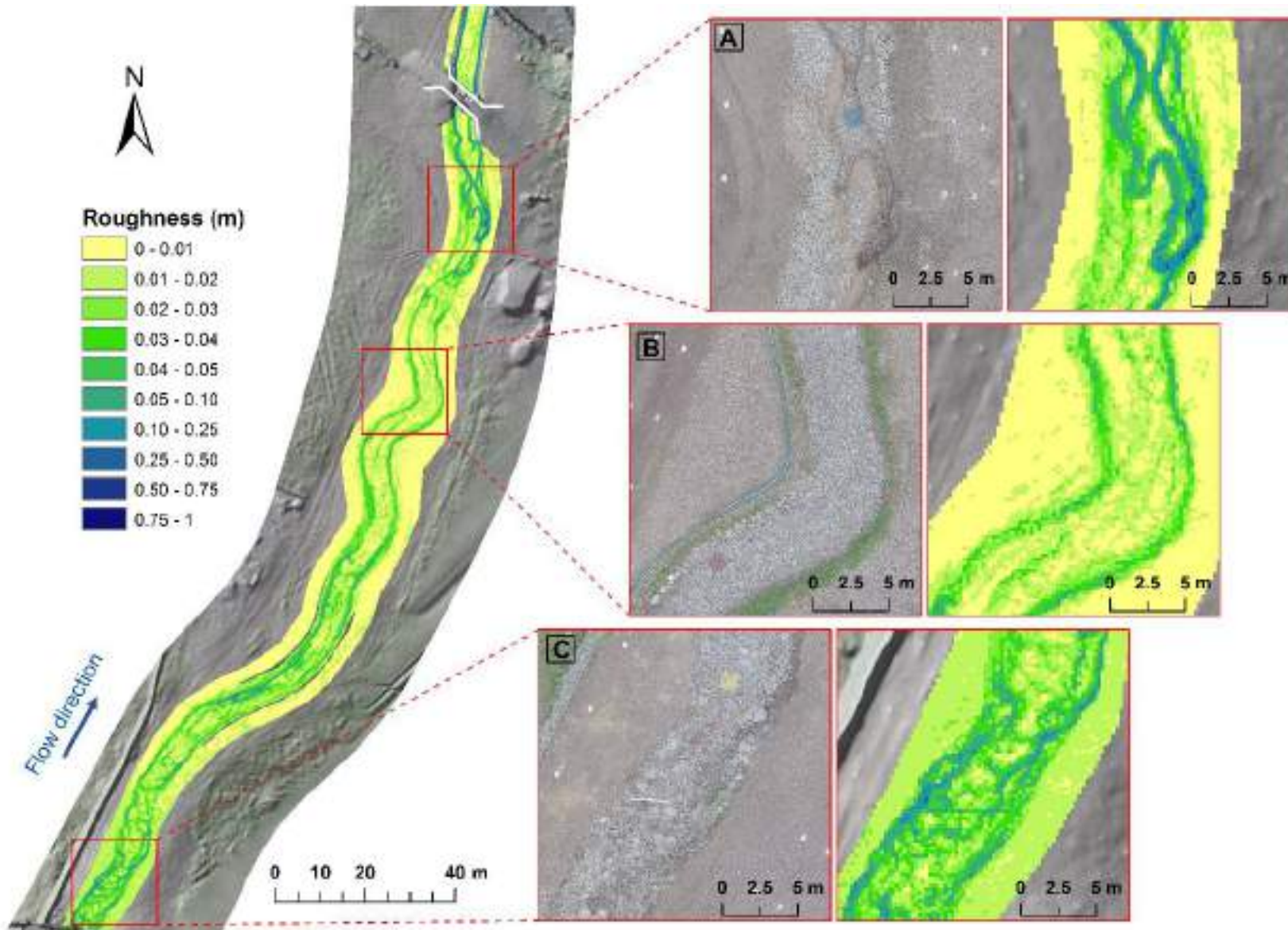


Figure 2.5. An example of roughness map (October 2014) of Ben Gill, with close-ups illustrating differences in roughness characteristics at various points along the channel. Roughness was estimated as the detrended standard deviation of the elevations (see text for more details). Aerial photos are presented as a reference and to help interpret roughness values. Squares (A), (B) and (C) refer to different zoom-ins, relating the observed roughness with the aerial image for different roughness conditions.

Roughness values obtained by this approach tend to correlate well with the median particle size of the sediments, as already indicated by Brasington et al. (2012). Although the correlation presented by these authors requires site-specific validation, it is evident that roughness maps can potentially be transformed into particle size maps that may add value to the information provided by image classification; in turn, this aids understanding of changes in bed texture in time and/or space.

2.4.3. Geomorphic change detection

Topographic changes (Figure 2.6) were thresholded by applying a statistical minLoD as described in the 'Error Analysis' section. In this case, we used $t = 1.28$ (i.e. 80% CI). A value of $t = 1.96$ (i.e. 95% CI) was also applied to see how changing the confidence interval affected the results (Table 2.3). By taking a more or a less conservative t value, the number of cells considered as recording real changes in Ben Gill, as well as the estimate of net change, varied appreciably.

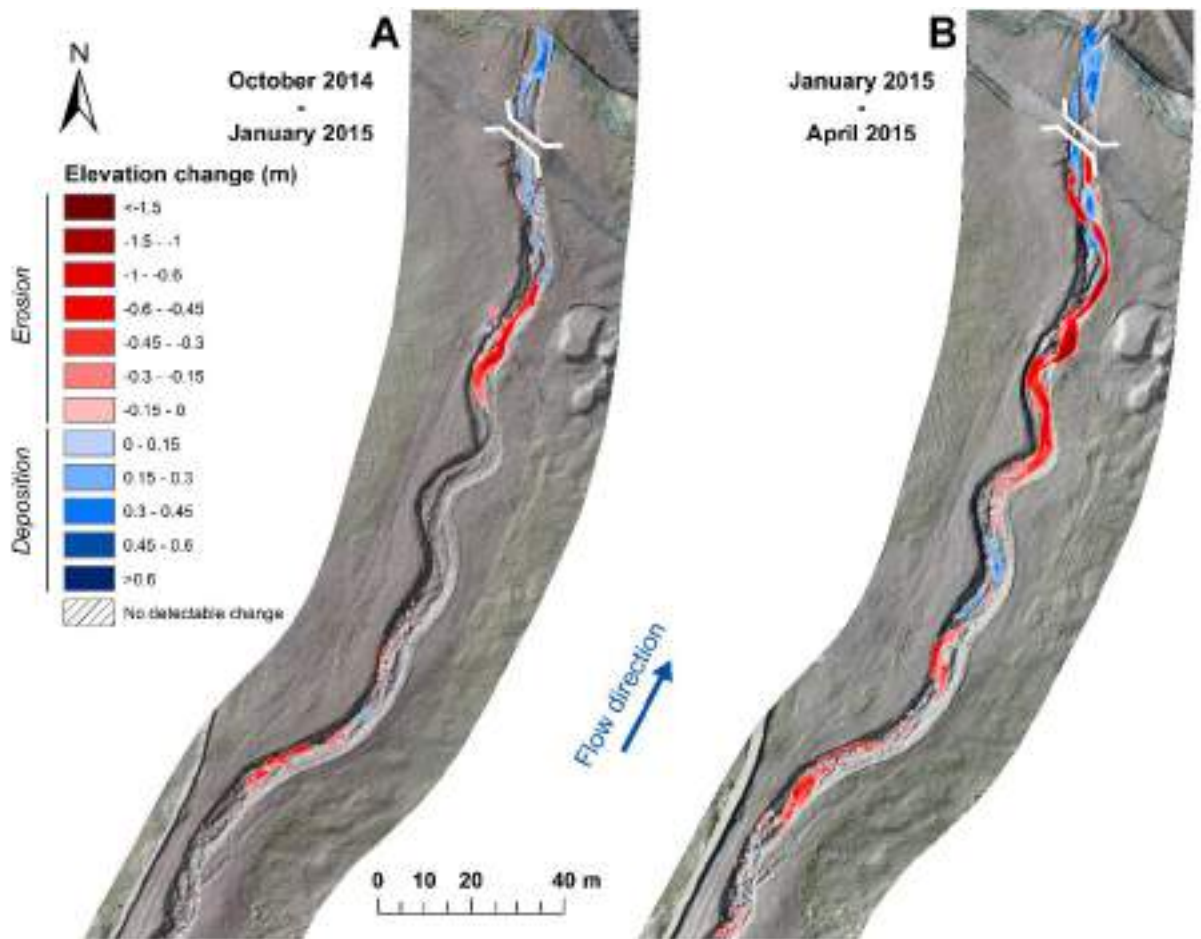


Figure 2.6. Example of DEMs of Difference (DoD) of Ben Gill. DoDs were thresholded using a minLoD (see text for more details): (A) October 2014-January 2015; (B) January 2015-April 2015. Note that raster cells with topographic changes below the minLoD are not coloured.

Table 2.3. Volumetric changes extracted from the two thresholded DoD presented in Figure 2.5. Two levels of thresholding have been applied, using statistical minLoD with two t-scores ($t > 1.28$ and $t > 1.96$; 80% and 95% Confidence Interval respectively, see text for more details).

	Minimum Level of Detection					
	80% CI ($t > 1.28$)			95% CI ($t > 1.96$)		
	Erosion m^3	Deposition m^3	Net change m^3	Erosion m^3	Deposition m^3	Net change m^3
October 2014- January 2015	-47.56	18.17	-29.39	-40.31	14.42	-25.88
January 2015- April 2015	-158.19	34.80	-123.38	-146.21	30.36	-115.85

Figure 2.6 and Table 2.3 indicate that erosion was the dominant process in Ben Gill over the study period (at 80% CI, 79.5% of the topographic changes were characterised as erosion), with only a small part at the downstream end of the channel experiencing deposition. Two main erosional sections are evident. Of these, the downstream section underwent the most significant changes at both of the time intervals considered here, although the scale of change was greater between January and April 2015 (Figure 2.6B) than between October 2014 and January 2015 (Figure 2.6A). The first DoD (Figure 2.6A) revealed little lateral change but extensive vertical erosion, with maximum levels of erosion and deposition of 1.07 m and 0.50 m respectively. Figure 2.6B illustrates the more intense change that occurred between January and April 2015, with erosion of more than 1 m in both lateral and vertical dimensions in some areas. The channel was subject to vertical deepening and bank erosion, as well as significant deposition at the lower end of the channel. Maximum levels of erosion (1.40 m) and deposition (0.62 m) were higher than observed in the first period. The evolution of the channel over the whole of the study period was also evident in changes in its long profile. There was an upstream propagation of two knick-points (see rectangles, Figure 2.7B), a phenomenon influencing spatio-temporal changes in patterns of erosion along the channel (Figure 2.7C). However, changes in median particle size (represented as roughness, Figure 2.7D) were not directly related to the migration of these identified knick-points.

Erosion from Ben Gill has led to the development of a confluence bar where it discharges into the Ehen (Figure 2.4A). This bar has grown progressively over the survey period and, by April 2015, was 34 m long and 12 m wide.

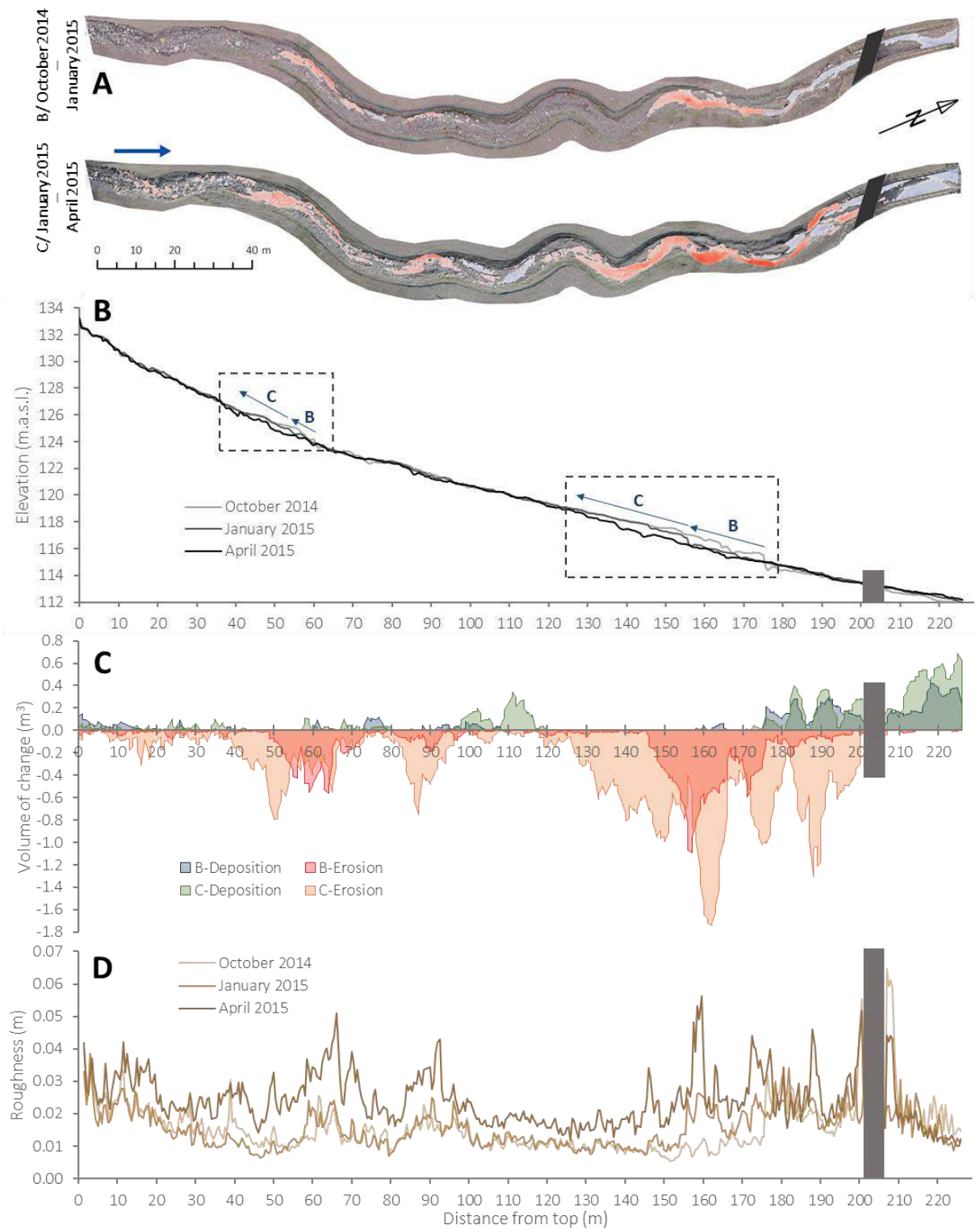


Figure 2.7. (A) DEMs of Difference (DoDs) created from the first 3 aerial surveys covering the newly created section of Ben Gill channel (red shows erosion and blue, deposition). (B) Longitudinal profiles of elevation of Ben Gill thalweg extracted from the three successive DEMs. (C) Longitudinal profiles of elevation change resulting from the computation of the DoDs presented in A. (D) Longitudinal profiles of channel roughness derived from the three successive DEMs, representing evolution of mean particle size.

2.4.4. Sediment budget

Total volumes of erosion and deposition, together with the net volume change, are given in Table 2.3. The estimate of net change in the second period (January to April 2015; -120m^3) is four times higher than that for the first (October 2014 to January 2015; -30m^3). Although the net volume of change is often used as a sediment budget term, strictly speaking it is only part of the budget since input or output values of sediment for the study reach are required to properly resolve the total budget.

2.5. DISCUSSION

2.5.1. Application of the workflow to Ben Gill

The workflow (Figure 2.3) was designed to capture the geomorphic evolution of the newly created Ben Gill channel. It was based on that used by others (e.g. Westoby et al. 2012; Javernick et al. 2014; Tamminga et al. 2014), but modified to reflect two important points. (i) As we were using a relatively low resolution camera fitted with a fish-eye lens, it was important to add preliminary stages to the workflow related to camera calibration, lens distortion and assessment of flight altitudes. (ii) As we were interested in assessing change, rather than simply characterising topography at a single point in time (as in Ely et al. 2016), it was important to add a stage to the workflow related to the assessment of model accuracy. The large number of markers, some used as GCPs and other as ChPs within a bootstrapping procedure, was critical to this assessment.

Changes in Ben Gill proved to be far greater than the minimum level of detection and so could be quantified confidently using a photogrammetric approach. Our approach was also practical and affordable. At current prices, the UAV (DJI Phantom I) costs £275, the GoPro Hero 3+ £265 and the Gimbal camera mount is around £200 (total cost= £740), while the set up and removal of the GCP network took only around 3 hours and 3-4 passes of the channel (as required to capture the necessary images) took approximately 25 minutes. Others have already stressed how UAV-based photogrammetry is cost effective and, indeed, may become the standard for topography production (Carbonneau and Dietrich 2016). While SfM photogrammetry is not, in itself, able to ensure that river restoration initiatives are successful, it can prove critical for the proper assessment of whether or not projects are achieving their geomorphic objectives.

The analysis of the data derived from SfM photogrammetry indicated that the newly created channel has undergone net erosion in the first 6 months following its connection to the Ehen. This has several implications in terms of meeting the objectives of the wider River Ehen restoration project. First and most importantly, the objective of re-establishing more dynamic and hence natural fluvial processes in the downstream reach of the Ehen seems to be on the way to being met. Previous work (Quinlan et al. 2015a), carried out under morphogenic floods (1.5 and 1.8 years return period events) has shown that the study section had become extremely stable, with little movement of either coarse or fine material. Although we have monitored only the first few months following the reconnection, the DoDs and related sediment budgets illustrate the magnitude of sediment volume now being delivered to the Ehen. Increased dynamism is evident from the development of a bar at the Ehen-Ben Gill confluence. Ongoing analysis of this bar using multi-temporal DEMs, in parallel with studies of bed mobility (marked tracers), will allow us to assess quantitatively its temporal evolution in relation to competent discharges in the Ehen, and hence the timing of sediment delivery further down into the Ehen system and how this is changing the sedimentary conditions previously reported (Quinlan et al. 2015a). The second important point to come from the photogrammetric analysis is that a large proportion of the newly engineered channel is composed of very fine material. This material is part of the alluvial fan which the channel cuts across (a fan formed by the original Ben Gill), but which has become exposed as a result of the erosion of the coarse material used to line the new channel. This is notable within the context of *M. margaritifera* habitat, as fine material potentially contributes to increases in suspended sediment in the Ehen at times when Ben Gill is flowing. Our workflow allows us to keep track of the erosion of this material and the hence risks posed to mussels by high suspended sediment concentrations. Although they can survive short-lived periods of high suspended sediment concentrations, the deposition of fines on the bed can create sub-optimum conditions for mussels, especially juveniles (Quinlan et al. 2015b). Ongoing analysis of Ben Gill will provide a more in-depth understanding of the processes occurring in the channel, as well as the volumes and timing of material delivered to the Ehen. Finally, outputs from the SfM photogrammetry approach provide valuable details on the processes driving the observed erosional patterns in the channel (Figure 2.7). Monitoring the migration of knick-points and the evolution of roughness are part of a toolset that are useful to understand and potentially forecast the geomorphic evolution of Ben Gill's channel.

From a technical point of view, the workflow provides a formalised framework within which various testing and calibration procedures can be undertaken. We have shown that, with careful calibration, use and testing, fish-eye lenses such as fitted to GoPro cameras can be used for photogrammetric applications in fluvial geomorphology. Although image quality is somewhat lower than from non-distorted lens (Thoeni et al. 2014), an appropriate calibration of the camera combined with particular attention to the GCP network setup and a good understanding of the way the SfM software works can lead to scientifically robust and defensible results. These results stemmed from the fact that: (i) we used the highest resolution GoPro available (at the time of study), (ii) flying altitude was rather low (12 to 16 m), (iii) flying speed was low, in order to reduce shutter-speed induced blur, (iv) overlap between images was very high, (v) *a-priori* calibration of the camera included k_3 and k_4 distortion parameters, (vi) flight paths were controlled and images selected so that the channel (i.e. area of interest) was in the centre of the images, reducing edge-related distortions, and (vii) the dome effect was greatly reduced by the very high density of GCPs. Together these elements of the workflow proved key to the assessment of changes in Ben Gill. Although it is possible to use mini GPS systems fitted to drones to allow direct georeferencing of images, this is currently at the cost of accuracy (Carbonneau and Dietrich 2016). Thus, the high density control network remains critical especially in cases where the detection of geomorphic change relies on high accuracy.

This workflow allowed to reach the maximum capacity of the equipment used for the study. Nonetheless, there are other technologies available that might improve upon what we have done. Heavy payload drones capable of carrying digital single-lens reflex cameras (with flat lenses and higher resolution), could, for example, improve the quality of the results and outputs. Similarly, the use of GPS flight assistance and autopilot in newer generation drones would help optimise flying paths and altitudes in order to improve image overlap and flight efficiency.

The high density control network ensured the high quality of the point cloud produced from our camera and assessment of model accuracy and precision. This is important for all river restoration studies, but is likely to be particularly critical in cases where the magnitude of the response to intervention proves to be lower than observed in Ben Gill.

In relation to the assessment and application of a minLoD in Ben Gill, deposition was more affected by thresholding than erosion (Table 2.3). This is in general agreement with other studies (Brasington et al. 2003; Wheaton et al. 2010b) which have stressed the limits of

interpreting DoDs and sediment budget estimates. Although applying a lower CI results in lower information loss, it can be at the cost of a less realistic or overly simplistic estimation of uncertainties. Wheaton et al. (2010) argue that using a Fuzzy Inference System function could help improve spatially variable estimates of surface representation uncertainties.

2.5.2. Wider relevance

As highlighted by several authors (e.g. Micheletti et al. 2014; Tarolli 2014; Smith et al. 2015 and others), the application of SfM photogrammetry has become very affordable. When applied with a solid testing procedure prior to data acquisition, it can provide high quality and insightful data. The potential benefits of applying such techniques to monitor and understand the post-restoration geomorphic evolution of river channel habitat is rather self-evident: not only can photogrammetry provide quantitative evidence of the geomorphic success or failure of a project, but it can also help predict likely future changes, e.g. when combined with hydraulic modelling. Williams et al. (2013), Tamminga et al. (2014) and Javernick et al. (2015), for instance, have successfully used DEMs derived from SfM photogrammetry to run 2D hydraulic models, while Smith et al. (2014b) provide comparisons of hydraulic models developed using SfM photogrammetry. Overall, SfM-based DEMs form a rich and detailed support for hydrological and hydraulic modelling.

Physical habitat complexity and heterogeneity are key influences on ecological diversity (Allan and Castillo 2007), so being able to quantify these aspects of the habitat template of rivers properly is fundamental to understanding ecological responses to restoration measures. As SfM photogrammetry provides information that can be used to characterise habitat continuously at scales ranging from the grain to the reach, it can provide the basis for much improved representation of physical habitat. Thus, we suggest that it should be used more widely in river restoration monitoring programmes to gather information that is important both geomorphologically and ecologically.

Submerged areas constrain the application of photogrammetry due to the adverse effects of turbidity, turbulence, light penetration depth, and light refraction at the air-water interface (Lane 2000; Westaway et al. 2000; Woodget et al. 2014). However, there are increasing numbers of examples to show that channel bathymetry can successfully be extracted from aerial images (e.g. Westaway et al. 2001; Lane et al. 2010; Tamminga et al. 2014; Woodget et al. 2014; Javernick et al. 2015). In cases where the nature of the river may preclude the

application of photogrammetry altogether (e.g. presence of dense riparian vegetation) alternative tools exist to collect high quality topographic information (e.g. Acoustic Doppler Current Profilers, Williams et al. 2013). Thus, while the tools used to produce HRT data may differ from one project to another, the workflow detailed in Figure 2.3 remains applicable to all, as it simply provides the framework for consistent and robust analyses.

2.6. CONCLUDING REMARKS

We have shown that SfM photogrammetry based on images collected using a UAV-mounted GoPro camera can be used to assess the effectiveness of river restoration measures. However, it is important to follow a procedure that is tailored to individual projects and the equipment used. The workflow presented here was successfully applied to the River Ehen restoration project, allowing us to obtain high resolution topographic data as well as orthophotos from which multiple outputs were extracted (DEMs, DoDs, roughness and facies maps). Thus, the workflow fulfilled its main purpose of providing key information on the geomorphic evolution of the channel, notably the amount of material transported and potentially available in the sediment-starved system downstream. When applied with appropriate preparation and experimentation prior to field data collection, the SfM photogrammetry can greatly improve the characterisation of channel morphology that should be a fundamental part of all river restoration projects.

It is likely that the current project is a rare example of restoring natural fluvial dynamics in a sediment-starved system using non-invasive techniques. The re-introduction of sediment to the Ehen has been achieved not by artificial augmentation, but by reinstating a functional high energy headwater tributary and its catchment. While Ben Gill itself is not critical ecologically, its hydrologic and geomorphic functioning is fundamental to the restoration of the Ehen system. Ongoing monitoring of the evolution of Ben Gill, together with a thorough assessment of its effects on the Ehen geomorphology and the ecological responses to these changes, will eventually allow us to fully assess the success of the Ehen restoration project.

2.7. LIST OF ABBREVIATIONS

ChP: Check Point

CI: Confidence Interval

DEM: Digital Elevation Model

DoD: DEM of Difference

GCD: Geomorphic Change Detection

GCP: Ground Control Point

GIS: Geographic Information System

HRT: High Resolution Topography

LiDAR: airborne laser surveying technology, created from “Light” and “raDAR”

minLoD: minimum Level of Detection

MVS: Multi-View Stereo

rtk-GPS: real-time kinematic Global Positioning System

SfM: Structure-from-Motion

ToPCAT: Topographic Point Cloud Analysis Toolkit

UAV: Unmanned Aerial Vehicle

2.8. REFERENCE LIST

- AgiSoft LLC (2015a). AgiSoft Lens. Version 0.4.2 beta. Retrieved from: <http://www.agisoft.ru/products/lens>.
- AgiSoft LLC (2015b). Agisoft PhotoScan Professional Edition. Version 1.2.3. Retrieved from: <http://www.agisoft.ru/downloads/installer/>.
- Allan JD, Castillo MM (2007). Stream Ecology: Structure and Function of Running Waters, 2nd Ed. Springer, Dordrecht, The Netherlands
- Ashmore PE, Church M (1998). Sediment transport and river morphology: a paradigm for study. In: Klingeman PC, Beschta RL, Komar PD, Bradley JB (eds) *Gravel-Bed Rivers in the Environment*. Water Resource Publ., Highland Ranch, CO, pp 115–148
- Bangen SG, Wheaton JM, Bouwes N, Bouwes B, Jordan C (2014). A methodological intercomparison of topographic survey techniques for characterizing wadeable streams and rivers. *Geomorphology* 206:343–361
- Boon PJ (1998). River restoration in five dimensions. *Aquatic Conservation: Marine and Freshwater Ecosystems* 8:257–264
- Brasington J, Langham J, Rumsby B (2003). Methodological sensitivity of morphometric estimates of coarse fluvial sediment transport. *Geomorphology* 53:299–316
- Brasington J, Rumsby BT, McVey RA (2000). Monitoring and modelling morphological change in a braided gravel-bed river using high resolution GPS-based survey. *Earth Surface Processes and Landforms* 25:973–990
- Brasington J, Vericat D, Rychkov I (2012). Modeling river bed morphology, roughness, and surface sedimentology using high resolution terrestrial laser scanning. *Water Resources Research* 48:1–18
- Carbonneau PE, Dietrich JT (2016). Cost-Effective Non-Metric Photogrammetry from Consumer-Grade sUAS: Implications for Direct Georeferencing of Structure from Motion Photogrammetry. *Earth Surf Process Landforms*. doi: 10.1002/esp.4012
- Chaplot V, Darboux F, Bourennane H, Leguédois S, Silvera N, Phachomphon K (2006). Accuracy of interpolation techniques for the derivation of digital elevation models in relation to landform types and data density. *Geomorphology* 77:126–141
- Church M (2006). Bed Material Transport and the Morphology of Alluvial River Channels. *Annual Review of Earth and Planetary Sciences* 34:325–354
- Civil Aviation Authority (2015). Unmanned Aircraft System Operations in UK Airspace - Guidance.
- Dietrich JT (2016). Riverscape mapping with helicopter-based Structure-from-Motion photogrammetry. *Geomorphology* 252:144–157
- Ely JC, Graham C, Barr ID, Rea BR, Spagnolo M, Evans J (2016). Using UAV acquired photography and structure from motion techniques for studying glacier landforms: application to the glacial flutes at Isfallsglaciären. *Earth Surf Process Landforms*. doi: 10.1002/esp.4044
- European Union (2000). Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. *Official Journal of the European Communities* L237:1–73
- Fuller IC, Large ARG, Charlton ME, Heritage GL, Milan DJ (2003). Reach-scale sediment

- transfers: an evaluation of two morphological budgeting approaches. *Earth Surface Processes and Landforms* 28:889–903
- Heritage GL, Milan DJ (2009). Terrestrial Laser Scanning of grain roughness in a gravel-bed river. *Geomorphology* 113:4–11
- James MR, Robson S (2012). Straightforward reconstruction of 3D surfaces and topography with a camera: Accuracy and geoscience application. *J Geophys Res Earth Surf*. doi: 10.1029/2011JF002289
- Javernick L, Brasington J, Caruso B (2014). Modeling the topography of shallow braided rivers using Structure-from-Motion photogrammetry. *Geomorphology* 213:166–182
- Javernick L, Hicks DM, Measures R, Caruso B, Brasington J (2015). Numerical modelling of braided rivers with Structure-from-Motion-derived terrain models. *River Research and Applications* 32:1071–1081
- Lague D, Brodu N, Leroux J (2013). Accurate 3D comparison of complex topography with terrestrial laser scanner: Application to the Rangitikei canyon (N-Z). *ISPRS Journal of Photogrammetry and Remote Sensing* 82:10–26
- Lamouroux N, Gore JA, Lepori F, Statzner B (2015). The ecological restoration of large rivers needs science-based, predictive tools meeting public expectations: An overview of the Rhône project. *Freshwater Biology* 60:1069–1084
- Lane SN (2000). The measurement of river channel morphology using digital photogrammetry. *Photogrammetric Record* 16:937–961
- Lane SN, Chandler JH (2003). The generation of high quality topographic data for hydrology and geomorphology: new data sources, new applications and new problems. *Earth Surface Processes and Landforms* 28:229–230
- Lane SN, Westaway RM, Hicks DM (2003). Estimation of erosion and deposition volumes in a large, gravel-bed, braided river using synoptic remote sensing. *Earth Surface Processes and Landforms* 28:249–271
- Lane SN, Widdison PE, Thomas RE, Ashworth PJ, Best JL, Lunt IA, Sambrook Smith GH, Simpson CJ (2010). Quantification of braided river channel change using archival digital image analysis. *Earth Surface Processes and Landforms* 35:971–985
- Micheletti N, Chandler JH, Lane SN (2015). Structure from Motion (SfM) Photogrammetry. In: Cook SJ, Clarke JH, N. LS (eds) *Geomorphological Techniques*. British Society for Geomorphology, London, UK, pp 1–12
- Micheletti N, Chandler JH, Lane SN (2014). Investigating the geomorphological potential of freely available and accessible structure-from-motion photogrammetry using a smartphone. *Earth Surface Processes and Landforms* 40:473–486
- Micusík B, Pajdla T (2006). Structure from motion with wide circular field of view cameras. *IEEE transactions on pattern analysis and machine intelligence* 28:1135–1149
- Milan DJ, Heritage GL, Large ARG, Fuller IC (2011). Filtering spatial error from DEMs: Implications for morphological change estimation. *Geomorphology* 125:160–171
- Olden JD, Konrad CP, Melis TS, Kennard MJ, Freeman MC, Mims MC, Bray EN, Gido KB, Hemphill NP, Lytle D a., McMullen LE, Pyron M, Robinson CT, Schmidt JC, Williams JG (2014). Are large-scale flow experiments informing the science and management of freshwater ecosystems? *Frontiers in Ecology and the Environment* 12:176–185

- Passalacqua P, Belmont P, Staley DM, Simley JD, Arrowsmith JR, Bode CA, Crosby C, DeLong SB, Glenn NF, Kelly SA, Lague D, Sangireddy H, Schaffrath K, Tarboton DG, Wasklewicz T, Wheaton JM (2015). Analyzing high resolution topography for advancing the understanding of mass and energy transfer through landscapes: A review. *Earth-Science Reviews* 148:174–193
- PhotoModeler (2013). Using the GoPro Hero 3 for 3D Photogrammetry Modeling and Measuring. [online] Available from: <http://info.photomodeler.com/blog/using-the-gopro-hero-3-for-3d-photogrammetry-modeling-and-measuring/>. (Accessed 8 Aug 2014)
- Quinlan E, Gibbins CN, Batalla RJ, Vericat D (2015a). Impacts of Small Scale Flow Regulation on Sediment Dynamics in an Ecologically Important Upland River. *Environmental Management* 55:671–686
- Quinlan E, Gibbins CN, Malcolm I, Batalla RJ, Vericat D, Hastie L (2015b). A review of the physical habitat requirements and research priorities needed to underpin conservation of the endangered freshwater pearl mussel *Margaritifera margaritifera*. *Aquatic Conservation: Marine and Freshwater Ecosystems* 124:107–124
- Smith B, Clifford NJ, Mant J (2014a). The changing nature of river restoration. *WIREs Water* 1:249–261
- Smith MW (2014). Roughness in the Earth Sciences. *Earth-Science Reviews* 136:202–225
- Smith MW, Carrivick JL, Hooke J, Kirkby MJ (2014b). Reconstructing flash flood magnitudes using “Structure-from-Motion”: A rapid assessment tool. *Journal of Hydrology* 519:1914–1927
- Smith MW, Carrivick JL, Quincey DJ (2015). Structure from motion photogrammetry in physical geography. *Progress in Physical Geography* 40:247–275
- Smith MW, Vericat D (2015). From experimental plots to experimental landscapes: Topography, erosion and deposition in sub-humid badlands from Structure-from-Motion photogrammetry. *Earth Surface Processes and Landforms* 40:1656–1671
- Storz-Peretz Y, Laronne JB (2013). Morphotextural characterization of dryland braided channels. *Bulletin of the Geological Society of America* 125:1599–1617
- Tamminga A, Hugenholtz C, Eaton B, Lapointe M (2014). Hyperspatial remote sensing of channel reach morphology and hydraulic fish habitat using an Unmanned Aerial Vehicle (UAV): a first assessment in the context of river research and management. *River Research and Applications* 31:379–391
- Tarolli P (2014). High-resolution topography for understanding Earth surface processes: Opportunities and challenges. *Geomorphology* 216:295–312
- Thoeni K, Giacomini A, Murtagh R, Kniest E (2014). A comparison of multi-view 3D reconstruction of a rock wall using several cameras and a laser scanner. *Proceedings of ISPRS Technical Commission V Symposium XL*:573–580
- United Utilities (2012). Hydrodynamic and Sediment Transport Modelling Report - Project Name: Ennerdale and Ben Gill - Project No: 80020012.
- Vericat D, Brasington J, Wheaton J, Cowie M (2009). Accuracy assessment of aerial photographs acquired using lighter-than-air blimps: low-cost tools for mapping river corridors. *River Research and Applications* 25:985–1000
- Vericat D, Wheaton JM, Brasington J (2017). Revisiting the morphological approach: opportunities and challenges with repeat high resolution topography. In: Tsustumi D,

- Larone JB (eds) *Gravel-Bed Rivers: Processes and Disasters*. Wiley, Tokyo, Japan, pp 121–158
- Weng Q (2006). An Evaluation of Spatial Interpolation Accuracy of Elevation Data. In: Rield A, Kainz W, Elmes GA (eds) *Progress in Spatial Data Handling*. Springer-Verlag, Berlin, pp 805–824
- Westaway RM, Lane SN, Hicks DM (2000). The development of an automated correction procedure for digital photogrammetry for the study of wide, shallow, gravel-bed rivers. *Earth Surface Processes and Landforms* 25:209–226
- Westaway RM, Lane SN, Hicks MD (2001). Remote Sensing of Clear-Water, Shallow, Gravel-Bed Rivers Using Digital Photogrammetry. *Photogrammetric Engineering & Remote Sensing* 67:1271–1281
- Westoby MJ, Brasington J, Glasser NF, Hambrey MJ, Reynolds JM (2012). “Structure-from-Motion” photogrammetry: A low-cost, effective tool for geoscience applications. *Geomorphology* 179:300–314
- Wheaton JM, Brasington J, Darby SE, Kasprak A, Sear D, Vericat D (2013). Morphodynamic signatures of braiding mechanisms as expressed through change in sediment storage in a gravel-bed river. *Journal of Geophysical Research: Earth Surface* 118:759–779
- Wheaton JM, Brasington J, Darby SE, Merz J, Pasternack GB, Sear D, Vericat D (2010a). Linking geomorphic changes to salmonid habitat at a scale relevant to fish. *River Research and Applications* 26:469–486
- Wheaton JM, Brasington J, Darby SE, Sear DA (2010b). Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets. *Earth Surface Processes and Landforms* 35:136–156
- Williams RD, Brasington J, Hicks M, Measures R, Rennie CD, Vericat D (2013). Hydraulic validation of two-dimensional simulations of braided river flow with spatially continuous aDcp data. *Water Resources Research* 49:5183–5205
- Williams RD, Brasington J, Vericat D, Hicks DM (2014). Hyperscale terrain modelling of braided rivers: fusing mobile terrestrial laser scanning and optical bathymetric mapping. *Earth Surface Processes and Landforms* 39:167–183
- Woodget AS, Carbonneau PE, Visser F, Maddock IP (2014). Quantifying submerged fluvial topography using hyperspatial resolution UAS imagery and structure from motion photogrammetry. *Earth Surface Processes and Landforms* 64:47–64

CHAPTER 3.

THE IMPORTANCE OF A SMALL EPHEMERAL TRIBUTARY FOR FINE SEDIMENT DYNAMICS IN A MAIN-STEM RIVER

Baptiste Marteau, Ramon J. Batalla, Damià Vericat and Chris Gibbins.



*Ben Gill channel, facing downstream.
Photo: Baptiste Marteau, June 2015.*

Paper published in the journal *River Research and Applications* (33): 1564-1574 [2017]

CHAPTER 3. THE IMPORTANCE OF A SMALL EPHEMERAL TRIBUTARY FOR FINE SEDIMENT DYNAMICS IN A MAIN-STEM RIVER

3.1. ABSTRACT

Studies of ephemeral streams have focussed mainly in arid and semi-arid regions. Such streams also occur widely in temperate regions, but much less is known about their influence on fluvial processes in main-stem rivers here. In this paper we present evidence of the importance of a small ephemeral temperate stream for main-stem fine sediment dynamics. The paper focuses on a restoration project (River Ehen, NW England) which involved the reconnection of a headwater tributary to the main-stem river. We present data on suspended sediment transport two years prior to and two years following the reconnection. Despite the small size and non-perennial flow of the tributary, and the early stage of this adjusting system, its reconnection resulted in an increase of 65% in the sediment yield of the upper River Ehen. During both the pre- and post-reconnection periods, a higher proportion of the annual yield was conveyed during short events with relatively high suspended sediment concentrations. Following the reconnection, the magnitude and frequency of such events increased, primarily due to sediment being delivered from the tributary at times when main-stem flows were not elevated. Overall, the main-stem remains supply limited and so is highly dependent on sediment delivered from the tributary. The study helps stress that even non-perennial tributaries yielding only a small increase in catchment size (+1.2% in this case) can have a non-negligible influence on main-stem fluvial dynamics. Their role as sediment sources may be especially important where, as in the case of the Ehen, the main-stem is regulated and the system is otherwise starved of sediments.

Keywords: Ephemeral stream, fine sediment, suspended load, channel reconnection, river restoration, temperate region, regulated river, River Ehen.

3.2. INTRODUCTION

The transport dynamics of the finer fraction of river sediment loads (i.e. less than 2 mm diameter) have been studied intensively. Fine sediment generally represents the most important part of the sediment budget of a river (Walling and Webb 1987; Vericat and Batalla 2006) and so is quantitatively significant. Fine sediment is also important functionally, because of the role it plays in habitat formation. For example, fine particles play an important role as architects of riverbed structure, and help strengthen the banks, encourage the establishment of vegetation, enhance bed compactness and clog gravel interstices (Church 2006; Parker 2007). Fine sediment also has important implications for the entrainment of coarser bed material (Dudill et al. 2016 and references therein) and may have negative effects on benthic organisms when present in excessive amounts (Wood and Armitage 1997; Jones et al. 2012). Interest in the effects of fine sediment on aquatic organisms was triggered primarily by concerns over human activities such as agriculture, deforestation and mining (Rabení et al. 2005). However, some rivers carry naturally high fine sediment loads, whether as a result of glacial processes (e.g. Gurnell et al. 1996) or loss of material from highly erodible surfaces (e.g. badlands; Buendía et al. 2011). Irrespective of whether causes are natural or anthropogenic, increased fine sediment loads generally lead to reductions in the diversity of aquatic organisms (Buendía et al. 2013b). Nonetheless, the exact response of organisms remains difficult to predict because effects depend on the interaction of factors such as concentration, duration of exposure, particle-size distribution and chemical composition (Bilotta and Brazier 2008).

The variety of effects of fine sediment in rivers reflects differences in sediment sources and characteristics (Sear et al. 2016), and the processes involved in its production, transport and deposition through the channel network (Wood and Armitage 1997). Primary sediment production areas are confined largely to upper (i.e. headwater) parts of catchments (Charlton 2008). Tributaries can have a major influence on the delivery of fine material to main-stem channels (Webb et al. 2000; Collins and Walling 2006), although this can vary over short temporal and small spatial scales, linked to hydro-climatic, hydrologic and hydraulic conditions (Buendía et al. 2014; Piqué et al. 2014). Some of this variability stems from spatial variation in the relative availability of fine sediment sources, and how local variation in precipitation interacts to switch different tributaries *on-and-off* at different times (López-Tarazón et al. 2011; Tena and Batalla 2013).

Interest in tributaries and their confluences has increased since the 1980s, with work focusing on the effects of tributary sediment delivery on downstream morphology (Rice and Church 2001), sedimentary conditions (Rice and Church 1998) and ecology (Rice et al. 2001b, 2008). Most emphasis has been on the role of relatively large, perennial tributaries in supplying coarse material to main-stem reaches (Benda et al. 2004; Ferguson et al. 2006), with a particular focus on downstream fining and the effects of tributary inputs on the fluvial equilibrium of the receiving river (Pizzuto 1995; Rice 1998). Less work has been conducted on fine sediment delivery from small, low-order tributaries, although exceptions include studies on the Colorado River, USA (Webb et al. 2000; Griffiths and Topping 2015) and the River Isábena, Spain (Francke et al. 2014).

Historically, catchment-scale studies have relied on traditional mapping techniques (i.e. aerial photographs, satellite imagery and survey maps) to provide information on river channel characteristics that are relevant for helping to understand sediment fluxes (e.g. drainage density, length of channel network, slope). However, these techniques lack the resolution to characterise low-order streams (i.e. smaller headwater tributaries; Benstead and Leigh, 2012) and, consequently, the extent of such streams may be underestimated (Meyer and Wallace 2001). For the most part this has not been seen as problematic, as the influence of small tributaries on main-stem river reaches has been considered inconsequential (sediment contribution thought to be simply a function of size; Rhoads, 1987; Benda et al. 2004). This view is reinforced by the fact that many small tributaries are intermittent and so deliver material infrequently (Datry et al. 2014). However, others have argued that the role of these small systems has been under-estimated (Benstead and Leigh 2012). Tena et al. (2012) found that the sediment contribution from intermittent tributaries increased the maximum suspended sediment concentration of a main-stem river three-fold. However, like many studies of intermittent or ephemeral streams, this work was undertaken in a dryer region (the Mediterranean); studies of the importance of such streams in other regions (e.g. temperate ones) remain scarce.

In this paper we present evidence of the importance of small, ephemeral tributaries for fine sediment dynamics in main-stem rivers located in temperate regions. The paper is focussed on a headwater tributary of the River Ehen in NW England. Flows in the main-stem Ehen are regulated by a lake and associated weir. A tributary (Ben Gill) that enters the Ehen just downstream from the weir was diverted in the 1970s as part of the water supply network, such

that for more than 40 years it no longer delivered its sediment and water to the Ehen. However, it was reconnected in autumn 2014. We demonstrate the importance of this tributary by presenting data on the suspended sediment load of the Ehen two years before and two years after the reconnection. We also discuss the timing and magnitude of fine sediment loads in the Ehen in relation to hydrological conditions, within the context of this early adjusting stage of the reconnected tributary. Specific objectives of the paper are to: (i) characterise variation in fine sediment transport across a variety of temporal scales (event, annual, and pre- vs. post-reconnection), (ii) assess contribution of the tributary to the fine sediment load of the Ehen, and (iii) assess the links between fine sediment dynamics and the flow regime.

3.3. STUDY AREA

The River Ehen flows south-westwards and discharges to the Irish Sea (Figure 3.1a & b). It has a total catchment area of 155.8 km². The hydrological regime of the Ehen is regulated by Ennerdale Water, although because of the water abstractions and the design and management of the weir, impacts are limited mainly to modification of low flow percentiles. The lake is an important drinking water supply for West Cumbria. It is a natural water body (occupying a formally glaciated valley), although its storage capacity was increased by the construction of a 1.3 m high weir (in 1902) and the diversion of Ben Gill (in the 1970s, Figure 3.1c). Ben Gill is a first order ephemeral headwater tributary, with a small (0.55 km²), steep (mean catchment slope: 25%) mountainous and responsive catchment. It is considered to be ephemeral (as opposed to intermittent) as it flows for less time than it is dry, and usually in response to rainfall (Uys and O’Keeffe 1997). When flow recedes, Ben Gill is left dry along most of its length. Although it is not gauged, previous estimates suggest that it flows for approximately ¼ of the time (Quinlan et al. 2015a).

The upper section of Ben Gill flows over a series of waterfalls and step-pool sections, where it forms a steep gully. This upper section represents 85% of the total length of the Ben Gill and has always remained highly dynamic due to its steep gradient. Dominant vegetation here consists of shallow acid grassland with heather and bracken. When it reaches the valley floor, the channel flattens out. Consequently, prior to its diversion, sediment transported from the upper section of Ben Gill deposited to form an alluvial fan in the 300-m long lower section. Average gradient here is 9% and landcover is rough pasture. Originally, Ben Gill discharged to the Ehen approximately 40 m downstream from the lake outlet (i.e. weir). In the 1970s it was

diverted into the lake through an underground culvert positioned at the marked break in slope between the upper and lower sections (fan apex, Figure 3.1c). Thus, the relatively long upper section has remained a functional channel, while the short section (c. 15% of total length) below the diversion point, where it crosses the fan, was filled in and has terrestrialised. Since the diversion, sediment supplied from the upper section accumulated around the culvert, and was periodically removed and used locally as building material.

Discharge (hereafter Q) in the River Ehen is gauged at Bleach Green (Figure 3.1c). The catchment area here is 44.5 km². Although this is only 28% of the total catchment of the River Ehen, this upper area contributes 45% of the catchment's 1800 mm long-term mean annual rainfall (Alvarez-Codesal and Sweeting 2015). The river at Bleach Green has a long-term mean daily Q of 2.70 m³ s⁻¹ (1973-2016 data) with minimum and maximum daily Q of 0.124 and 80.2 m³ s⁻¹ respectively. The compensation flow released from the weir (via a fish-pass) has varied over time; it was 0.37 m³ s⁻¹ until 2012 but is currently 0.92 m³ s⁻¹, sometimes phased down to 0.69 m³ s⁻¹ depending on lake level.

Ennerdale Water acts as a sediment trap, with limited sediment transfer to the section immediately downstream (Quinlan et al. 2015a). Further downstream, the river meanders through argillaceous rocks of the Skiddaw group and sandstones (Brown et al. 2008). Here, important sediment contributions come from bank erosion, tributary inputs and diffuse agricultural runoff.

The Ehen was designated as a Special Area of Conservation (SAC) in 1995 as it supports an estimated 550,000 freshwater pearl mussels *Margaritifera margaritifera*, L. (Killeen and Moorkens 2013), the largest remaining population in England. As part of work to help conserve this important population, Ben Gill was reconnected to the Ehen in October 2014, in an attempt to reactivate the delivery of coarse sediment. The diversion culvert was disabled and a new 300-m long section of channel was engineered over the alluvial fan, following the approximate course of the original stream. The bed of the new section was lined with cobble-size material, with some larger (boulder-size) clasts along the banks (see Marteau et al. 2016 for more details). In an attempt to limit the first flush delivery of fine sediment to the main-stem, the bed was thoroughly washed, section-by-section, before the most downstream point was excavated and opened to connect to the Ehen. The wash-water was stored in temporary off-channel settlement ponds; settled fine material was removed from site, with remaining wash-water pumped to the lake.

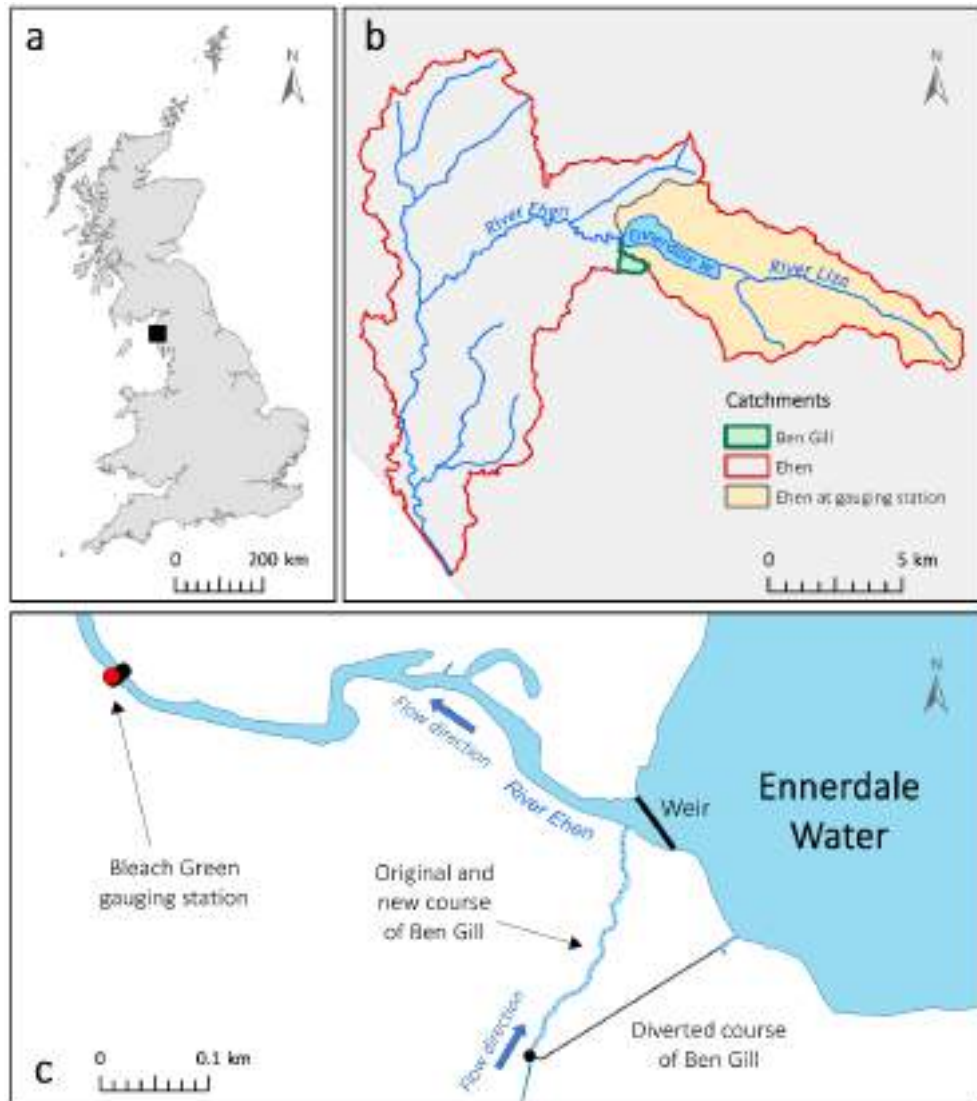


Figure 3.1. Details of the study area and site: (a) Location of the study area within the UK. (b) The Ehen catchment, including the Ben Gill and upper Ehen sub-catchments. (c) A detailed map of the study area showing key features discussed in the text. The red dot shows location of the turbidity meter.

3.4. METHODS

3.4.1. Rainfall and discharge

The current study is focussed on a 4-year period, covering the two hydrological years immediately before the reconnection of Ben Gill (i.e. October 2012 – September 2014) and the first two years after (i.e. October 2014- September 2016). Daily precipitation was recorded by the Environment Agency at Ennerdale Bridge, 1.8 km downstream from the Ehen-Ben Gill confluence. The River Ehen is gauged by the Environment Agency at Bleach Green (Figure 3.1c; see Quinlan et al. (2015a) for more details). Discharge data from Bleach Green (15-min interval)

were used to produce time-series for the study period. Additionally, mean daily values for the 1974-2016 period were used to compute flow percentiles and values of water yield, to set the study period within a longer-term perspective.

3.4.2. Suspended sediment

Turbidity (NTU) was measured in the Ehen at Bleach Green using a YSI® 6600 probe with self-cleaning wipers. The manufacturer reports a 0.1 NTU resolution for this instrument, with an accuracy of $\pm 2\%$ or 0.3 NTU (whichever is greater). Turbidity was recorded at 15-min intervals over the 4-year study period. The probe was maintained by the Environment Agency, and retrieved for cleaning and calibration every 2 to 3 months. Quinlan et al. (2015a) generated an NTU-Suspended Sediment Concentration (SSC) calibration prior to the reconnection of Ben Gill. This calibration was produced by sequentially adding fine sediment (collected from the bed at Bleach Green) to a bucket of water to create known concentrations, with turbidity measured for each increment in sediment (further details in Quinlan et al. 2015a). The present study uses the pre-reconnection data produced by these authors, except that for the calibration curve the regression was forced through the origin. This calibration is used to derive SSC values and compute sediment loads for the pre-reconnection period. Because of the very low values of turbidity recorded by Quinlan et al. (2015a) (maximum of 8.6 NTU), this calibration only encompassed the lower end of the probe's range (0-400 NTU). A second calibration was produced for the post-reconnection period, using the same procedure but covering the entire range of the probe (0-1000 NTU) to capture the greater turbidity values recorded post-reconnection; this was used to estimate SSC and loads for this period. The difference in range covered by the two calibrations does not impact interpretation of the results since each curve is used only to compute SSC and load within its own range (i.e. the ranges recorded within respective periods).

The slope of the NTU-SSC relationship prior to the reconnection was 2.06 (regression $r^2 = 0.99$, $P < 0.001$; Figure 3.2) while that for the post-reconnection period was 1.66 ($r^2 = 0.99$, $P < 0.001$). These slope values are significantly different (Ancova, $df = 81$, $F = 229.19$, $P < 0.001$).

Organic content of fine sediment remained low (below 10% on average), with no apparent seasonal or annual variations. The highest values of organic content were measured at very low SSC, and could not be differentiated from uncertainties associated with the probe accuracy and

laboratory processing procedures. Thus, no attempt was made to correct SSC values for organic content.

Suspended sediment load (SSL) and water yield were computed from 15-min data. SSL was calculated by multiplying SSC by Q for 15-min time steps. Values were then summed to compute loads at the monthly and annual timescales.

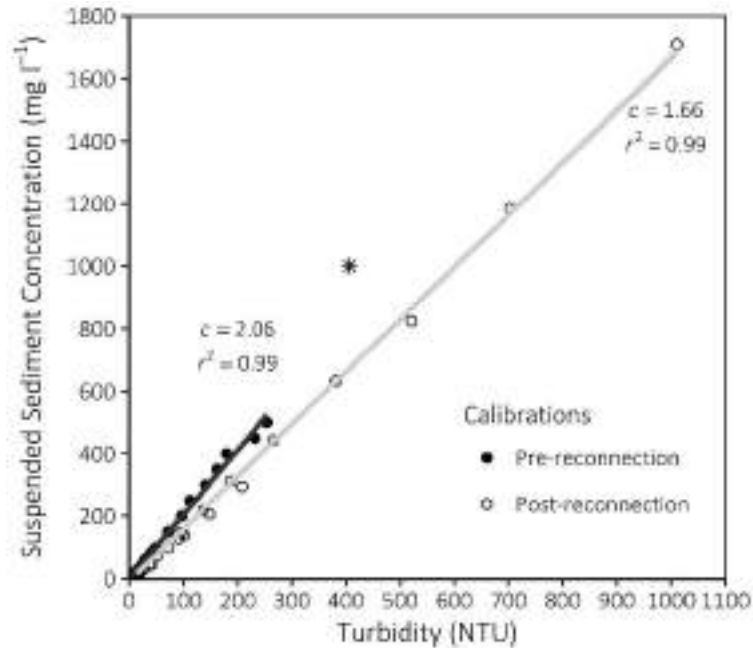


Figure 3.2. Calibration information for the turbidity probe, showing NTU-SSC relationships pre- (black dots) and post-reconnection (white dots) based on empirical calibration (see text for further details). Note that the starred value was found to have a high leverage on the pre-reconnection regression curve (Cook's distance > 1) and so was not used for the line fitting.

3.5. RESULTS

3.5.1. Hydrological context

Over the 4-year study period, precipitation averaged just under 2000 mm per year. Annual precipitation values were 1799 mm in 2012-2013, 1901 mm in 2013-2014, 1921 mm in 2014-2015 and 2329 mm in 2015-2016. Most events were less than 20 mm per day, with a total of 9 events exceeding 50 mm (Figure 3.3a). An exceptional rainfall event, the highest recorded during the 4 years, occurred on the first day of the reconnection: in total, 104 mm fell within the 24 hour period, with impacts on the morphology of the new channel (Marteau et al. 2016) and implications for fine sediment delivery to the main-stem (detailed in Section 4.2). The 2014-

2015 hydrological year was the wettest within the study period, with precipitation 26% greater than the two pre-reconnection years.

Despite being regulated by Ennerdale Water and its weir, the Ehen remains relatively flashy and regularly experiences high flows (Figure 3.3a). Its flow regime follows typical patterns for the NW of England, with lower flows in late spring and summer and higher flows in the winter, but with some high events also occurring in late summer. The median discharge (Q_{50} , the discharge exceeded for 50% of the time) for the study period was $1.98 \text{ m}^3 \text{ s}^{-1}$, which is greater than the long-term median value (1974-2016 = $1.38 \text{ m}^3 \text{ s}^{-1}$). Minimum mean daily Q was $0.71 \text{ m}^3 \text{ s}^{-1}$ (30/07/2013) while minimum instantaneous Q was $0.31 \text{ m}^3 \text{ s}^{-1}$ (11/02/2015). Maximum mean daily Q was $44.5 \text{ m}^3 \text{ s}^{-1}$ (15/11/2015, 30-year return period), with the instantaneous maximum value being $54.0 \text{ m}^3 \text{ s}^{-1}$. This maximum has only been exceeded twice over the 42-year period of record (CEH, National Flow Archive website, AMAX dataset).

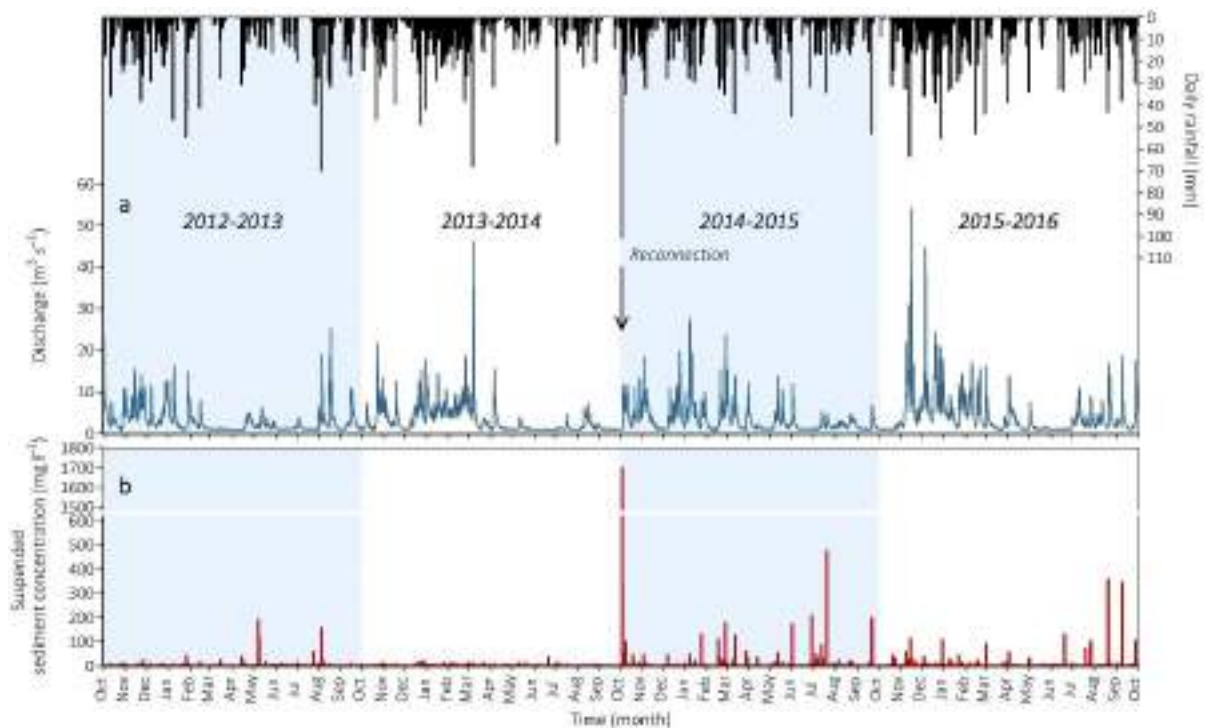


Figure 3.3. (a) Discharge of the River Ehen and local daily rainfall. (b) Suspended sediment concentration in the River Ehen. Discharge and suspended sediment concentration measured at Bleach Green at 15-min intervals. Rainfall was recorded at Ennerdale Bridge. Black arrow shows the day of Ben Gill reconnection.

Flow duration curves (Figure 3.4) indicate that the 2015-2016 hydrological year was substantially wetter than the 3 previous years, with higher median, mean and maximum Q s. Low flows were similar for each year of the study period, with most of the differences observed at higher flows (approximately Q_{10} and higher); for example, Q in 2015-2016 was above 10 m^3

s^{-1} for almost 10% of the time, markedly higher than the 3 other years (between 4 and 5% of the time). The flow duration curve for year immediately preceding reconnection (2013-2014) was very similar to the years before and after, differing only for the highest range of discharges, which were exceeded only around 0.2% of the time. The occurrence of both similar and rather different hydrological regimes pre- and post-reconnection provides a useful basis for assessing the effects of the reconnection on suspended sediment transport.

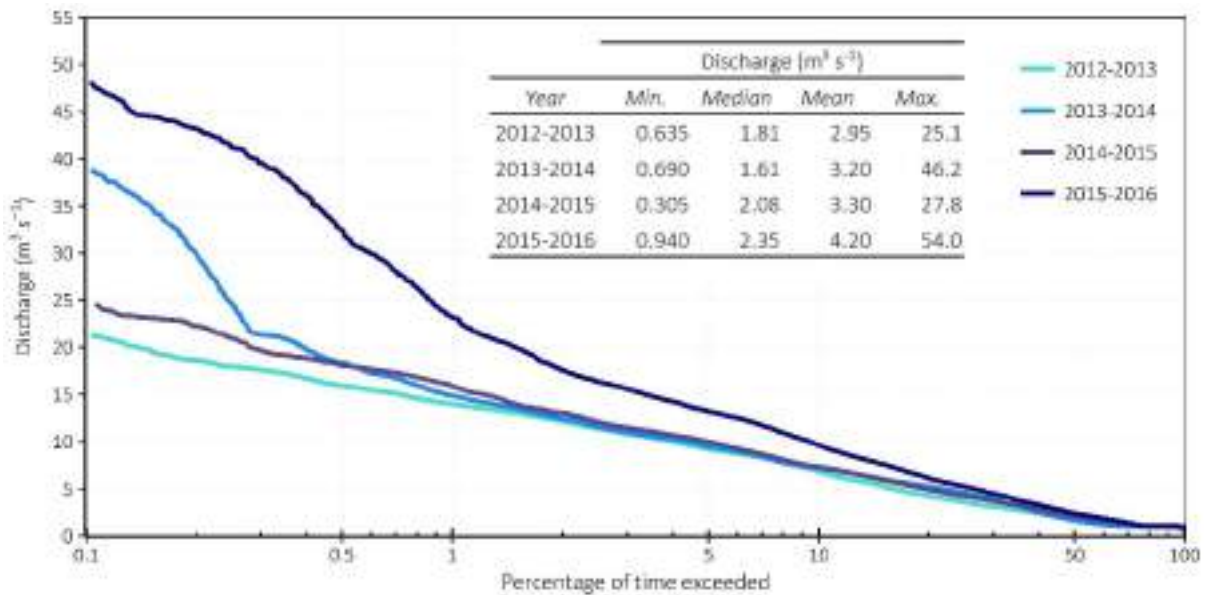


Figure 3.4. Flow duration curves of the study years expressed as the percentage of time a given discharge is equalled or exceeded. Data are for Bleach Green gauging station, measured at 15-min intervals. The inset table summarises key hydrological statistics for each year.

3.5.2. Variations in suspended sediment transport

Episodes of high SSC were generally scarce during the pre-reconnection period (Figure 3.3b). The two most important periods of fine sediment transport were in summer 2013. These occurred during floods that followed a prolonged period of low flow; they peaked at 190 mg l^{-1} but were short-lived (max 24 hours). The high rainfall event on the first day of the reconnection generated visible erosion in the newly created Ben Gill channel, and was responsible for a plume of fine sediment entering the main-stem of the River Ehen. Turbidity exceeded the probe's maximum value (1000 NTU) for 15 minutes during the day, and so the calculated SSC of 1700 mg l^{-1} is probably an underestimate of the true instantaneous value. This value represents a nine-fold increase in maximum instantaneous SSC compared to the maximum recorded pre-reconnection. Although such an extreme value has not been recorded again (as of September 2016), high SSC values have proven to be more frequent after the

reconnection of Ben Gill; for instance, the maximum pre-reconnection SSC of 190 mg l^{-1} has been exceeded seven times since October 2014, including some long-lasting events (Figure 3.3b).

The relationship between Q and SSC has been affected by the reconnection, as indicated by the difference between Figure 3.5a and b. The relationship prior to the reconnection shows little scatter, with the majority of the highest SSC events confined to low discharges (Figure 3.5a). The difference post-reconnection is most evident at low and medium discharges (Figure 3.5b). While patterns remain unchanged at high flows (green square, Figure 3.5b), the scatter in the relationship is considerably greater below $20 \text{ m}^3 \text{ s}^{-1}$; this is particularly visible for flows below $5 \text{ m}^3 \text{ s}^{-1}$ (blue square, Figure 3.5b). Overall, Figure 3.5 illustrates how the magnitude of SSCs increased following the reconnection, and how the reconnection has altered the basic hydraulic and sedimentary dynamics of the Ehen.

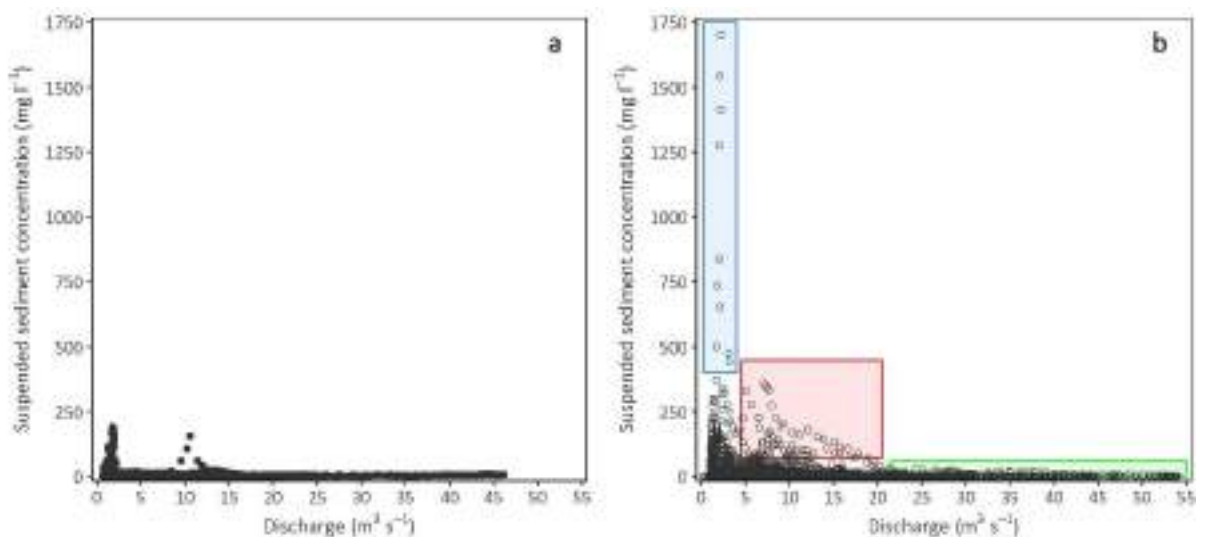


Figure 3.5. Relationship between discharge and suspended sediment concentration in the River Ehen, for the pre- reconnection (a) and post-reconnection (b) periods. Coloured rectangles in (b) highlight parts of the graph that are further described in the text. Data were recorded at Bleach Green at 15-min interval.

Despite the increased frequency and magnitude of high SSC events following the reconnection, it is notable that there is no marked difference in the respective mean and median values (Table 3.1). Note also that maximum SSCs in 2015-2016 coincided with very high flows (30-year return period) which lead to appreciable volumes of sediment being transported through the channel (between 57 and 60 t per month, in November and December 2015; Figure 3.6).

Table 3.1. Statistics of suspended sediment concentration computed from 15-min data (Bleach Green gauging station) for the River Ehen. Note that 1st and 3rd Qt. indicate the first and the third quartile of the SSC data set.

Year	Suspended Sediment Concentration (mg l ⁻¹)					
	Min.	1st Qt.	Median	Mean	3rd Qt.	Max.
2012-2013	0.206	0.883	1.029	1.86	1.44	190
2013-2014	0.206	0.617	0.823	1.08	1.23	33.9
2014-2015	0.166	0.498	0.664	2.00	1.16	1702
2015-2016	0.166	0.498	0.664	1.37	1.00	357

3.5.3. Contribution of the tributary to main-stem sediment loads

Water yield followed a similar pattern each year (Figure 3.6), with low values in early summer (June) and high values in early to mid-winter (November to January). Maximum (26.84 hm³) and minimum (2.45 hm³) monthly water yields were recorded in December 2015 and June 2014 respectively. Prior to the reconnection, monthly suspended sediment load (SSL) tended to follow the same pattern as water yield, with greater volumes of water leading to higher sediment loads. In the month that the reconnection took place (October 2014), SSL was the highest recorded during the study period (65.4 t); notably, this high value followed on the back of the lowest SSL value recorded (September 2014, 1.81 t). Patterns of monthly SSL in 2015-2016 were more difficult to explain solely by water yield. For instance, floods in November and December triggered monthly SSLs similar to October 2014, but water yields were appreciably higher (around 25 hm³ in November and December 2015 compared to only 13 hm³ in October 2014). Additionally, similar amounts of sediment were transported in January 2014 and August 2016, although water yields were different between these months.

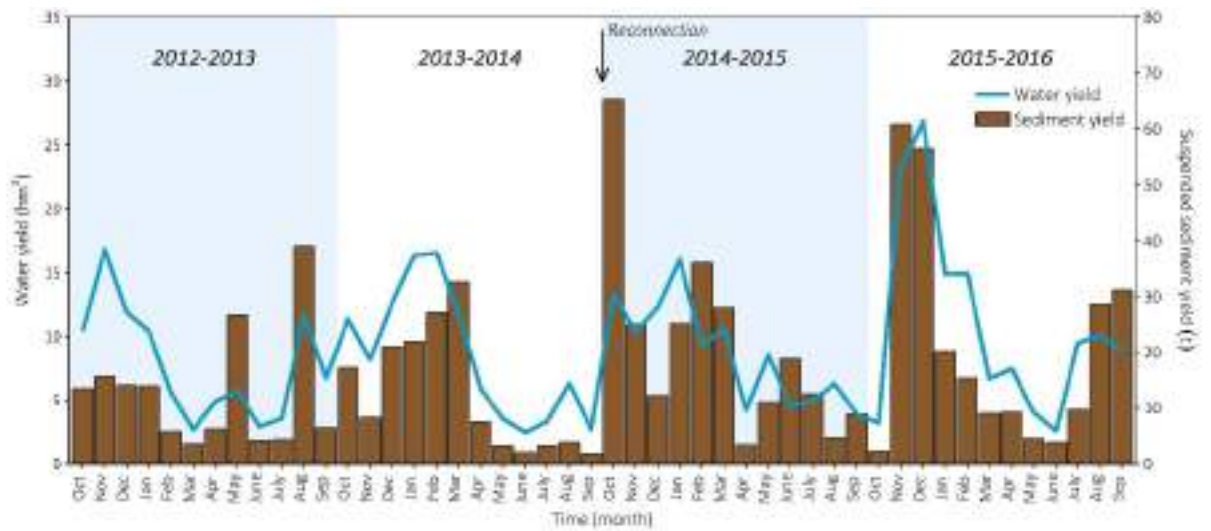


Figure 3.6. Monthly water and sediment yield for the study period.

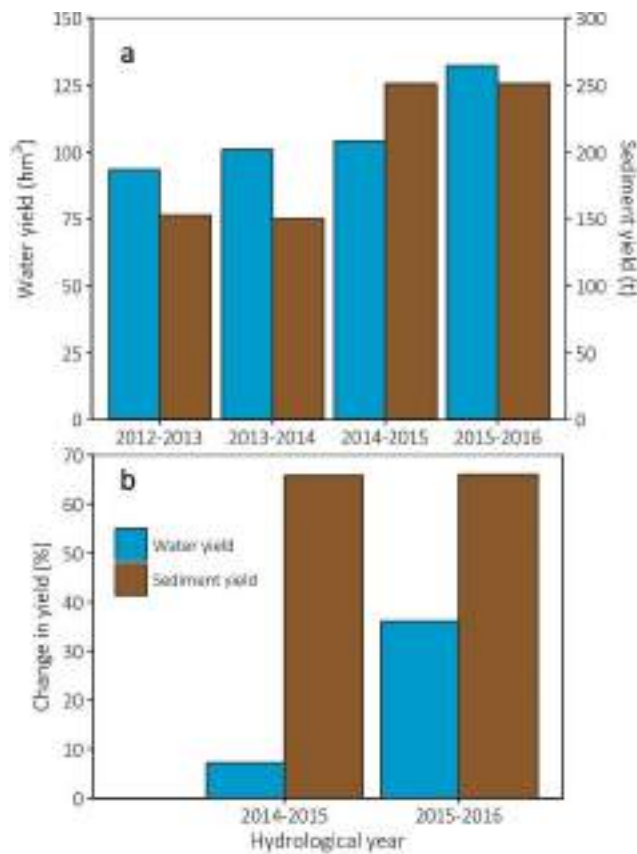


Figure 3.7. (a) Water and sediment yield for each of the hydrological years of the study period. (b) Change in water and suspended sediment yield following the reconnection. Changes are assessed in respective years relative to the pre-reconnection period.

Annual water yield was generally similar for the first three years of the study (ranging between 93 and 105 hm³), but increased markedly in the final year (132 hm³; Figure 3.7A). Overall, these values sit slightly above the long-term average of 85.4 hm³ (1974-2016 data). Sediment yield was similar for the two pre-reconnection years (153.1 and 149.6 t, Figure 3.7A) but post-reconnection values increased by 65% on average (i.e. 250.9 and 251.2 t respectively, Figure 3.7B), highlighting the role of Ben Gill in supplying sediment. Post-reconnection, water yields were also slightly higher (7% in 2014-2015, and 36% in 2015-2016), reflecting the higher precipitation values (+4% and +26% respectively).

3.5.4. Links between fine sediment dynamics and flow regime

The cumulative frequency curves (Figure 3.8) provide an insight in the transport duration of both water and sediment yields. Despite sitting on either side of the reconnection, transport durations of the water yield for the years 2012-2013 and 2014-2015 were similar, as were the years 2013-2014 and 2015-2016. Overall, 50% of the water yield was transported within 20% (2012-2013 and 2014-2015) to 25% (2013-2014 and 2015-2016) of the time. The similarity suggests that the reconnection of Ben Gill did not create a shift in time concentration patterns for water yields. However, time-concentration for the sediment loads clearly shifted after the reconnection, with a higher proportion of sediment transported in a much shorter amount of time in the post-reconnection period. For instance, 1% of the time concentrated 17 to 23% more of the sediment yield after the reconnection. This was true for both of the post-reconnection years, regardless of differences in their hydrology and the magnitude of the sediment yield. The higher proportion of sediment now being transported in a shorter amount of time reflects the increased importance of intense but short-lived SSC events (Figure 3.3b).

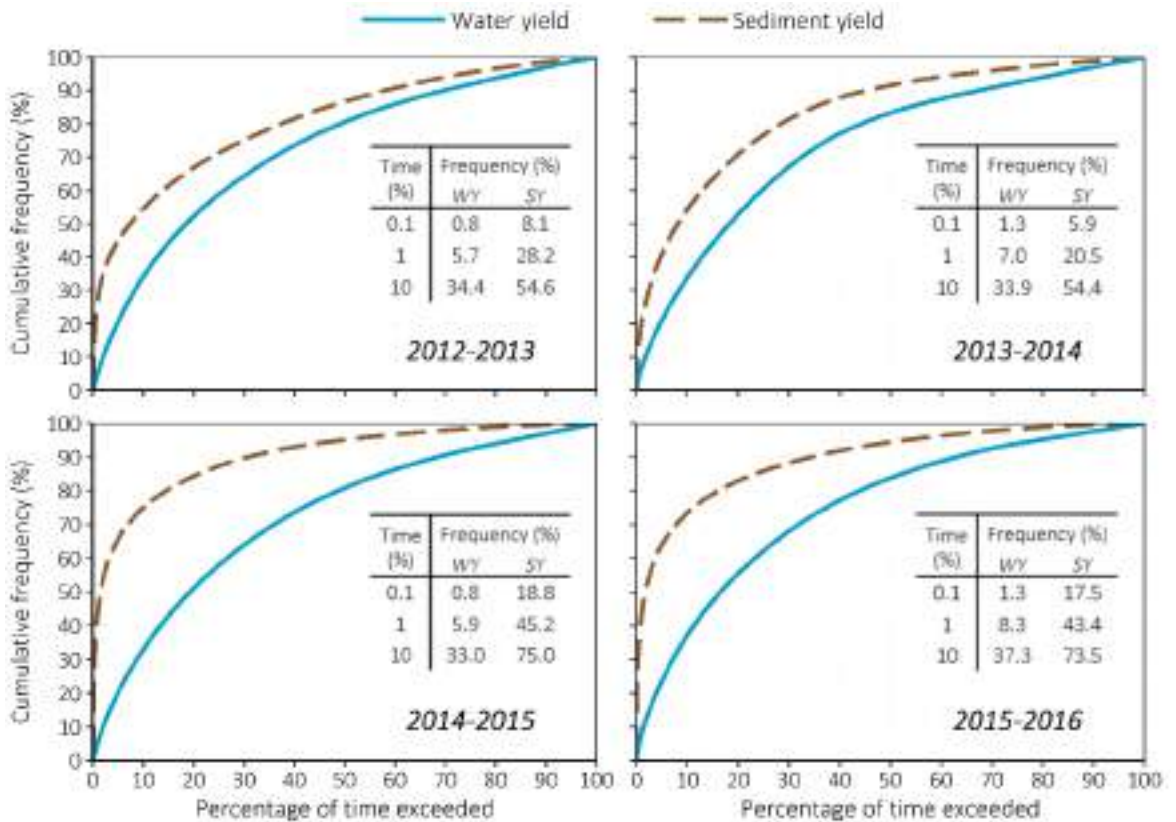


Figure 3.8. Cumulative frequency curves of water and suspended sediment yield for each of the hydrological years. Years 2012-2013 and 2013-2014 represent pre-reconnection data, while years 2014-2015 and 2015-2016 represent post-reconnection data. Inset tables summarise some statistics for each of the years (i.e. key percentiles of water and sediment yield (WY and SY respectively) transported for a given proportion (%) of time).

3.6. DISCUSSION

3.6.1. Context

Non-perennial water courses compose a substantial proportion of the total length, number and discharge of the world's streams and rivers (Datry et al. 2014). They are diverse (hydraulically, geomorphologically and ecologically) and widespread, being found in most terrestrial biomes (Larned et al. 2010). Temperate regions support many non-perennial streams which, just like their dryland counterparts, are experiencing altered hydrological regimes related to global change (Stanley et al. 1997). Studies designed to understand their importance for sediment supply are crucial to assess the likely impacts of future changes in climate, land cover or water use on river integrity. Ben Gill is an example of a non-perennial stream in a temperate region; it is notable in being ephemeral despite being located in the wettest region (the NW) of England. Additionally, the reconnection of Ben Gill involved the engineering of its lower part (c.

15%) through its former alluvial fan. Since this study only covers two years post-reconnection, the channel is still subject to geomorphic adjustments. Thus, it is possible that the magnitude of observations will change over time, although the ephemeral nature of the tributary suggest that most of the processes (and their consequences) will remain.

Though not grossly different, there were a number of differences in the flow regimes of the study years, with corresponding differences in water yield. Most of the variability related to the major floods of winter 2015; these resulted in higher water yields but had no impact on the time concentration of transport (Figure 3.8). Moreover, the higher water yield in 2015-2016 was found to be a simple response to increase in precipitation (+26% compared to pre-reconnection period) rather than any potential effect of the reconnection. Although we did not measure turbidity or SSC within Ben Gill itself, no changes other than the reconnection occurred in the upper part of the catchment over the study period; thus, we attribute this change in fine sediment yield to a small (0.55 km²), headwater tributary which only flows for approximately ¼ of the time.

3.6.2. Sedimentary effects of the reconnection in the Ehen

3.6.2.1. Temporal variation in fine sediment transport

Ben Gill has experienced much erosion since it was reconnected, and this has resulted in the delivery of both fine and coarse sediment to the Ehen. Marteau et al. (2016) estimated that a minimum of 150 m³ of sediment was delivered to the Ehen in the first six months after the reconnection. Data presented in the current paper indicate that large volumes of fine material are also now being delivered as a result of the reconnection.

The very high SSC recorded on the day following the reconnection coincided with an unusually high local rainfall event. This coincidence of timing was unfortunate from a management perspective, given the sensitivity of aquatic organisms to fine sediment. Despite efforts by the engineering company to remove fine particles from the newly created channel immediately prior to the day of the reconnection, it is possible that a small part of the plume of sediment was linked to the flushing of any fine material remaining on the bed surface. Over 35.7 t of fine entered the Ehen from Ben Gill over 48h, representing 55% of the month's sediment yield and approximately 14% of the annual yield. However, given the scale of the rainfall event and the

magnitude of the erosion it generated, most of the plume originated from the erosion of subsurface fine material.

Maximum SSC values in the Ehen have increased post-reconnection, but this is not the case for minimum and mean values, and the quartiles. This difference indicates that fluvial dynamics in the Ehen at base-flow remain largely unaffected by the reconnection. Moreover, the time concentration of suspended sediment yield has changed since the reconnection, with a higher proportion of the sediment yield now being transported through the channel in a shorter period of time. This supports the conclusion that the influence of Ben Gill on annual fine sediment yields comes through large volumes of material being transported during short-lived events, when Ben Gill is flowing.

3.6.2.2. Contribution of Ben Gill to the River Ehen fine sediment yield

Suspended sediment loads in the Ehen following the reconnection increased by 65% on average. This non-negligible change is evident despite the fact that Ben Gill increased catchment size at the confluence by only 1.2%. The increased load equates to an increase in specific sediment yield from $3.39 \text{ t km}^2 \text{ y}^{-1}$ pre-reconnection to $5.56 \text{ t km}^2 \text{ y}^{-1}$ post-reconnection. If we consider the average increase of 100 t y^{-1} to be eroded from Ben Gill catchment, then the specific yield from this tributary can be estimated at around $181 \text{ t km}^{-2} \text{ y}^{-1}$.

Specific yields for the Ehen catchment are rather low when compared to other catchments, while those for Ben Gill are closer to the higher values reported in the literature. For example, Worrall et al. (2013) reported a long-term average sediment flux of $22.2 \text{ t km}^{-2} \text{ y}^{-1}$ for the UK (5th percentile and 95th percentile of 5.4 and $107.7 \text{ t km}^{-2} \text{ y}^{-1}$ respectively). Foster and Lees (1999) reported long-term sediment yields of 7 to $86 \text{ t km}^{-2} \text{ y}^{-1}$ from their own research in the north of England, set against published values for the region ranging from 0.8 to $488 \text{ t km}^{-2} \text{ y}^{-1}$ (see references therein). They argue that the higher values can be attributed to human alterations to catchments, including agriculture and heather burning (Foster and Lees 1999). The estimated specific sediment yield of over $180 \text{ t km}^{-2} \text{ y}^{-1}$ for Ben Gill falls close to the range of yields recorded in ephemeral Mediterranean basins (50 to $200 \text{ t km}^{-2} \text{ y}^{-1}$, Walling and Webb 1996; Rovira and Batalla 2006). This highlights the potential for small ephemeral tributaries to deliver large volumes of sediment regardless of their size and the overall water yield.

3.6.2.3. Links between fine sediment dynamics and flow regime

In general, flows in the Ehen and Ben Gill are rather synchronous (Quinlan et al. 2015a). However, they are occasionally out of phase and maximum SSCs in the Ehen occur during the rare times when Ben Gill is flowing but flows in the Ehen are not elevated much beyond base-flow. When sediment delivered from Ben Gill coincides with high Q in the Ehen, it is diluted and quickly conveyed downstream; exhaustion occurs once Ben Gill again ceases to flow, which is typically rather soon. Thus, hydraulically speaking the Ehen could carry more sediment, but remains limited by the supply during floods; i.e. it will transport sediment as long as material is available. This and the ongoing adjustment in sediment dynamics after the reconnection are reflected in the Q -SSC relation observed in the Ehen, which contains much scatter; less than 0.01% of the variation in SSC can be explained by variation in Q (Figure 3.5). Fluvial dynamics at low flows are largely controlled by the timing of sediment supply from Ben Gill, with potentially very high SSC events occurring (blue square, Figure 3.5b). Material from previous high SSC events temporarily stored in the bed of the Ehen becomes available for transport on the rising limb of hydrographs, but is quickly exhausted. The scatter shows the variability in the amount of sediment available in the channel (red square), which remains very limited. Subsequent higher Q have no influence on SSCs, because all the material has already been exhausted, or inputs from Ben Gill are diluted by the large volumes of water (green square, Figure 3.5b). Thus, the influence that the reconnection is having on the Q -SSC relationship in the Ehen remains limited to low-intermediate discharges. This indicates that despite its small contributing area, Ben Gill is affecting the basic hydraulic-sediment transport relations in the Ehen for a certain range of Q s.

3.6.3. Implications

3.6.3.1. Potential ecological consequences for the River Ehen

The reconnection of Ben Gill forms part of catchment-wide initiative in the Ehen focussed on conservation of freshwater mussels. The reconnection aimed to help re-naturalise the hydrological regime of the Ehen and supply the coarser sediment which is an important part of the habitat required by mussels. New coarse sediment is now delivered to the Ehen (Marteau et al. 2016), so one of the objectives of the reconnection is already being achieved. However, it is also clear that Ben Gill is now delivering much fine sediment; indeed, data indicate that it has become the main driver of suspended sediment dynamics in the section of the Ehen

immediately downstream from the confluence. This has potential implications for biota, not just because of the absolute volumes involved but because temporal mismatch between sediment released from Ben Gill and high flows in the Ehen can lead to high SSC events at relatively low discharges, facilitating in-channel sedimentation. The effects of this sedimentation on biota can be direct (abrasion, clogging of gills) and indirect (deposition and subsequent consequences for benthic habitat), causing, for instance, changes in macroinvertebrate drift patterns (Béjar et al. 2017), and reduced survival of salmonid embryos (Sear et al. 2016) and freshwater pearl mussels (reviewed by Quinlan et al. 2015b).

Effects of the reconnection on fine sediment in the Ehen are not limited to changes in concentration and load. The empirical calibration produced for the post-reconnection period yielded a regression coefficient which was significantly different to that for the pre-reconnection period (Figure 3.2). This shift in the NTU-SSC relationship can be interpreted as a change in the quality of suspended sediment; material found in suspension now differs in composition (particle size, shape, colour, organic content etc.) compared to before the reconnection. This change may be critical ecologically (see for example Sear et al. (2016) in relation to fish, and Österling et al. (2010) in relation to pearl mussels). Thus, understanding how this new source of fine sediment is affecting in-channel fine sediment patterns, both quantitatively and qualitatively, as well as its effects on biota, will be key for assessing the overall effects of the reconnection.

3.6.3.2. Wider repercussions

Climate models suggest that the number of non-perennial streams will increase globally in the near future, particularly in regions where water appropriation is occurring (Larned et al. 2010). While arid and semi-arid regions will see patterns of intermittency shift towards a reduction in the number of days of flow (e.g. Garcia et al. 2016), temperate regions are predicted to experience increased seasonality in flows, with increased high flow magnitudes and reduced low flows (van Vliet et al. 2013). In some areas, the latter may result in small perennial streams becoming intermittent or even ephemeral. The influence of Ben Gill on sediment dynamics in the Ehen helps stress the potential functional implications of tributaries becoming disconnected from their main-stems due to changes in flow.

Globally, the erosion and fluxes of fine sediment have been altered dramatically by human activities. Land clearance, mining and agriculture are important causes of larger volumes of soil

and fine sediment now being washed into river networks (Trimble and Crosson 2000; Walling 2006), while dams trap a substantial fraction of fine material and so reduce loads (e.g. 60%, Yellow River, Walling, 2006; around 90%, River Ebro, Vericat and Batalla, 2006). Our study of the Ehen indicates that the disconnection of headwater tributaries may have a major influence on fine sediment fluxes (e.g. Zhang et al. 2015). However, it also shows that reconnection of such tributaries can help restore hydro-sedimentary dynamics, and that the reconnection of even small watercourses can play an important role in river rehabilitation efforts.

3.7. FINAL REMARKS

The Ehen system is regulated and, as a whole, remains supply limited (as per Quinlan et al. 2015a) and highly dependent on sediment delivered from Ben Gill. Our results indicate that the transport of fine sediment in the Ehen is not hydraulically driven (i.e. not controlled solely by increases in discharge) but relies greatly on the ephemeral characteristics of Ben Gill. Despite its limited influence on the hydrology of the Ehen, Ben Gill's impacts include quantitative and qualitative aspects of the fine sediment flux, as well as the temporal dynamics of this flux. The work shows that small ephemeral headwater tributaries can play a non-negligible role in driving main-stem sediment dynamics, even in temperate regions, and may be particularly important in catchments where main-stem rivers are regulated. Appreciation of this role can be important, given climate change and related water scarcity, and the likely societal pressures for flow regulation to provide water for human needs.

3.8. REFERENCE LIST

- Alvarez-Codesal S, Sweeting RA (2015). Historic changes in the Upper River Ehen Catchment. A Report for United Utilities. FBA unpublished report (S/0016/W)
- Béjar M, Gibbins CN, Vericat D, Batalla RJ (2017). Effects of suspended sediment transport on invertebrate drift. *River Res Appl*. doi: 10.1002/rra.3146
- Benda L, Andras K, Miller D, Bigelow P (2004). Confluence effects in rivers: Interactions of basin scale, network geometry, and disturbance regimes. *Water Resources Research* 40:1–15
- Benstead JP, Leigh DS (2012). An expanded role for river networks. *Nature Geoscience* 5:678–679
- Bilotta GS, Brazier RE (2008). Understanding the influence of suspended solids on water quality and aquatic biota. *Water Research* 42:2849–2861
- Brown D, Butterill G, Bayliss B (2008). Ben Ghyll Geomorphology report. Environment Agency, Version 2.0, Penrith, Cumbria
- Buendía C, Gibbins CN, Vericat D, Batalla RJ (2014). Effects of flow and fine sediment dynamics on the turnover of stream invertebrate assemblages. *Ecohydrology* 7:1105–1123
- Buendía C, Gibbins CN, Vericat D, Batalla RJ, Douglas A (2013). Detecting the structural and functional impacts of fine sediment on stream invertebrates. *Ecological Indicators* 25:184–196
- Buendía C, Gibbins CN, Vericat D, López-Tarazón JA, Batalla RJ (2011). Influence of Naturally High Fine Sediment Loads on Aquatic Insect Larvae in a Montane River. *Scottish Geographical Journal* 127:315–334
- Charlton R (2008). Fundamentals of fluvial geomorphology. Routledge, London
- Church M (2006). Bed Material Transport and the Morphology of Alluvial River Channels. *Annual Review of Earth and Planetary Sciences* 34:325–354
- Collins AL, Walling DE (2006). Investigating the remobilization of fine sediment stored on the channel bed of lowland permeable catchments in the UK. *Sediment dynamics and the hydromorphology of the fluvial system (Proceedings of a symposium held in Dnudee, UK)* 306:471–479
- Datry T, Larned ST, Tockner K (2014). Intermittent Rivers: A Challenge for Freshwater Ecology. *BioScience* 64:229–235
- Dudill A, Frey P, Church M (2016). Infiltration of fine sediment into a coarse mobile bed: a phenomenological study. *Earth Surf Process Landforms*. doi: 10.1002/esp.4080
- Ferguson RI, Cudden JR, Hoey TB, Rice SP (2006). River system discontinuities due to lateral inputs: Generic styles and controls. *Earth Surface Processes and Landforms* 31:1149–1166
- Foster IDL, Lees JA (1999). Changing headwater suspended sediment yields in the LOIS catchments over the last century: A paleolimnological approach. *Hydrological Processes* 13:1137–1153
- Francke T, Werb S, Sommerer E, López-Tarazón JA (2014). Analysis of runoff, sediment

- dynamics and sediment yield of subcatchments in the highly erodible Isábena catchment, Central Pyrenees. *Journal of Soils and Sediments* 14:1909–1920
- Garcia C, Gibbins CN, Pardo I, Batalla RJ (2016). Long term flow change threatens invertebrate diversity in temporary streams: evidence from an island. *Science of the Total Environment* 580:1453–1459
- Griffiths RE, Topping DJ (2015). Inaccuracies in sediment budgets arising from estimations of tributary sediment inputs: An example from a monitoring network on the southern Colorado Plateau. *Proceedings of the 3rd Joint Federal Interagency Conference on Sedimentation and Hydrologic Modeling, April 19-23* 583–594
- Gurnell A, Hannah D, Lawler D (1996). Suspended sediment yield from glacier basins. *Erosion and sediment yield: global and regional perspectives (Proceedings of the Exeter Symposium, July 1996)* 236:97–104
- Jones JI, Murphy JF, Collins AL, Sear DA, Naden PS, Armitage PD (2012). The impact of fine sediment on macro-invertebrates. *River Research and Applications* 28:1055–1071
- Killeen I, Moorkens E (2013). Environmental Monitoring of the River Ehen freshwater pearl mussel population 2012: A report to United Utilities. Malacological Services, Dublin
- Larned ST, Datry T, Arscott DB, Tockner K (2010). Emerging concepts in temporary-river ecology. *Freshwater Biology* 55:717–738
- López-Tarazón JA, Batalla RJ, Vericat D (2011). In-channel sediment storage in a highly erodible catchment: the River Isábena (Ebro Basin, Southern Pyrenees). *Zeitschrift für Geomorphologie* 55:365–382
- Marteau B, Vericat D, Gibbins C, Batalla RJ, Green DR (2016). Application of Structure-from-Motion photogrammetry to river restoration. *Earth Surface Processes and Landforms* 42:503–515
- Meyer JL, Wallace JB (2001). Lost linkages and lotic ecology: rediscovering small streams. In: Press MC, Huntly NJ, Levin S (eds) *Ecology: Achievement and Challenge*, The 41st S. Blackwell Science Ltd., London, UK, pp 259–317
- Österling ME, Arvidsson BL, Greenberg LA (2010). Habitat degradation and the decline of the threatened mussel *Margaritifera margaritifera*: influence of turbidity and sedimentation on the mussel and its host. *Journal of Applied Ecology* 47:759–768
- Parker G (2007). Transport of gravel and sediment mixtures. In: Garcia MH (ed) *Sediment Engineering: Theories, Measurements, Modeling and Practice*, ASCE Manual n.54. American Society of Civil Engineers, Reston, Virginia, pp 165–264
- Piqué G, López-Tarazón JA, Batalla RJ (2014). Variability of in-channel sediment storage in a river draining highly erodible areas (the Isábena, Ebro Basin). *Journal of Soils and Sediments* 14:2031–2044
- Pizzuto JE (1995). Downstream Fining in a Network of Gravel-Bedded Rivers. *Water Resources Research* 31:753–759
- Quinlan E, Gibbins CN, Batalla RJ, Vericat D (2015a). Impacts of Small Scale Flow Regulation on Sediment Dynamics in an Ecologically Important Upland River. *Environmental Management* 55:671–686

- Quinlan E, Gibbins CN, Malcolm I, Batalla RJ, Vericat D, Hastie L (2015b). A review of the physical habitat requirements and research priorities needed to underpin conservation of the endangered freshwater pearl mussel *Margaritifera margaritifera*. *Aquatic Conservation: Marine and Freshwater Ecosystems* 124:107–124
- Rabeni CF, Doisy KE, Zweig LD (2005). Stream invertebrate community functional responses to deposited sediment. *Aquatic Sciences* 67:395–402
- Rhoads BL (1987). Changes in stream channel characteristics at tributary junctions. *Physical Geography* 8:346–361
- Rice S (1998). Which tributaries disrupt downstream fining along gravel-bed rivers? *Geomorphology* 22:39–56
- Rice S, Church M (1998). Grain size along two gravel-bed rivers: statistical variation, spatial pattern and sedimentary links. *Earth Surface Processes and Landforms* 23:345–363
- Rice SP, Church M (2001). Longitudinal profiles in simple alluvial systems. *Water Resources Research* 37:417–426
- Rice SP, Greenwood MT, Joyce CB (2001). Macroinvertebrate community changes at coarse sediment recruitment points along two gravel bed rivers. *Water Resources Research* 37:2793–2803
- Rice SP, Kiffney P, Greene C, Pess GR (2008). The Ecological Importance of Tributaries and Confluences. In: Rice SP, Roy AG, Rhoads BL (eds) *River Confluences, Tributaries and the Fluvial Network*. John Wiley & Sons, Ltd, Chichester, UK, pp 209–242
- Rovira A, Batalla RJ (2006). Temporal distribution of suspended sediment transport in a Mediterranean basin: The Lower Tordera (NE Spain). *Geomorphology* 79:58–71
- Sear DA, Jones JI, Collins AL, Hulin A, Burke N, Bateman S, Pattison I, Naden PS (2016). Does fine sediment source as well as quantity affect salmonid embryo mortality and development? *Science of the Total Environment* 541:957–968
- Stanley EH, Fisher SG, Grimm NB (1997). Ecosystem Expansion and Contractions in Streams. *Bioscience* 47:427–435
- Tena A, Batalla RJ (2013). The sediment budget of a large river regulated by dams (The lower River Ebro, NE Spain). *Journal of Soils and Sediments* 13:966–980
- Tena A, Batalla RJ, Vericat D (2012). Reach-scale suspended sediment balance downstream from dams in a large Mediterranean river. *Hydrological Sciences Journal* 57:831–849
- Trimble SW, Crosson P (2000). U.S. Soil Erosion Rates- Myth and Reality. *Science* 289:248–249
- Uys MC, O’Keeffe JH (1997). Simple Words and Fuzzy Zones: Early Directions for Temporary River Research in South Africa. *Environmental Management* 21:517–531
- van Vliet MTH, Franssen WHP, Yearsley JR, Ludwig F, Haddeland I, Lettenmaier DP, Kabat P (2013). Global river discharge and water temperature under climate change. *Global Environmental Change* 23:450–464
- Vericat D, Batalla RJ (2006). Sediment transport in a large impounded river: The lower Ebro, NE Iberian Peninsula. *Geomorphology* 79:72–92

- Walling DE (2006). Human impact on land-ocean sediment transfer by the world's rivers. *Geomorphology* 79:192–216
- Walling DE, Webb BW (1987). Material transport by the world's rivers: evolving perspectives. *Water for the Future: Hydrology in Perspective (Proceedings of the Rome Symposium)* 164:313–329
- Walling DE, Webb BW (1996). Erosion and sediment yield: a global overview. *Erosion and Sediment Yield: Global and Regional Perspectives (Proceedings of the Exeter Symposium)* 236:3–19
- Webb RH, Griffiths PG, Melis TS, Hartley DR (2000). Sediment Delivery by Ungaged Tributaries of the Colorado River in Grand Canyon. U.S. Geological Survey, Water-Resources Investigations Report 00-4055
- Wood PJ, Armitage PD (1997). Biological Effects of Fine Sediment in the Lotic Environment. *Environmental Management* 21:203–217
- Worrall F, Burt TP, Howden NJK (2013). The flux of suspended sediment from the UK 1974 to 2010. *Journal of Hydrology* 504:29–39
- Zhang X, Tang Q, Long Y, He X, Wen A (2015). Recent changes of suspended sediment yields in the Upper Yangtze River and its headwater tributaries. *IAHS-AISH Proceedings and Reports* 367:297–303

CHAPTER 4.

ASYNCHRONICITY OF FINE SEDIMENT SUPPLY AND ITS EFFECTS ON TRANSPORT AND STORAGE IN A REGULATED RIVER

Baptiste Marteau, Ramon J. Batalla, Damià Vericat and Chris Gibbins.



*Ben Gill delivering fine sediments during an event.
Photo: Baptiste Marteau, February 2015.*

Paper published in the *Journal of Soils and Sediments* (DOI: 10.1007/s11368-017-1911-1) [2018]

CHAPTER 4. ASYNCHRONICITY OF FINE SEDIMENT SUPPLY AND ITS EFFECTS ON TRANSPORT AND STORAGE IN A REGULATED RIVER

4.1. ABSTRACT

A disconnected ephemeral tributary was reconnected to the regulated River Ehen (NW England) as part of a river restoration initiative, providing a renewed delivery of sediment to a highly stable and armoured channel. This chapter (1) assesses spatial and temporal dynamics of suspended and stored sediments in the Ehen, (2) characterises the composition of stored sediment, (3) develops fine sediment budgets for downstream river reaches, and (4) assesses the controls on the storage of fine sediment in the riverbed.

A 3-km study section in the upper part of the River Ehen was divided into two reaches. Suspended sediments were monitored at the downstream limits of each reach over a 2-year period. In-channel storage was measured in three morphological units within the upper reach, on thirteen occasions over the same period. Samples were used to assess changes in volumes of stored fine sediment, as well as the grain sizes and organic content of the material. A time-lapse camera facing the confluence of the tributary was used to conceptualise different flow scenarios. These scenarios reflect the degree of synchronicity between flows in the main-stem and those in the tributary. Fine sediment budgets were developed for each reach to assess the relative contribution of different sources of sediment.

The reconnection significantly affected suspended sediment loads in the Ehen. Bed storage increased 2-fold, with changes most evident in slow-flowing morphological units. Changes in the composition of stored sediment were less marked than changes in the quantity of material. Changes in bed storage were controlled by the degree of synchronicity between flows in the Ehen and those in the newly reconnected tributary. Hydrological events were classified according to the degree of synchronicity between flows in Ben Gill and those in the Ehen, with total asynchronicity being responsible for the main episodes of fine sediment deposition in the Ehen. Overall, the estimated sediment budgets provide insights into the importance of non-perennial sources of sediment in supply-limited systems such as the Ehen. Although bed storage values are within the range of those published for UK rivers, the increase observed

since the reconnection, together with the persistence of a static pavement, highlights the ecologically critical conditions of the regulated main-stem River Ehen.

Intermittent sources control fine sediment transport dynamics in the upper River Ehen. In this regulated river, ongoing deposition associated with increased low and medium sized flow events exerts more of a control on bed storage than large but rare floods. Management actions to limit delivery of material from lateral sources could help prevent further deterioration of habitat conditions for biota sensitive to fine sediment. Given the ongoing adjustment in the newly reconnected tributary, continued monitoring is needed to capture further morpho-sedimentary response in the main-stem.

Keywords: ephemeral tributary, flow asynchronicity, fine sediment, in-channel sediment storage, river restoration, River Ehen.

4.3. INTRODUCTION

The storage of fine sediment within the gravel matrix of river and stream beds represents an essential component of the sediment budget of river basins (Trimble 1983). Sediment stored in-channel varies in quantity and quality over time and space, in response to sediment input from the basin (Wilson et al. 2004), local geomorphological conditions (e.g. particle mobility, grain size, surface sorting and texture; Milhous 1973; Adams and Beschta 1980; Frostick et al. 1984; Walling and Quine 1993) and the nature of the flow regime, including both temporal and spatial variation in hydraulics (Diplas and Parker 1985). The characteristics of the fine material also influence its transport and storage dynamics (e.g. fall velocity and Reynold's number of the particles; Diplas and Parker 1985). Thus, as not all the material produced and transferred to the drainage network reaches the basin's outlet immediately (Reid and Dunne 1996; Walling et al. 1998), fine sediment transport is best considered an intermittent process.

Large proportions of the fine sediment load transported by rivers are conveyed in short periods of time, during major competent events. However, new material delivered from the catchment is not always the main source of sediment during such events – the re-suspension of material stored temporarily in the channel can increase the magnitude and frequency of suspended sediment transport (e.g. Peticrew et al. 2007; Navratil et al. 2010) and can control transport during periods between floods (Smith and Dragovich 2008). The scale of removal of sediment stored on the bed depends not only on flow conditions but the depth and cohesive properties of the material (Diplas and Parker 1992). Consequently, understanding patterns of in-channel sediment storage is critical for elucidating the sediment dynamics of a river, whether focussed on the reach (e.g. Smith et al. 2003; Collins and Walling 2007a) or network (e.g. Walling et al. 1998; Wilson et al. 2004) scale. As fine sediment deposition is well known for having marked biological effects (Wood and Armitage 1997; Bilotta and Brazier 2008; Buendía et al. 2014), understanding fine sediment dynamics is also critical for assessing the factors influencing river ecological status (Buendía et al. 2013b, a).

Excessive volumes of fine sediment are most problematic for species that live buried within the subsurface zone for a part or the whole of their life cycle (e.g. salmonids, Soulsby et al. 2001; Greig et al. 2005), where clogging can impact oxygen supply. Fine sediment deposition is especially important for those organisms that are fully sessile or less mobile, because they have no means of immediate escape at the timescale of depositional events. For example, the

freshwater pearl mussel *Margaritifera margaritifera* (L.) is threatened by a range of anthropogenic instream habitat changes, but is particularly vulnerable to the effects of fine sediment deposition (see review by Quinlan et al. 2015b). Although the debate is still ongoing about whether the effects of fine sediment are primarily caused by its physical (e.g. clogging) or chemical properties (e.g. Biochemical Oxygen Demand; Quinlan et al. 2015b), it is clear that fines influence mussel survival and recruitment (Bauer 1988; Buddensiek et al. 1993; Geist and Auerswald 2007; Tarr 2008). Thus, gathering information on the characteristics and dynamics of fine sediment (its grain size distribution, organic content, temporal patterns of storage and conveyance) is important to better assess the quality of riverbed habitat for aquatic organisms (Österling et al. 2010; Quinlan et al. 2015b).

Collecting empirical data on in-channel fine sediment storage is constrained by the highly variable nature of the river environment and the technical limitations of sampling methods (Diplas and Parker 1992). Conventional approaches comprise indirect and direct methods (Collins and Walling 2007a). Indirect methods rely on comparison of suspended sediment loads for upstream and downstream locations, to infer changes in sediment storage within the reach (e.g. Miller and Shoemaker 1986). Direct methods include core sampling, sediment trapping and resuspension of stored material. Of these, the re-suspension method first presented by Lambert and Walling (1988) is being used increasingly (e.g. Collins and Walling 2007a; López-Tarazón et al. 2011; Piqué et al. 2014); it has been shown to perform well across different types of substrate and provides valuable information on material stored in both the surface and subsurface zones, as well as its size characteristics (Duerdoth et al. 2015).

This paper reports the results of work undertaken to understand fine sediment transport and storage dynamics in an ecologically important river. The river (the Ehen, NW England) is the focus of a major restoration project, designed to conserve its important pearl mussel population. The restoration project includes the re-naturalisation of the hydrological regime of the Ehen and the reconnection of an ephemeral tributary, Ben Gill, to help reinstate more natural (dynamic) fluvial processes. The objective of re-introducing coarse sediment into the Ehen from this tributary is already being achieved (Marteau et al. 2016). However, recent work has shown that much fine material is also being delivered, and since its reconnection the tributary has become the main driver of fine sediment dynamics in the river system (Marteau et al. 2017). The timing of water and sediment delivery from the tributary does not always coincide with competent flows in the Ehen, leading to important differences in suspended

sediment concentrations, with potential implications for the quality of benthic habitat of mussels. The aim of this paper is therefore to better understand the dynamics of fine sediment transport and storage in the 3 km section of the main-stem Ehen immediately downstream from the tributary. This section supports high mussel densities and so is considered critical for the population. Specific objectives of the paper are to: (i) examine the spatial and temporal dynamics of suspended sediment loads in the study section, (ii) assess the characteristics of the fine sediment stored in the upper reach, (iii) develop fluvial sediment budgets for two contrasting reaches within the study section, and (iv) characterise the flow scenarios that control in-channel storage in the River Ehen.

4.4. MATERIAL AND METHODS

4.4.1. Study area and context

The River Ehen (NW England) is home to the largest remaining population of freshwater pearl mussels in England. The Ehen is typical of many pearl mussel rivers in that the population of this important species faces many threats (Young et al. 2001) and has experienced limited recruitment over the last 20 years (<1%, O’Leary 2013), resulting in an ageing population. Habitat conditions in the upper River Ehen were described by Quinlan et al. (2015a) as being suboptimum for mussels due to compaction and stability of the riverbed and the extremely limited movement of the surface layer.

The Ehen and its tributaries drain a total catchment of 155.8 km², with the upper part of the catchment mainly represented by the River Liza and Ennerdale Water (Figure 4.1B). Flows in the Ehen are regulated by Ennerdale Water (a post-glacial lake) and its associated weir (Figure 4.1C). This regulation mostly affects low and peak flows. In order to improve local water supply, the weir was heightened (to 1.3 m) in the 1970s and an ephemeral stream (Ben Gill, the main headwater tributary) was diverted to the lake. For over 40 years, the River Ehen has therefore been deprived of water and sediment from this tributary, leading to rising concerns over habitat suitability for mussels and their hosts (Atlantic salmon *Salmo salar* L. and brown trout *Salmo trutta* L.). This prompted the decision to reconnect Ben Gill to the Ehen as part of the restoration initiative underway across the catchment.

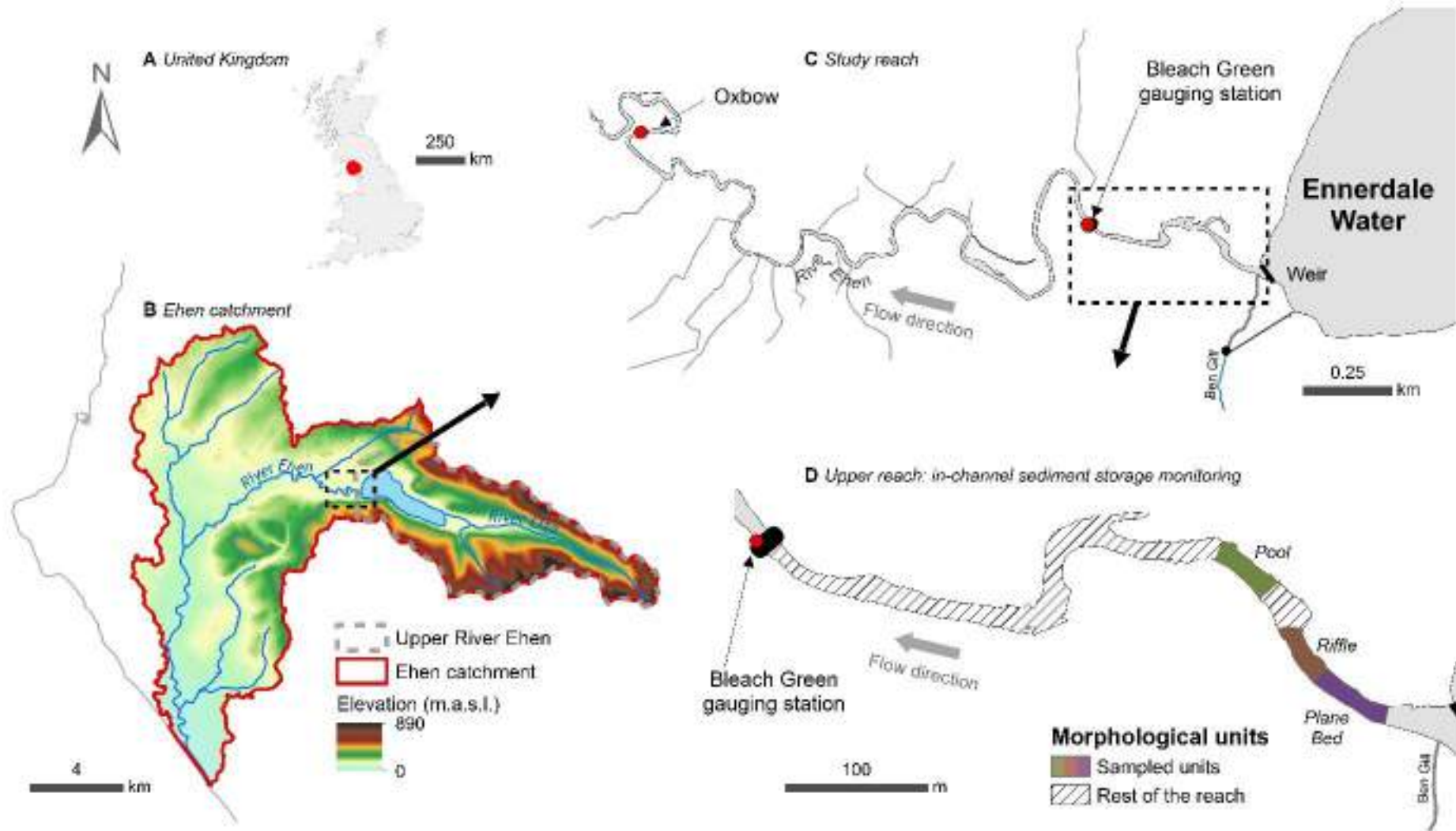


Figure 4.1. Location of the River Ehen study area; a) within the United Kingdom, b) Digital Elevation Model of the Ehen catchment, c) the entire study section where suspended sediment was monitored, and d) the main (upper) study reach where in-channel sediment storage was monitored.

Ben Gill (Figure 4.1C-D) is an ephemeral first order headwater tributary which drains a small (0.55 km²) but steep catchment (average slope 25%). The upper part of the catchment is covered by shallow acid grasslands with heather and bracken, overlying the remains of glacial tills. The channel then runs over a series of waterfalls and step-pool sections, where it forms a steep gully. This upper part represents c. 85% of the length of the channel and has always remained unaffected by the diversion. When reaching the valley floor, the channel flattens out and runs through an old alluvial fan. In the 1970s, Ben Gill was diverted at the break in slope between these two sections (the fan apex), with water conveyed to the lake via an underground culvert. Coarse sediment delivered from the upper section accumulated around the diversion point and was periodically removed from site. As a result, the lower section (c. 15% of the overall channel length) has filled-in and gradually terrestrialised. The reconnection of Ben Gill involved the creation of a new c. 300-m long section of channel through the alluvial fan, following its approximate original course. This section of channel was designed to be 5-m wide and 0.5-m deep, and lined with cobbles and boulders.

Since its reconnection in October 2014, Ben Gill has been delivering relatively large amounts of fine sediment but limited volumes of water to the Ehen. The timing of sediment delivery does not always coincide with high flows in the Ehen (Marteau et al. 2017), potentially leading to high rates of deposition downstream from the confluence.

This study focuses on the upper section of the Ehen, immediately downstream from Ennerdale Water (Figure 4.1C) and the confluence of Ben Gill.

Bleach Green gauging station is in the middle of the study section, where the catchment area is 44.5 km². Ben Gill enters the Ehen immediately downstream from Ennerdale Water; the reach between here and the Gauging Station is 0.55 km long and has a relatively low sinuosity (1.2). Prior to the reconnection of Ben Gill, the bed of this reach was extremely stable, with a static armoured layer capable of resisting bankfull flows (Quinlan et al. 2015a). The lower part of the study section (the 2.52 km reach downstream from the Gauging Station) has a different planform (sinuosity 1.97). The Oxbow (Figure 4.1C) represents the lowermost point of the study section; here catchment area is 47.0 km² (i.e. 2.5 km² more than at the Gauging Station, and 3.0 km² more than at Ennerdale weir). No previous studies have assessed bed conditions in this lower reach. It differs from the upper reach in receiving water and sediment from drainage ditches and a number of small non-perennial tributaries.

4.5. DATA ACQUISITION AND MONITORING

4.5.1. Discharge and flow conditions

Bleach Green gauge is operated by the Environment Agency (EA) and records discharge (Q) at 15-min intervals (Figure 4.1C & D). The accuracy of this gauge was not specifically assessed, but is estimated to have a maximum error of $\pm 8\%$ (Sauer and Meyer 1992). The current study covers a period of just over 2 years, from July 2014 (3 months before the reconnection of Ben Gill) until August 2016. Discharge data for the Gauging Station (15-min interval) were used to produce flow time series for the study period and estimate water yield. Mean daily values for the 1974-2016 period were used to compute flow percentiles, to help set the study period within a longer-term context.

Ben Gill is not gauged, although Quinlan et al. (2015a) reported that over their 18 month monitoring period, it flowed for approximately 23% of the time. Information on flow conditions in Ben Gill during the present study were collated from a variety of sources. Between June 2014 and June 2015, information from staff from the agencies involved in the restoration project (EA, Natural England, United Utilities and engineering contractors) was collated to determine whether Ben Gill was flowing. Because of the engineering work being undertaken in Ben Gill and Ennerdale Weir, contractors were on site on a more or less daily basis and so records for this one year period are comprehensive. In June 2015, a time-lapse camera was installed to record flow events in Ben Gill (1 hr interval), so for the second part of the study period continuous records are available. The camera was positioned on the true right bank and faced in the direction of the Ben Gill confluence, allowing inspection of flows in Ben Gill as well as whether Ennerdale lake was overtopping the weir. Images and information from staff notes were used to estimate the number of days that Ben Gill was flowing, and hence the timing and duration that it was delivering water and sediment to the Ehen.

4.5.2. Suspended sediment

Suspended Sediment Concentration (SSC) in the Ehen was calculated from turbidity (NTU) recorded using YSI® 6600 probes with self-cleaning wipers. These probes have a 0.1 NTU resolution and $\pm 2\%$ or 0.3 NTU accuracy (whichever is greater). One turbidity probe was located at the Gauging Station (Figure 4.1C & D) and placed directly in the water column, logging at 15-min intervals. A second probe was installed at the Oxbow, also placed directly in the water

column and logging at 15-min intervals. Both probes were maintained by EA, and retrieved for cleaning and calibration every 2 to 3 months.

An empirical NTU-SSC relationship was produced to compute SSC from turbidity readings (see Marteau et al. (2017) for more details). This relationship was developed using fine sediments transported during floods. Water samples were collected during flood events and brought to the laboratory, where they were concentrated and/or diluted to prepare samples of known SSC. Samples used covered the entire range of the turbidity probes. Because the probes were regularly retrieved and swapped around, and since they were all re-calibrated in the same lab against the same standards, a single NTU-SSC relationship was developed and used for the two monitoring stations. The standard deviation of the residuals from the linear regression representing this relationship was 0.9; this standard deviation was used to assess error in suspended loads. The organic fraction of total suspended sediment was rather low (below 10% on average), with no apparent seasonal or annual variations. The highest values of organic matter were measured at very low SSCs and so could not be differentiated from uncertainties associated with sample processing and probe accuracy. Thus, no attempt was made to correct SSC values for organic matter.

Suspended Sediment Loads (SSL) were calculated by multiplying SSC by Q at a given time-step (15-min). Due to good mixing, the use of a single probe was adequate for calculating SSC and SSL for each monitoring station. Data available were not sufficient to provide a detailed uncertainty analysis for SSL estimates. To provide an approximation of uncertainties, an average error (E_{SSL}) was determined considering the three main sources of error. The first source of error is the one associated with the turbidity sensors (E_S), for which the accuracy provided by the manufacturer was used ($\pm 2\%$). Second, errors associated with the measurement of discharge (E_Q) were considered as being of $\pm 8\%$ following Sauer and Meyer (1992). The last source of error stemmed from the empirical NTU-SSC relationship (i.e. E_R , the standard deviation of residuals from the linear regression ($\pm 0.9\%$)). These three sources of error were used to estimate the average total error (E_{SSL}) following the error propagation:

$$E_{SSL} = \sqrt{(E_Q)^2 + (E_S)^2 + (E_R)^2} \quad (4.1)$$

The E_{SSL} is used to provide a value of uncertainty (\pm) for SSL and sediment yield estimates.

Finally, from the SSC and SSL data, duration curves and cumulative yields were produced for the whole study period, as well as for individual seasons. Seasons were considered to extend for 3 months; they began with summer 2014, covering July, August and September 2014, and so on.

4.5.3. In-channel fine sediment storage

Storage was monitored in the upper reach, between the confluence of Ben Gill and the Gauging Station (Figure 4.1D). Bed substrate here consisted mainly of gravels and pebbles, with occasional cobbles. Fine sediment was considered as particles with a diameter <2 mm, including sands (200-63 μm), silts (63-3.9 μm) and clays (3.9-1.2 μm) (Wenworth Scale, as per Bunte and Abt 2001). Note that the minimum range of the clay corresponds to the pore size of the filters used for laboratory processing. Storage was determined using the re-suspension technique of Lambert and Walling (1988). This method involved isolating a patch of the bed using an open-ended plastic cylinder (diameter 0.43 m and height 0.65 m), which was carefully placed on the surface of the bed and held tight by pressing down on the handles, creating a seal. A layer of foam around the bottom of the cylinder helped ensure a tight seal with the riverbed. Stored sediment was then sampled within the area isolated by the cylinder (0.145 m²) by disturbing the water and sediment with a shovel. Disturbance was at two levels: 1, only the water column was stirred actively (for c. 30s) to re-suspend the fine sediment on the surface of the bed (agitation A1); 2, the top c. 10 cm of gravel was energetically disturbed (for c. 30s) to re-suspend any remaining surface sediment together with the fines contained in the top layer of the sediment matrix (agitation A2). Water and associated suspended sediments were collected in 0.5 L bottles for each agitation (1 sample for A1, 2 replicate samples for A2). The sediment content of these samples was assumed to reflect the remobilisation of fine sediment covering the surface and contained within the bed material matrix, respectively. In addition, one complementary water sample was collected prior to the agitation process and used as a blank (i.e. to determine the ambient SSC to be subtracted from A1 and A2 samples).

Stored sediment was sampled on 13 occasions over the study period, timed to reflect potential changes related to flow (Figure 4.2). Three morphological units (pool, riffle, and plane bed) were sampled on each occasion, with 5 samples collected from each unit (i.e. 15 samples in total on each occasion). The 5 samples were positioned to capture potential spatial variability within each unit (distributed as up- and downstream, left and right hand-side, and centre of

each unit). Sampling locations were kept similar over the study period but, to avoid sampling a patch that was previously disturbed, were not identical. This sampling design yielded a total of 780 samples from which in-channel fine sediment storage was assessed.

Water samples were filtered using 1.2 μm Whatman[®] glass microfiber filters and dried in an oven for 12 h at over 65°C. Subsequently, filters were weighed to determine sediment concentration. The amount of sediment stored per surface area unit U (in g m^{-2}) at a given location i was calculated as:

$$U_i(t) = \frac{C_i(t) \cdot V_i(t)}{S} \quad (4.2)$$

with the suspended sediment concentration C_i (in g l^{-1}) measured in the laboratory and associated with each level of agitation, the volume of water V_i (in l) determined from the depth of the water column above the bed and the area S (in m^2) covered by the cylinder. In this case, C_i was calculated by integrating the two different levels of agitation after subtracting concentration from the blank. Thus, there is no differentiation between the surface and subsurface storage.

To determine the organic content of the samples, filters were subsequently placed in a furnace for 3 hours at 550°C to burn-off all organic matter (i.e. loss on ignition method–LOI, %). Because of the small amount of sediment collected for some of the samples, the weight of the remaining inorganic fraction was corrected for potential loss of weight from the filter during the LOI process, by burning a series of blank filters throughout the lab processing period for comparison.

Finally, the remaining (inorganic) sediment was carefully scraped off the filters and processed with a Laser Particle Analyser (LS 13 320, Beckman Coulter Inc.[®]) to measure the volumetric size distribution of the material.

4.5.4. Data processing and analysis

Sediment storage for a given morphological unit and sampling date was calculated as the average of the 5 samples. Following López-Tarazón et al. (2011) and Piqué et al. (2014), sample data were then extrapolated to estimate total storage in the whole of the upper reach (i.e. between Ben Gill and the Gauging Station). For this, the area of the reach occupied by each of the three morphological units was first assessed during low flow conditions; 29% of the reach

was classified as riffle, 34.6 % pool and 36.4 % plane bed. Mean storage values ($t\ m^{-2}$) for each sampled unit were then multiplied by respective areas (m^2) to estimate total storage (t) across the reach, using:

$$S_s = \sum_{i=1}^3 U_i * A_i \quad (4.3)$$

where U_i is the average sediment released at a given morphological unit i ($t\ m^{-2}$), and A_i is the area of the channel bed at unit i (m^2). Uncertainties in the estimates of in-channel sediment storage were determined using the 95% confidence interval.

Separate suspended sediment budgets were computed for the two reaches (Upper = Ben Gill to Gauging Station, lower = Gauging Station to Oxbow; Figure 4.1). The two monitoring stations (at the Gauging Station and the Oxbow) allowed assessment of the differences in SSL and, consequently, the relative contribution of different sources of sediment to the sediment yield at the outlet of the study section (Oxbow monitoring station). For the upper reach, the information used to build the sediment budget consisted of suspended sediment yield at the output (i.e. Gauging Station) and in-channel sediment storage extrapolated over the reach. Additionally, information from previous published work (Marteau et al., 2017) showing the fraction of sediment yield delivered by Ben Gill, the only tributary flowing into this part of the river, was used. The sediment budget for the lower reach was built using input and output suspended sediment yields (i.e. Gauging Station and Oxbow monitoring stations respectively).

Flow and suspended sediment characteristics were assessed during sampling periods which are represented as boxes and letters in Figure 4.2. The main flow parameters used to help interpret sediment dynamics were mean Q, peak Q, number of flood events, and water yield in the Ehen. The main sediment parameters analysed were mean SSC, peak SSC, mean SSL, peak SSL, and sediment yield (SY). Additionally, information about the frequency and duration of flows in Ben Gill (i.e. whether this sediment source was connected, and for how long) was summarised for each sampling occasion using the time-lapse images.

To test for significant changes in in-channel storage over time and space, two-way ANOVAs on ranked data were performed. Principal Component Analysis (PCA) was used to help assess spatio-temporal patterns in several parameters (volumes of sand, clay and silt; particle size quantiles and median (D_{90} , D_{50} and D_{10}), the proportion and total amount of organic matter, and the total amount of stored sediment). This analysis used standardised data and provided information on changes in the characteristics of stored sediment over time and differences

between morphological units; it also provided information on the parameters changing or differing most, as well as any correlations between them. All analyses were performed with the software R v.3.3.3 (R Core Team 2017).

4.6. RESULTS

4.6.1. Hydrological conditions

As reported previously (Quinlan et al. 2015a; Marteau et al. 2017), the hydrological regime of the River Ehen remains relatively variable and flashy, despite being regulated by Ennerdale Water and the weir (Figure 4.2A). Patterns in flow are typical for the NW of England; lower flows occur in summer and higher flows in winter, but with some high flow events in late spring. Discharge for the study period ranged from $0.31 \text{ m}^3 \text{ s}^{-1}$ (11/02/2015) to $54.0 \text{ m}^3 \text{ s}^{-1}$ (15/11/2015, $Q_{0.03}$); mean and median discharges were $3.50 \text{ m}^3 \text{ s}^{-1}$ and $1.99 \text{ m}^3 \text{ s}^{-1}$ respectively, which are slightly higher than long-term respective values ($2.72 \text{ m}^3 \text{ s}^{-1}$ and $1.38 \text{ m}^3 \text{ s}^{-1}$, 1974-2016). It is noticeable that flows in November and December 2015 were particularly high (i.e. third highest discharge recorded) as a result of excessive rainfall experienced across the region. Flows were around compensation flow (i.e. $0.92 \text{ m}^3 \text{ s}^{-1} \pm 10\%$) for about 21% of the time, with some prolonged periods of low flow (e.g. mid-May to mid-July 2016).

Hydrological conditions between successive sampling occasions varied considerably (Table 4.1). Flow events were considered as being those when discharge increased over 1.5 times the baseflow. In total, 18 high flow events were recorded during sampling period *i*, partly due to the long time-span of this period but also because of precipitation which resulted in frequent increases in discharge (notably in November and December). Conversely, period *g* had lower Q_s , with a peak of $2.10 \text{ m}^3 \text{ s}^{-1}$ and no high flow events.

Ben Gill flowed for an estimated 19.4% of the time, slightly less than during the period covered by Quinlan et al. (2015a). Flows in Ben Gill responded rapidly to local rainfall events, but recession was also quick; periods of flow lasted from just few hours to a few days. The average duration of flows was 30.4 hours, with a minimum of 1 hour and a maximum of 13 days.

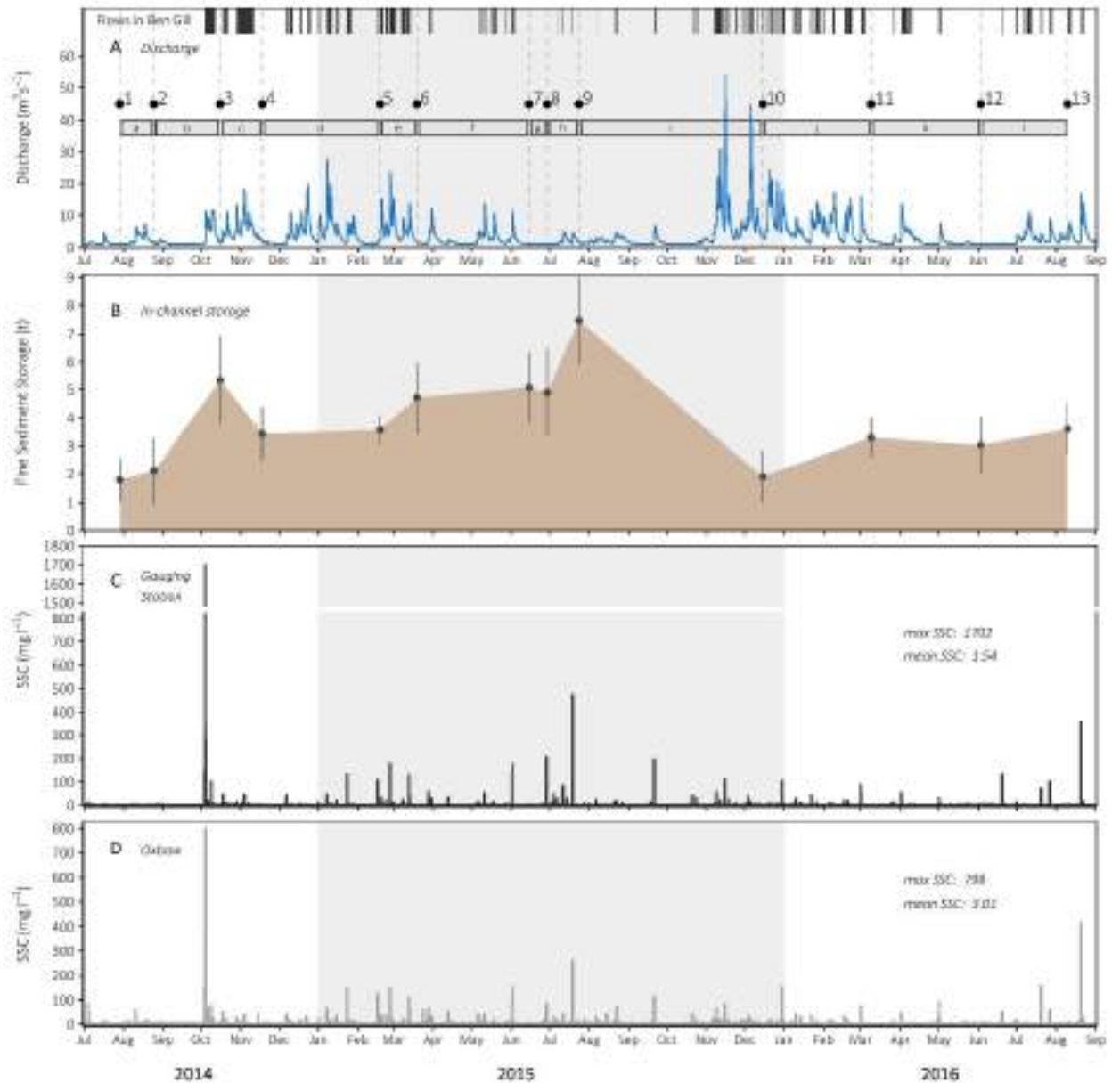


Figure 4.2. Overview of the hydrological and sedimentary conditions in the River Ehen during the study period. (A) Discharge, as measured at the gauging station (blue, bottom), and flows in Ben Gill (black, top). The dots and numbers refer to in-channel storage sampling occasions, while boxes and letters refer to sampling periods. (B) In-channel sediment storage, calculated following the extrapolation described in the Methods section (errors bars = 95% confidence interval). (C) Suspended sediment concentration (SSC) at the gauging station. Note that to show the full range, there is a break in the y-axis between 800 and 1500 mg l⁻¹. (D) Suspended sediment concentration at the Oxbow. See Figure 4.1 for details of location

Table 4.1. Flood magnitude and frequency in the River Ehen, and connection patterns in Ben Gill during sampling periods a to l.

Sampling period	River Ehen		Ben Gill			Type of scenario dominant	Effects on in-channel storage
	Number of events	Peak flow <i>m³ s⁻¹</i>	Number of connections	Number of days connected	Average duration of connection <i>days</i>		
<i>a</i>	3	7.21	<i>Pre-reconnection</i>				Shows uncertainty of method and stochastic variability
<i>b</i>	3	11.70	1	8.17	8.17	Scenario 2 (extreme SSCs)	Significant deposition
<i>c</i>	8	18.20	2	17.52	8.76	Scenario 3	Small removal
<i>d</i>	16	27.80	9	15.43*	1.71*	Scenario 2 & 3	Gradual build up of storage
<i>e</i>	6	23.70	6	14.58	2.43	Scenario 2	
<i>f</i>	10	13.70	12	10.36	0.86	Scenario 2	Shows uncertainty of method and stochastic variability
<i>g</i>	0	1.21	1	0.27	0.27	Scenario 1	
<i>h</i>	2	5.08	3	1.47	0.49	Scenario 1	Sharp increase in storage
<i>i</i>	18	54.00	28	19.81	0.71	Scenario 1 & 2, then 2 & 3	Potential build-up of storage (though no data), then significant but selective removal of fines
<i>j</i>	15	24.30	24	27.00	1.13	Scenario 3	Storage remains constantly ~2x higher than pre-reconnection conditions, but fluctuations limited by relative balance between each scenarios
<i>k</i>	3	13.70	7	10.27	1.47	Scenario 2 & 3	
<i>l</i>	10	10.90	10	8.70	0.87	Scenario 1, 2 & 3	

Average duration of connection: 1.27 days (1d 6h).

Minimum: 0.04 days (~1h). Maximum: 13.69 days (13d 16h).

* The duration of events 4,5,6 and 8 could not be defined precisely due to the absence of photographic evidence. The duration of these events was estimated as the mean duration of all other recorded events.

4.6.2. Suspended sediment transport

The Gauging Station is located approximately 600 m downstream from the confluence, with SSC data for here used as an index of input from Ben Gill; there is no other tributary in this reach and the assumption is that lateral inputs are negligible.

The Gauging Station showed no major episode of high SSCs prior to the reconnection of Ben Gill, although some events were observed at the Oxbow (Figure 4.2C & D). At the Gauging Station, mean SSC was 1.55 mg l⁻¹, with the maximum recorded on the first day after the reconnection of Ben Gill (04/10/2014, Figure 4.2C) and estimated at over 1700 mg l⁻¹ (i.e. the upper limit of the turbidity-meter). Maximum SSC at the Oxbow (800 mg l⁻¹) was also recorded on the first day after the reconnection; here, the mean for the study period was 3.00 mg l⁻¹. High SSC events recorded at the Gauging Station were also visible at the Oxbow (Figure 4.2C & D), although the latter experienced a higher number of lower magnitude events.

Uncertainties in the calculation of SSL (E_{SSL}) were determined to be $\pm 8.3\%$. SSLs and water yields (Figure 4.3) were generally highest in autumn and lowest in summer, apart from summer 2016 which saw high flow events (due to intense rainfall) in late August and early September (Figure 4.2). On average SSL at the Oxbow was 2 times higher than at the Gauging Station (between 1.5 and 4.5 times higher; Figure 4.3 & Table 4.2).

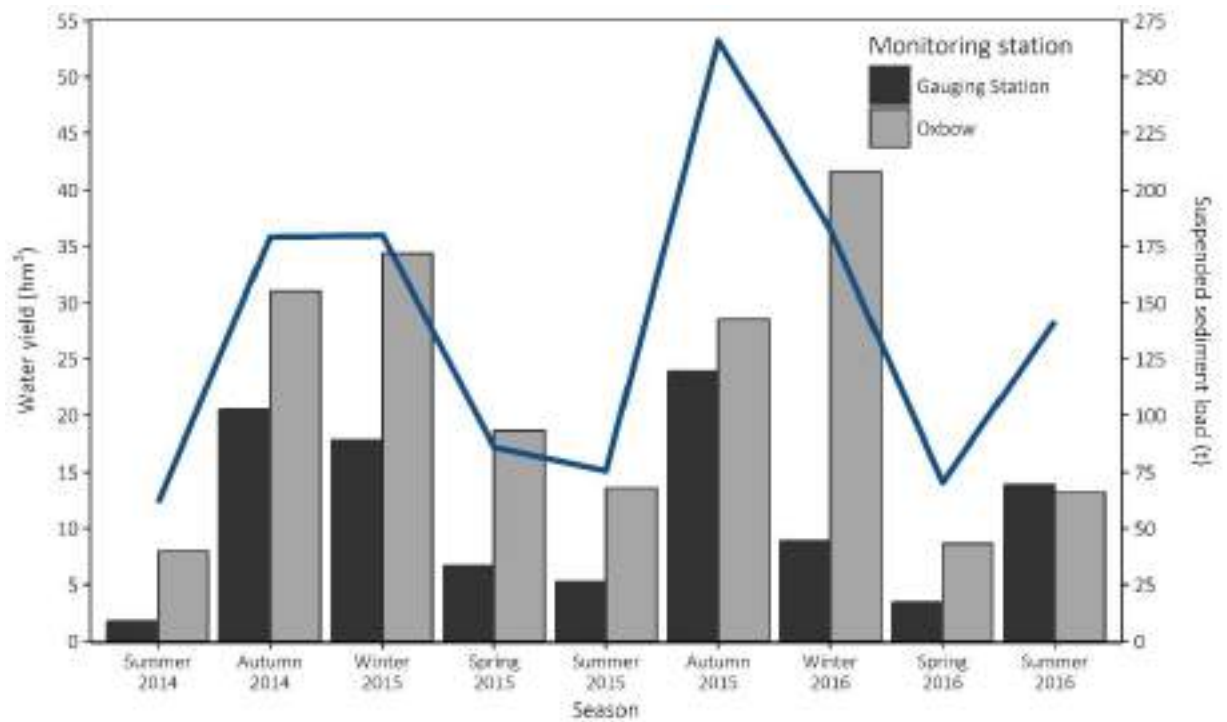


Figure 4.3. Suspended sediment loads (bars) and water yield (line) at each of the monitoring, at a seasonal scale.

Table 4.2. Summary statistics of flow and sedimentary conditions in the Ehen during to sampling periods a to l.

Sampling Number	period	of days	Gauging Station					Oxbow			
			Q_{max}	Q_{mean}	WY	SSL _{max}	SSL _{mean}	SY	SSL _{max}	SSL _{mean}	SY
			$m^3 s^{-1}$		hm^3	$kg 15min^{-1}$	$kg 15min^{-1}$	t	$kg 15min^{-1}$	$kg 15min^{-1}$	t
a	27	7.21	2.42	5.64±0.45	19.1±1.6	1.31±0.11	3.40±0.3	107±8.9	8.46±0.70	21.9±1.8	
b	52	11.7	2.35	10.5±0.8	3280±270	11.0±0.9	55.0±4.6	2050±170	19.5±1.6	97.4±8.1	
c	33	18.2	5.34	15.2±1.2	634±53	11.4±1.0	36.0±3.0	626±52	18.2±1.5	57.6±4.8	
d	92	27.8	3.98	31.6±2.5	597±50	4.72±0.39	41.7±3.5	878±73	13.6±1.1	120±10	
e	29	23.7	6.01	15.1±1.2	1940±160	19.9±1.7	55.4±4.6	1980±160	33.1±2.8	92.1±7.6	
f	88	13.7	2.47	18.8±1.5	1200±100	4.21±0.35	35.6±3.0	1080±90	9.55±0.79	80.7±6.7	
g	14	1.21	1.00	1.21±0.10	219±18	2.52±0.21	3.38±0.28	76.5±6.4	3.03±0.25	4.08±0.34	
h	25	5.08	1.93	4.18±0.33	1310±110	4.84±0.40	11.6±1.0	755±63	7.77±0.64	18.7±1.6	
i	144	54.0	4.01	49.9±4.0	1410±120	7.21±0.60	99.7±8.3	1320±110	15.7±1.3	217±18	
j	85	24.3	6.49	47.7±3.8	1100±91	9.40±0.78	76.7±6.4	1610±133	20.7±1.7	169±14	
k	86	13.7	2.00	14.9±1.2	250±21	1.96±0.16	16.2±1.3	269±1.3	3.52±0.29	29.1±2.4	
l	68	10.9	2.39	14.0±1.1	331±27	2.25±0.19	14.7±1.2	310±1.2	4.10±0.3	26.8±2.2	

Q: discharge

WY: Water Yield

SSL: Suspended Sediment Load

SY: Sediment Yield

A larger fraction of the SSL was transported in a shorter time at the Gauging Station than the Oxbow (Figure 4.4A); thus, fine sediment transport at the Gauging Station was characterised by shorter, more intense throughputs of material. If input from upstream was the only driver of SSL in the lower reach, the transport duration curves for the two stations would be more or less identical. That they are different is evidence of the contribution of additional sources in the lower reach, while the nature of the difference indicates that these new sources deliver material in a more diffuse way, extending over longer periods of time.

Cumulative SSLs at the two monitoring stations showed broadly similar patterns (Figure 4.4B); both increased progressively over the period, generally ran parallel and sometimes coincided. However, notable breaks in slope occurred in February-March 2015 and November-December 2015. For all of these breaks, the more marked increase at the Gauging Station allowed the yield here to re-join that at the Oxbow, which because of more continuous increases had advanced more. However, the timing of these 'catch-up' events was not consistent. The departure observed in January-February 2015 was quickly recovered during period e, when the average duration of connection of Ben Gill was high (i.e. 2.43 days). In 2016, however, the departure observed in December-February was followed by a relatively dry spell (March to August, Figure 4.2A). Only after the last sampling occasion (T13) did another episode of high SSCs at the Gauging Station occur, allowing the cumulative SSL to re-join that of lowermost station.

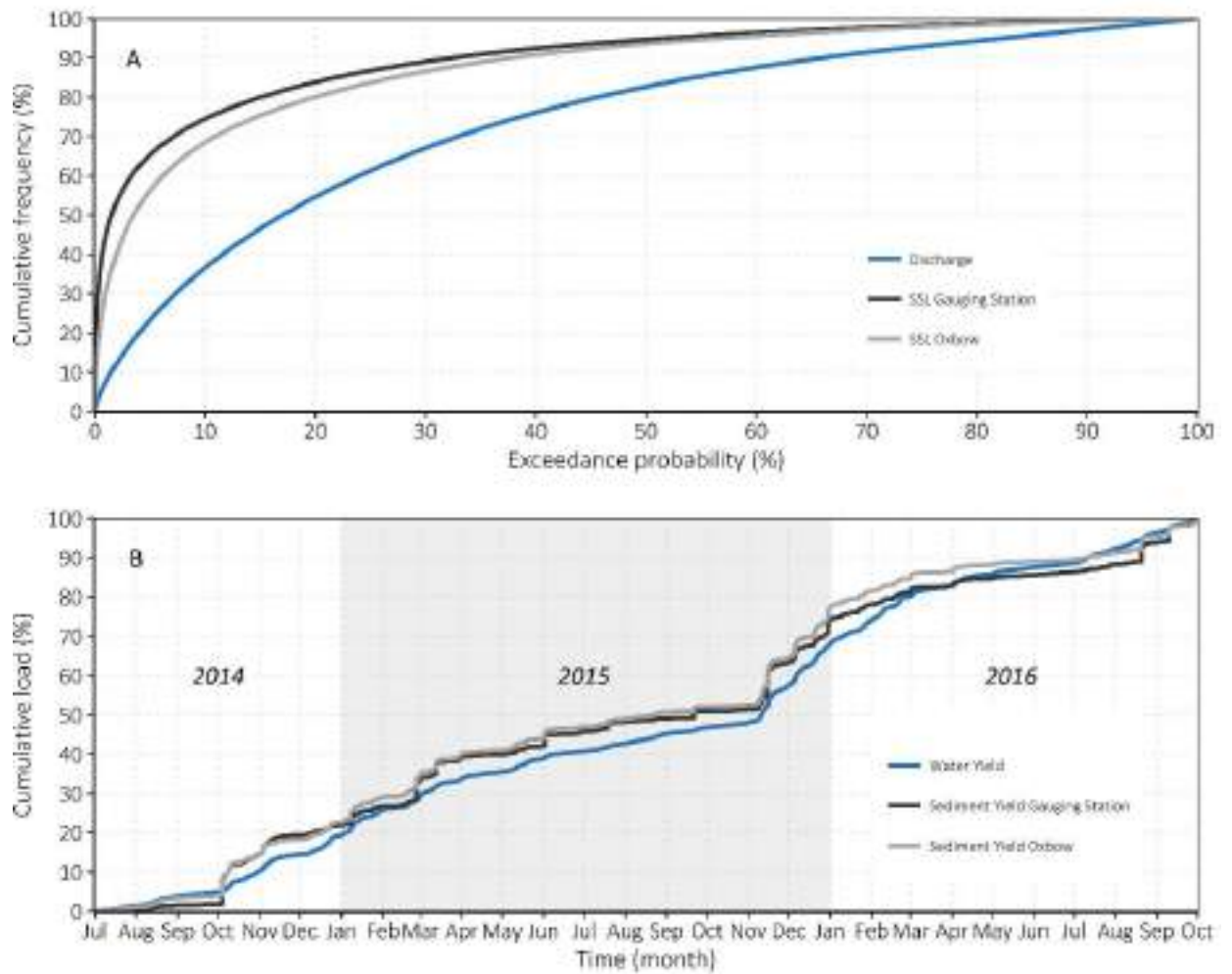


Figure 4.4. (A) Transport duration curves, presented as the cumulative frequency of exceedance probabilities, for discharge and suspended sediment load at the two monitoring stations. (B) Cumulative load over time for water yield and suspended sediment yields at the monitoring stations.

4.6.3. In-channel sediment storage

4.6.3.1. Quantitative changes over time

The storage of in-channel fine sediment varied considerably over a number of spatial and temporal scales during the study period. Changes in total storage between successive sampling occasions ranged from -5.56 ± 1.56 to $+3.24 \pm 0.91$ t (Table 4.3). Decreases were associated with major flood events (notably November and December 2015) while the most marked increase followed immediately from the reconnection of Ben Gill (October 2014). Overall storage of fines remained rather constant following the December 2015 floods (between 3 ± 0.85 and 3.6 ± 1.01 t), although values were appreciably higher than the average preceding the reconnection (c. 1.8 ± 0.50 t).

Table 4.3. Summary statistics of water yield, in-channel storage, suspended sediment loads and sediment budget for each sampling period.

Sampling period	Water Yield	In-channel Storage	Sediment Load		Sediment Budget			
	Gauging Station	Upstream Reach ¹	Gauging Station	Oxbow	Change in in-channel storage ² upstream reach	Transfer ⁴ into downstream reach ³	Fraction of in-channel storage in budget of upper reach	Fraction of locally sourced sediments ⁴ in budget of lower reach
	<i>hm³</i>	<i>t</i>	<i>t</i>	<i>t</i>	<i>t</i>	<i>t</i>	%	%
<i>a</i>	5.64±0.45	2.11±0.59	3.40±0.28	21.9±1.8	+0.31±0.09	18.5±1.5	9.1±2.6	84.5±7.0
<i>b</i>	10.5±0.8	5.34±1.50	55.0±4.6	97.4±8.1	+3.24±0.91	42.5±3.5	5.9±1.7	43.6±3.6
<i>c</i>	15.2±1.2	3.43±0.96	36.0±3.0	57.6±4.8	-1.91±0.53	21.6±1.8	5.3±1.5	37.4±3.1
<i>d</i>	31.6±2.5	3.58±1.00	41.7±3.5	120±10	+0.15±0.04	78.3±6.5	0.4±0.1	65.2±5.4
<i>e</i>	15.1±1.2	4.72±1.32	55.4±4.6	92.1±7.6	+1.14±0.32	36.6±3.1	2.1±0.6	39.8±3.3
<i>f</i>	18.8±1.5	5.08±1.42	35.6±3.0	80.7±6.7	+0.36±0.04	45.1±3.7	1.0±0.3	55.9±4.6
<i>g</i>	1.21±0.10	4.90±1.37	3.38±0.28	4.08±0.34	-0.18±0.32	0.70±0.06	5.3±1.5	17.1±1.4
<i>h</i>	4.18±0.33	7.46±2.09	11.6±1.0	18.7±1.6	+2.56±0.72	7.03±0.58	22±6.2	37.7±3.1
<i>i</i>	49.9±4.0	1.90±0.53	99.7±8.3	217±18	-5.56±1.56	117±9	5.6±1.6	54.0±4.5
<i>j</i>	47.7±3.8	3.31±0.93	76.7±6.4	169±14	+1.41±0.39	92.2±7.7	1.8±0.5	54.6±4.5
<i>k</i>	14.9±1.2	3.04±0.85	16.2±1.3	29.1±2.4	-0.27±0.08	13.0±1.1	1.7±0.5	44.5±3.7
<i>l</i>	14.0±1.1	3.61±1.01	14.7±1.2	26.8±2.2	+0.57±0.16	12.1±1.0	3.9±1.1	45.1±3.8
<i>Total</i>	238±19	50.3±14.1	450±37	934±78	+1.81±0.51	490±41	3.9±1.1	52.0±4.3

¹ Reach between the confluence of Ben Gill and Bleach Green Gauging Station

² Change in in-channel sediment storage calculated as the difference between storage at time *t* and time *t*-1

³ Reach between Bleach Green gauging station and the Oxbow

⁴ Locally sourced sediment (i.e. lateral inputs, bank erosion, release from the bed) of the downstream reach calculated as the difference between the sediment load input (Gauging station) and output (Oxbow)

Average storage over the study period was 475 g m^{-2} , although this varied considerably between morphological units and periods (from 15.1 to 2140 g m^{-2} ; Figure 4.5). There were some significant temporal patterns (ANOVA, $P < 0.0001$, $F = 5.387$, $df = 12$), with values of storage on sampling occasion T3 (post-reconnection) significantly higher than T1 & 2 (pre-reconnection) (Tukey's test, $P = 0.03$) and sampling occasion T10 different to T9 (Tukey's test, $P = 0.003$). These changes were particularly noticeable in the pool (Figure 4.5). Mean storage values in the pool were significantly greater than in the other two units (ANOVA and Tukey's tests: pool-riffle $P < 0.0001$, pool-plane bed $P < 0.0001$), while the riffle and plane bed did not differ ($P = 0.065$). The magnitude of variation in storage was lower in the riffle (coefficient of variation: Pool = 0.46 , Riffle = 0.26 , Plane Bed = 0.50).

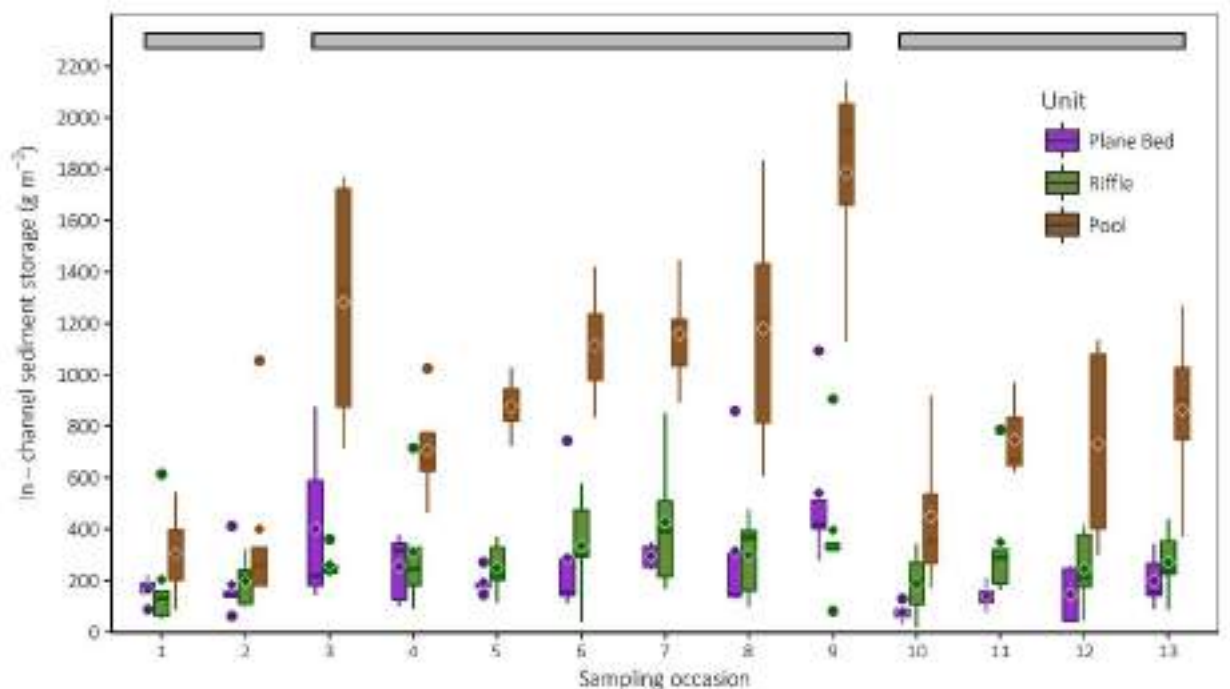


Figure 4.5. Boxplot of in-channel sediment storage (combined levels A1 and A2) per sampling occasion. Coloured diamonds represent mean values and coloured points show outliers. Horizontal bars above the plot link successive dates that did not differ significantly, i.e. a break in the bar means significant difference between two successive sampling occasions.

4.6.3.2. Flow asynchronicity and its influence on fine sediment transport and storage

The regulation by Ennerdale Water and its 1.3-m high weir had subtle but important effects on the timing of flow events in the Ehen relative to those in Ben Gill. Although high flow events still occur in the Ehen (Figure 4.2A), the number and magnitude of small to medium sized events are controlled by the weir. The compensation flow outlet controls flows when lake levels are

below weir crest, with only periods of more prolonged or intense precipitation capable of increasing lake levels above weir crest and hence increasing discharge in the Ehen. These factors can generate temporal mismatch between high flows in the Ehen and episodes of flow in Ben Gill. Localised rainfall events may also contribute to this mismatch.

Using the time-lapse camera facing the confluence, a conceptual framework of flow scenarios was developed to characterise the relationship between flows in the Ehen and Ben Gill (Figure 4.6). *Scenario 1: 'total asynchronicity'*. This scenario follows (a) episodes of long-lasting low flows in the Ehen, when rainfall over the headwater areas is just enough to re-fill the reservoir but not enough to overspill the weir, while (b) the rainfall is sufficient to trigger flows in Ben Gill and its connection to the Ehen. This scenario can be exacerbated by the sometimes localised nature of precipitation, which may mean that Ben Gill receives more rain than the upstream catchment which feeds into Ennerdale Water. This leads to high SSCs in the Ehen. *Scenario 2: 'partial synchronicity'*. Here, the difference in response time to rainfall between Ben Gill and the Ehen means that SSC rises sharply once Ben Gill starts flowing (Figure 4.6b), but concentrations are later diluted as Q increases in the Ehen and the inputs from the tributary decrease (exhaustion of sediment supply from the tributary). *Scenario 3: 'total synchronicity'*. In this scenario, Q in the Ehen increases prior to the connection of Ben Gill. Once Ben Gill starts flowing and delivering water, sediment from the tributary is rapidly diluted and SSCs remain low throughout the event. Scenario 3 occurs, for example, when lake levels are already high and precipitation causes rapid weir overspill.

These scenarios represent a useful framework for understanding changes in SSC and storage related to rainfall and associated increases in Q. They are used below to conceptualise changes occurring between successive sampling intervals during the study period (Figure 4.2A). Tables 4.1 and 4.2 provide key hydrological and sedimentary data for the intervals, as well as comments on the flow scenarios prevailing during each one. Key points are summarised below.

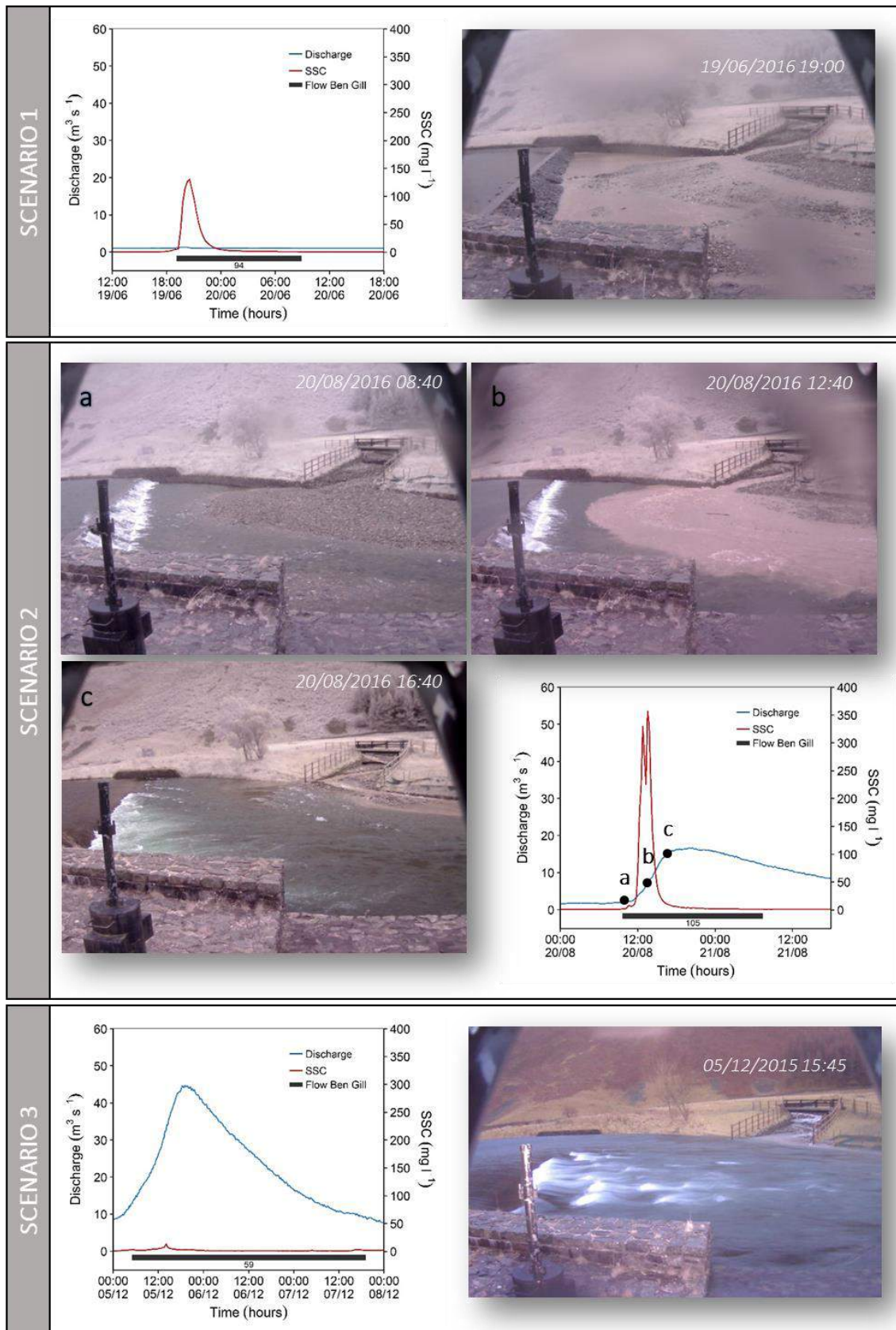


Figure 4.6. Different scenarios observed at the confluence of Ben Gill (stream facing the camera) with the River Ehen (flowing from the left) since the reconnection (see text for more details on each scenario). Discharge (blue line) and Suspended Sediment Concentration (SSC, red line) are measured at the gauging station. Flows in Ben Gill (grey bar) is determined from time-lapse photos.

Period *a* captures conditions immediately prior to the reconnection, with no marked high flow events in the Ehen. SSCs were very low ($<10 \text{ mg l}^{-1}$) and apparent changes in mean storage were very limited ($+0.31 \pm 0.09 \text{ t}$).

The opening of the newly restored and connected Ben Gill channel occurred during period *b*. The very intense but localised rainfall that occurred on the first day the channel was connected ($>120 \text{ mm}$ over 24 h) resulted in a prolonged period of flow in Ben Gill (1 event, 8 days long) and medium flows in the Ehen ($Q_{\text{max}} = 11.70 \text{ m}^3 \text{ s}^{-1}$). This type 2 scenario resulted in high SSCs and a marked increase in total storage over the reach ($+3.24 \pm 0.91 \text{ t}$), which was especially evident in the pool (mean increased from around 400 to 1300 g m^{-2}).

Period *c* is an example of scenario 3, when flows in the Ehen and Ben Gill are synchronous. Although there was material being delivered by Ben Gill, the discharge in the Ehen (always greater than 5 and occasionally more than 10 $\text{m}^3 \text{ s}^{-1}$) appeared competent, with a net reduction in storage occurring (from 5.34 ± 1.50 to $3.43 \pm 0.96 \text{ t}$).

Conditions were broadly similar over periods *d* to *g*. There were some high SSC events associated with periods when Ben Gill was connected, but despite some medium to high discharges in the Ehen, in-channel storage gradually increased over the winter, spring and early summer. These periods were characterised by a succession of type 2 and type 3 scenarios, with the prevalence of deposition indicated by the gradual increase in storage.

Period *h* illustrates the extreme processes associated with scenario 1. The lack of competent flow ($Q_{\text{max}} = 5.1 \text{ m}^3 \text{ s}^{-1}$) associated with high SSCs (e.g. $SSL_{\text{max}} = 1.30 \text{ t } 15\text{min}^{-1}$) caused by flow events in Ben Gill allowed fine sediment to deposit on the bed of the Ehen (an increase of $2.56 \pm 0.72 \text{ t}$ storage). This represents the highest value of storage measured during the study period (reaching $7.46 \pm 2.09 \text{ t}$).

The first part of period *i* experienced hydro-sedimentary conditions similar to period *h*, with low peak flows and frequent connections of Ben Gill. This is likely to have contributed to a further increase in storage, although no sampling was performed to confirm this. However, period *i* ended with a series of high Qs ($Q_{\text{max}} = 54.0 \text{ m}^3 \text{ s}^{-1}$, 3 successive events higher than $27.8 \text{ m}^3 \text{ s}^{-1}$, i.e. highest peak Q of period *d*). Among the c. 20 flow events recorded in Ben Gill during the latter part of period *i*, only one was of type 2 scenario; all other events were type 3. These very wet conditions led to a significant decrease in storage ($-5.56 \pm 1.56 \text{ t}$), and a decrease in

variability, to levels similar to those prior to the reconnection. This shows the potential of such extreme events to remove stored fine material from all units.

Period *j* showed hydro-sedimentary conditions similar the latter part of period *i*, but with lower peak Q_s ($Q_{\max} = 24.3 \text{ m}^3 \text{ s}^{-1}$). Ben Gill was connected to the Ehen on numerous occasions during the period (24), but most events were of type 3 scenario (only 2 were of type 2). Despite frequent high flows, the channel experienced an increase in storage ($+1.41 \pm 0.39 \text{ t}$), highlighting the inability of the system, under some conditions, to convey all material supplied by Ben Gill.

The end of the study period (periods *k* and *l*) saw the channel experiencing mostly scenario 2 and 3 events, apart from a couple of scenario 1 events in June 2016 (see illustration in Figure 4.6). However, average storage tended to stabilise around $3.6 \pm 1.0 \text{ t}$ which, despite being higher than pre-reconnection conditions (2-fold increase), was controlled by the relative synchronicity between flows in Ben Gill and high Q in the Ehen.

4.6.3.3. Changes in grain-size and organic content over time

The average amount of organic matter stored in the riverbed varied between 5 and 71 g m^{-2} , with values always greatest in the pool. The organic component of the fine sediment ranged between 3.3 and 11.5% (average = 5.7%). There was no relationship between the proportion of fine material comprised of organic matter (% of total) and the total amount of organic matter (g); thus, variations in the proportion of organic matter were not a direct response to variations in the absolute amount of organic material ($r^2 = 0.03$, $P > 0.05$).

The majority of the stored sediment consisted of sand (average = 67.6%), with silt quite abundant (average = 26.5%) and clay usually minor (average = 5.9%). There were no significant changes in median particle size of the stored sediment associated with the opening of Ben Gill (Friedman's Test: $p = 0.073$). Median particle size (D_{50} , average = $164 \mu\text{m}$, range = $[80-298] \mu\text{m}$), D_{10} ($11 [6-32] \mu\text{m}$) and D_{90} ($495 [285-862] \mu\text{m}$) reflect the wide range of particle sizes collected from the bed.

The PCA used to characterise the overall characteristics of stored sediment highlighted the distinctiveness of the pool, and the fact that the other units were very similar (Figure 4.7). Together the two principal components explained approximately 88% of the variance in sediment characteristics, with the first component (59.3%) clearly driven by amount of material (total and amounts in the various size fractions) and the second (28.8%) driven by the relative

organic content (% of total) and sizes of the material. The separation of the pool was mainly due its greater amount of organic matter and the total amount of stored material. Arrow lengths for the variables were largely the same, so no particular sediment characteristics were more important for distinguishing between the samples than others. The exception was % organic which had a shorter arrow than all the others, indicating that it differed less between the samples.

The PCA also emphasised the relations between total sediment and the total and percentage of organic material. Samples with large quantities of fine sediment also had higher absolute amounts of organic material. The arrows for absolute and % of organic sediment point in opposite directions; thus, in samples with large amounts of organic sediment, this material makes up a relatively small proportion of the total fine storage. Arrows for all size percentiles point in the same direction (D_{90} , D_{50} and D_{10}), so samples with a large median size also had a large D_{90} etc.

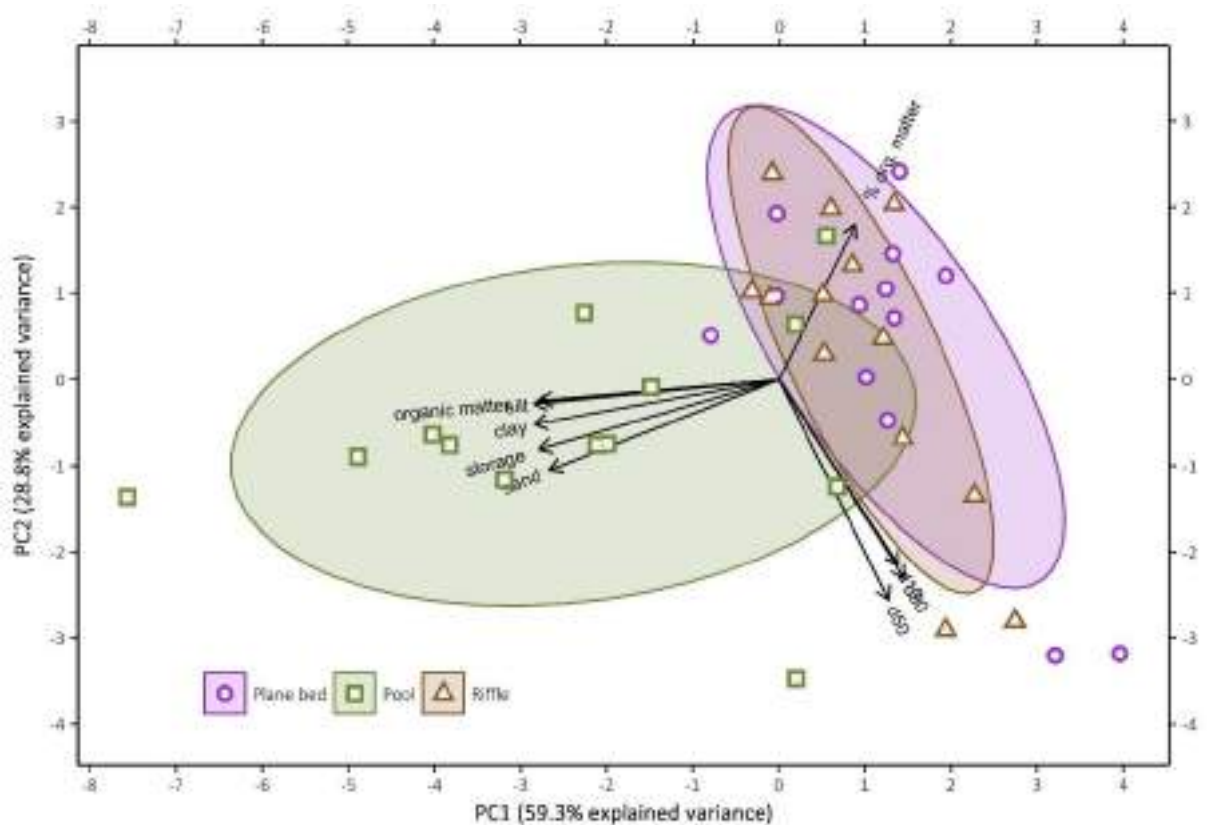


Figure 4.7. PCA ordination of the characteristics of the stored fine sediment. Symbols and ellipses are used to group the samples by morphological unit. Organic matter = absolute amount of organic matter; silt/sand/clay = absolute amount of each fraction; $d_{10}/d_{50}/d_{90}$ = particle size of each quantile (D_{10} , D_{50} , D_{90}); %org.matter = proportion of organic matter.

The maximum percentage of organic matter (10.2%) was observed prior to the reconnection. Subsequently, the amount organic matter remained relatively lower, with a peak of 6.1% in June 2016 (T12). This, along with the direction of the 2 arrows on Figure 4.7, suggests that morphological units differ little in the % of organic material when total amount of stored sediment is high, but differ in % organic content when fines are less prevalent.

4.6.4. Sediment budgets

In the upper reach, the release of sediment from the riverbed (Table 4.3) was responsible for a minimum average of 3.9% of the total fine sediment budget (3.2% year 1, 4.7% year 2). Values for individual sampling periods ranged from 0.4 to 22% (Table 4.2). Low values are characteristic of limited changes in storage (e.g. periods *d* and *f*), while high values correspond to periods of more intense activity (removal or deposition, such as periods *h* and *i*).

Input from directly upstream represented an average of 48% of the suspended sediment budget of the lower reach (i.e. difference between suspended sediment yield at the Oxbow and that of the Gauging Station); the remaining 52% is therefore taken to be composed of lateral inputs, re-suspension from the riverbed and bank erosion (Table 4). Values for individual sampling periods varied between 17.1 and 65.2% after reconnection, but with the highest values being for the pre-reconnection period (84.5%). The relative proportion of each of the processes is unknown, although we hypothesise that re-suspension from the riverbed will be of a similar order of magnitude to the upper reach (i.e. *c.* 4%). This leaves a potentially high proportion of the suspended sediment budget generated by lateral input from ditches and non-perennial tributaries, despite the relatively short distance between the monitoring stations (2.52 km) and limited additional catchment area (+2.5 km²).

Table 4.4. Reach-scale suspended sediment budgets for the study section.

	Upper reach	Lower reach
Lateral input*	39.4 ±5.0%	
In-channel storage	3.9 ±1.1%	52 ±4.3%
Bank erosion		
Input from upper catchment	56.7 ±6.1%	48 ±4.0%

* Lateral input for the upper section consists solely of the newly reconnected ephemeral tributary Ben Gill

4.7. DISCUSSION

The reconnection of Ben Gill aimed to restore the delivery of water and coarse sediment to the Ehen, and within a year there were signs that this was happening (Marteau et al. 2016). However, the reconnection has also changed suspended sediment dynamics in the Ehen (Marteau et al. 2017). The current paper aimed to assess the total sediment budget of the reach studied by previous authors, along with an adjacent reach further downstream, with a particular focus on in-channel bed storage and how the degree of synchronicity between flows in Ben Gill and the Ehen influences the movement of fine sediment through the system.

4.7.1. Flows and suspended sediment dynamics

Despite being regulated by the lake and weir, the hydrology of the River Ehen has retained a certain degree of variability. Regulation mostly affects low flow conditions when water in the lake does not overflow the weir and flows downstream are therefore controlled by the compensation release. Hydrological statistics for the study period are slightly higher than long term averages, primarily reflecting an increase in compensation flow since 2014 but also the very wet winter of 2015. Ben Gill is a non-perennial stream with a small catchment area. During the study period, it flowed for approximately the same percentage of time as the period covered by Quinlan et al. (2015a). Flows in Ben Gill respond rapidly to local rainfall events; it is a flashy stream, with flows lasting from just few hours to few days.

Total sediment loads in the two reaches were increased following the reconnection. Patterns of sediment transport differed slightly between the two monitoring stations: SSLs were higher at the downstream station (Oxbow), where transport was characterised by events of higher frequency but lower magnitude. This reflects the difference in the nature of sediment sources (Figure 4.4B also illustrates this difference). Cumulative SSL at the Oxbow departs from that of the Gauging Station in the wet winter months, when surface run-off is most frequent and creates low magnitude but frequent SSC events at the Oxbow. The cumulative SSL curve at the Gauging Station only 'catches-up' following repeated or long-lasting periods of delivery from Ben Gill.

Hydro-geomorphologically, the upper reach is controlled predominantly by flashy inputs from Ben Gill, while the lower reach receives sediment from ditches and surface run-off, which can be triggered by smaller rainfall events. It is also possible that human-induced sources of fine material (e.g. septic tanks) may contribute to this increase in sediment input, but in ways that are independent of rainfall or discharge. The catchment area at the Oxbow is only 2.5 km² greater than at the Gauging Station, but this additional area contributes 185 ±15 t km² y⁻¹, similar to the contribution of Ben Gill for the upper reach (181 ±15 t km² y⁻¹, Marteau et al. 2017). Such specific sediment yields fall within the upper range of values found in the UK (e.g. long-term average flux; 5th and 95th percentiles of 5.4 and 107.7 t km⁻² y⁻¹ respectively, Worrall et al. 2013) but are in line with those of agricultural and human-modified catchments (up to 488 t km² y⁻¹, Foster and Lees 1999).

4.7.2. In-channel sediment storage

Changes in fine sediment storage on the bed of the Ehen varied appreciably over time and space. The pool, where conditions are most favourable for deposition, experienced higher volumes of storage compared to the plane bed and riffle (e.g. mean maximum storage >1,800 g m⁻²) but was also significantly different in terms of the characteristics of the stored sediment. Here, stored sediment contained more organic matter (up to 71.5 g m⁻²). Although the riffle and plane bed did not differ significantly in terms of quantity and grain-size and organic composition, variations in storage were greater in the plane bed. The riffle, where velocities remain relatively higher even at low flows, appears to be less sensitive to deposition and removal of fine sediments. This unit was also the only one where deposition of fresh and loose

gravel was observed over the course of the study. Fresh deposits, originating from Ben Gill, usually contained little or no fine sediment.

Maximum storage of fine sediment peaked approximately a year after the reconnection of Ben Gill, reaching 7.46 ± 1.38 t, representing a 350% increase. By the end of the study, storage averaged 3.60 ± 0.81 t; although much less than the peak, this still represents a 2-fold increase compared to the period immediately pre-reconnection (summer 2014) and is also higher than the 2010-12 period monitored by Quinlan et al. (2015a).

Despite this increase, in-channel fine sediment storage in the Ehen is not particularly high compared to examples found in the literature. Within a British context, reported values vary between 40 g m^{-2} (tributary of the Piddle, Collins and Walling 2007b) and $80,000 \text{ g m}^{-2}$ (River Severn, Walling and Quine 1993). Most reported average values are between 200 and 2000 g m^{-2} (e.g. Walling et al. 1998, 2006; Owens et al. 1999; Wilson et al. 2004; Collins et al. 2005; Collins and Walling 2007b). High values of storage tend to be found in small agricultural catchments (e.g. Walling et al. 2002; $23,400 \text{ g m}^{-2}$) or lowland rivers (e.g. Heppell et al. 2009; $66,800 \text{ g m}^{-2}$) while low values are found in small urbanised catchments (e.g. West Midlands, Lawler et al. 2006; $50\text{-}110 \text{ g m}^{-2}$) and chalk streams (Acornley and Sear 1999). In the upper Ehen, average storage ranged from 224 (T1) to 907 g m^{-2} (T9) and included all particles between 0.012 and 2 mm. This corresponds to the lower range of values found in the literature, and is typical of rivers with limited sedimentary activity. Many authors consider fine sediment as being $<63 \mu\text{m}$ (i.e. silt and clay only) which only represents 32 % on average (volume) of the material stored in the Ehen.

Some authors have observed seasonal variations in fine sediment storage, sometimes higher in winter (e.g. Acornley and Sear 1999; Walling and Amos 1999) and sometimes in summer (e.g. Walling et al. 2003; Collins and Walling 2007a, b). Others have observed mixed patterns, arguing for the importance of cycles of vegetation growth and senescence (Heppell et al. 2009) or the greater influence of flow conditions and local channel characteristics (Marttila and Kløve 2014). The latter authors also found that, in a catchment exploited for peat and wood in central Finland, the high volumes of sediment delivered by headwater tributaries were quickly conveyed downstream; similar dynamics have been reported in Mediterranean streams (Francke et al. 2014; Piqué et al. 2014). No seasonal trends were observed in the variations of sediment storage in the River Ehen. Spatial variability increased with increased deposition, and vice-versa, despite the relatively simple morphology of the riverbed. Although the river is

capable of removing accumulated fine sediments, significant cleaning was only observed in response to high magnitude, low-frequency events. Thus, the absence of deposition plays a potentially greater role in controlling storage than the removal of fines during floods. This is an important consideration in this regulated system, where water abstraction from the lake can lead to frequent and long-lasting periods of low flow (i.e. compensation flows).

The average fraction of sand stored in the Ehen (67%) is consistent with findings from lowland vegetated rivers (e.g. Heppell et al. 2009), although the median particle size ($D_{50} = 164 \mu\text{m}$) is greater than other studies (e.g. Marttila and Kløve 2014; 7-60 μm). The major flow events of November-December 2015 influenced the relative proportions of sand and silt across the upper reach, with the proportion of silt being reduced to 14.5% and the proportion of sand increasing to 81.3% (clay \sim unchanged, 4.2%). It is noticeable, however, that this change cannot be attributed to the break-up of the paved layer, despite the magnitude of the floods during this period (highest $Q = 54.0 \text{ m}^3 \text{ s}^{-1}$, 30-year return period). The surface layer remained stable and retained a fair proportion of the sands and clays, releasing mostly the medium fraction of the finer particles (i.e. 4 to 62 μm). During their study of controlled releases of water under different antecedent conditions, Petticrew et al. (2007) found that the presence of an armour layer helped reduce the loss of fine sediment and it is likely that the paving in the Ehen exerts a similar influence on sediment loss at most flow conditions. We hypothesise that pore space in the pavement is reduced by its level of compaction; thus, sands may be too coarse, and clay too cohesive, to be washed out of the matrix. Rather than size-selective entrainment, the process occurring in the Ehen may therefore be best considered as size-selective retention. Additionally, bed conditions rapidly returned to pre-high flow conditions as more sediment was supplied to the river, coinciding with less competent discharges.

The organic fraction of stored sediment in the Ehen was rather low (<6% post-reconnection) compared to other studies (e.g. 9-17%, Walling et al. 1998; 30%, Marttila and Kløve 2014). The % organic fraction did not play an important role in discriminating between the three morphological units present in the study reach when volumes of stored sediments were high, but differed when the bed was cleaner, i.e. following high flow events, when less fine sediment was present.

4.7.4. Fluvial sediment budget and sources of material

Despite fluctuations over time, reflecting net losses associated with high Q events, data suggest that in-channel storage of fine sediment in the Ehen has increased since the reconnection in October 2014 (from 1.8 ± 0.70 to 3.6 ± 0.81 t). Generally, the contribution of in-channel storage to sediment budgets varies greatly in the UK (e.g. Exe, 1.6%; Lambert and Walling 1988; Severn, 2%; Walling and Quine 1993; Leadon, Tone and Torridge, 0.9 to 1.5%; Wilson et al. 2004) and can be appreciably higher than the Ehen (e.g. Frome and Piddle, 18-55%; Collins et al. 2005; Tern, Pang and Lambourn, 21-38%; Collins and Walling 2007a). The contribution of stored sediment to the sediment budget in the Ehen is thus rather limited compared to other rivers in the UK. However, it has decreased since the reconnection (8.9%, period *a* of this study; estimated as 11.9%, from Quinlan et al. (2015b), to 3.9% on average in this study). In fact, the increase in storage and release of fines from the bed belies the large increase in SSL (+65%) following the reconnection. It should also be noted that the total amount of sediment moving into and out of storage in the study reach is likely to be substantially greater than the estimates of mean total storage, due to the 'snapshot' nature of the sampling methods.

In their study of the conditions in the Ehen prior to the restoration work, Quinlan et al. (2015a) argued that sedimentary activity was very low, and sediment dynamics were likely to be driven mostly by locally sourced sediment; i.e. material eroded from the banks or re-suspended from the bed. Over the 40-year period that Ben Gill was disconnected, the lack of coarse sediment supply and the winnowing of relatively fine particles during high flows resulted in the appearance of a well-developed armour layer in the Ehen, becoming more and more resistant to even very high discharges. Marteau et al. (2017) estimated approximately 40% of the total suspended sediment yield in the upper reach is now supplied by Ben Gill, with the remaining percentage corresponding to input from the upper part of the catchment together with very localised bank erosion within the reach.

The simple conceptual framework used to identify the different flow scenarios proved to be helpful to characterise suspended sediment dynamics in the Ehen, with changes in storage controlled by the degree of synchronicity between flows in the main-stem and those in Ben Gill. Scenario 1 results in deposition while scenario 3 allows the system to remove part of the stored fine sediment (Table 4.1). Scenario 2 can have greater or lesser effects on storage, depending on the magnitude of the associated discharge. Scenario 3 events, especially when

associated with high peak flow (i.e. above $20 \text{ m}^3 \text{ s}^{-1}$) are responsible for the removal of stored sediment. During the 2-year study period, the most significant changes in storage followed two key events: the reconnection of Ben Gill (Scenario 2, period *b*) which corresponded with a very high SSC event, and a series of very high discharges (Scenario 3, period *i*) brought by two successive storms in November and December 2015. Both storms triggered significant changes in storage in the channel and so were useful to help understand the processes of deposition and removal of fine sediment in the system.

Period *a*, although short in duration, highlighted the major role played by lateral inputs to the lower reach prior to the re-connection of Ben Gill (>80% of sediment budget). The ratio has decreased since the reconnection of Ben Gill (average c. 50%). Although lateral inputs were not specifically quantified (i.e. budget estimates are based on suspended sediment monitored at the Gauging Station and the Oxbow), such sources of fine material (e.g. bank erosion) become increasingly important with increasing distance downstream. This conclusion is based on the magnitude of difference between the two reaches set against the limited uncertainties of the computed SSL ($\pm 8.3\%$).

4.7.5. Management perspective

The nature of the system described in the study is unusual, with the juxtaposition of a highly dynamic ephemeral stream discharging just downstream from an impoundment. The flow scenarios reported here reflect this juxtaposition, not just at the present time but potentially also before the tributary was disconnected. The extreme difference between the flow scenarios provides a wide gradient which has resulted in marked differences in the dominant process over the study period (sometimes rapid sediment accumulation, sometimes loss). In turn, the different fluvial processes occurring in response to the flow scenarios provides critical information to aid the management of the Ehen, especially from an ecological perspective.

The occurrence of events with total or partial asynchronicity (especially when flows in the Ehen are low) represent the most ecologically stressful ones. These phenomena can cause high SSCs, sometimes long-lasting, and are more likely to generate higher rates of deposition. High duration and magnitudes of deposition are known to be detrimental for pearl mussels. Thus, limited deposition and/or increased removal of fines, which are fundamental to the ecological success of the Ehen restoration project, are dependent on the ability of the river to respond rapidly to rainfall events. Given the characteristics of the system, it appears that focusing on

the prevention of deposition may lead to greater success. Indeed, limiting the occurrence of scenario 1 events, by stopping water abstraction for instance, would be easier to implement than enhancing the occurrence of scenario 3 events, which strongly depend on unpredictable periods of high rainfall. Further reduction of suspended sediments in the system could be tackled by looking in more detail at lateral and intermittent sources of sediment, especially for the lower reach of the study section, and applying efforts to control these. Farmlands are known to be an important source of fine sediment for rivers (Montgomery 2007), whether from crop topsoils, farm tracks or well-connected ditches (Collins et al. 2012). The identification of point sources of fine sediment in the Ehen is the subject of an on-going investigation by the UK Environment Agency and other partners in the restoration project, with the long-term aim of controlling and preventing further degradation of habitat conditions in this section of the river (APEM 2015).

The management of fine sediment in fluvial systems relies on a better understanding of the processes that control transfers as well as magnitude-frequency effects and geomorphic thresholds (Owens et al. 2005). On the one hand, the present study helps provide a better insight into the functioning of the Ehen as a fluvial system. On the other hand, much remains to be understood about the longer-term evolution of the river in response to the reconnection of Ben Gill and ongoing changes to abstraction from Ennerdale Lake and associated changes to the compensation flow. Over the 2 years of this study, the succession of high flows was unable to break the armoured layer. However, new pockets of coarse sediments originating from Ben Gill were observed in the upper study reach, showing that the Ehen is not only conveying the finer fraction of the newly delivered sediment. Displacement of the coarser material is likely to be the only means for the riverbed to experience a renewed vertical mixing and, potentially, a renewal (at least partial) of the bed surface texture and structure. Further monitoring of the geomorphic processes at play in the Ehen is required to better appreciate how it will respond to new mobile sediment and altered flows.

4.8. FINAL REMARKS

In supply-limited systems such as the Ehen, lateral inputs can represent a large fraction of the fluvial sediment load. The fine sediment yields of the two reaches reported in this study, located downstream from a lake and its associated weir, are largely controlled by intermittent sources of sediment: an ephemeral tributary for the upper section (Ben Gill) and a network of ditches,

small tributaries and surface runoff for the lower section (e.g. farmlands, anthropogenic source points). These inputs are significant, despite their relatively small contributing catchment areas.

SSCs in the upper reach, and whether or not this material is stored here or conveyed downstream, depend critically on the degree of synchronicity between the ephemeral Ben Gill and the main-stem. The three flow scenarios provide a useful framework to understand the circumstances under which benthic habitat might be sub-optimal for sensitive species, and in turn can help target management efforts to reduce the risks associated with certain combinations of hydrological conditions.

The relative contribution of stored sediment to the Ehen's sediment budget is highly variable and depends on a complex interaction between SSCs and flows, as well as antecedent hydro-sedimentary conditions. Although limited in the River Ehen due to the very stable conditions of the riverbed, at times stored sediment still contributes over 20% of the sediment budget. The variability in SSCs and storage over the 2-year period helps emphasise the intermittent nature of fine sediment transport processes in river channels. The intermittency of these processes in the Ehen is largely a result of flow regulation and the ephemeral nature of one of its main sources of fine sediment.

Bed storage showed cycles of increase and decrease associated with variation in the hydrological regime of the Ehen. Bed storage was higher at the end of the study period than at the beginning. However, it would be premature to assume that this situation will persist, as supply is driven by input from Ben Gill, a stream that is still adjusting to its new configuration, and whose future evolution (degree of erosion) remains unclear. We hypothesise that sediment delivery is still greatly influenced by the erosion of unconsolidated sediments from the Ben Gill alluvial fan, and that this will decrease as the new channel becomes more graded. Moreover, cycles of deposition and removal in the Ehen are likely to be altered by sedimentological and geomorphological changes which occur in response to the delivery of coarse material, as well as hydraulic feedbacks which affect entrainment and settlement.

4.9. REFERENCE LIST

- Acornley RM, Sear DA (1999). Sediment transport and siltation of brown trout (*Salmo trutta* L.) spawning gravels in chalk streams. *Hydrological Processes* 13:447–458
- Adams JN, Beschta RL (1980). Gravel bed composition in Oregon coastal streams. *Canadian Journal Of Fisheries and Aquatic Sciences* 37:1514–1521
- APEM (2015). Upper River Ehen and Ennerdale Water Catchment Walkover Survey. APEM Scientific Report 414068. Natural England, February 2016 v 0.1 Final: 21p.
- Bauer G (1988). Threats to the freshwater pearl mussel *Margaritifera margaritifera* L. in Central Europe. *Biological Conservation* 45:239–253
- Bilotta GS, Brazier RE (2008). Understanding the influence of suspended solids on water quality and aquatic biota. *Water Research* 42:2849–2861
- Buddensiek V, Engel H, Fleishauer-Rössing S, Wachtler K (1993). Studies on the chemistry of interstitial water taken from defined horizons in the fine sediments of bivalve habitats in several northern German lowland waters. II: Microhabitat of *Margaritifera margaritifera* L., *Unio crassus* P. and *Unio tumidus* P. *Archiv für Hydrobiologie* 127:151–166
- Buendía C, Gibbins CN, Vericat D, Batalla RJ (2014). Effects of flow and fine sediment dynamics on the turnover of stream invertebrate assemblages. *Ecohydrology* 7:1105–1123
- Buendía C, Gibbins CN, Vericat D, Batalla RJ (2013a). Reach and catchment-scale influences on invertebrate assemblages in a river with naturally high fine sediment loads. *Limnologica - Ecology and Management of Inland Waters* 43:362–370
- Buendía C, Gibbins CN, Vericat D, Batalla RJ, Douglas A (2013b). Detecting the structural and functional impacts of fine sediment on stream invertebrates. *Ecological Indicators* 25:184–196
- Bunte K, Abt SR (2001). Sampling surface and subsurface particle-size distributions in wadable gravel- and cobble-bed streams for analyses in sediment transport, hydraulics, and streambed. Gen. Tech. Rep. RMRS-GTR-74. Fort Collins, CO: U.S.D.A., Forest Service, Rocky Mountain Research Station
- Collins AL, Walling DE (2007a). Fine-grained bed sediment storage within the main channel systems of the Frome and Piddle catchments, Dorset, UK. *Hydrological Processes* 21:1448–1459
- Collins AL, Walling DE (2007b). The storage and provenance of fine sediment on the channel bed of two contrasting lowland permeable catchments, UK. *River Research and Applications* 23:429–450
- Collins AL, Walling DE, Leeks GJL (2005). Storage of fine-grained sediment and associated contaminants within the channels of lowland permeable catchments in the UK. *Sediment Budgets 1, IAHS Publication* 291:259–268
- Collins AL, Zhang Y, McChesney D, Walling DE, Haley SM, Smith P (2012). Sediment source tracing in a lowland agricultural catchment in southern England using a modified procedure combining statistical analysis and numerical modelling. *Science of the Total Environment* 414:301–317

- Diplas P, Parker G (1992). Deposition and removal of fines in gravel-bed stream. In: Billi P, Hey RD, Thorne CR, Tacconi P (eds) *Dynamics of Gravel-bed Rivers*. John Wiley & Sons, Ltd., Chichester, UK, pp 313–329
- Diplas P, Parker G (1985). Pollution of gravel spawning grounds due to fine sediment: Project Report No. 240. St. Anthony Falls Hydraulic Laboratory: 145p.
- Duerdoth CP, Arnold A, Murphy JF, Naden PS, Scarlett P, Collins AL, Sear DA, Jones JI (2015). Assessment of a rapid method for quantitative reach-scale estimates of deposited fine sediment in rivers. *Geomorphology* 230:37–50
- Foster IDL, Lees JA (1999). Changing headwater suspended sediment yields in the LOIS catchments over the last century: A paleolimnological approach. *Hydrological Processes* 13:1137–1153
- Francke T, Werb S, Sommerer E, López-Tarazón JA (2014). Analysis of runoff, sediment dynamics and sediment yield of subcatchments in the highly erodible Isábena catchment, Central Pyrenees. *Journal of Soils and Sediments* 14:1909–1920
- Frostick LE, Lucas PM, Reid I (1984). The infiltration of fine matrices into coarse-grained alluvial sediments and its implications for stratigraphical interpretation. *Journal of the Geological Society* 141:955–965
- Geist J, Auerswald K (2007). Physicochemical stream bed characteristics and recruitment of the freshwater pearl mussel (*Margaritifera margaritifera*). *Freshwater Biology* 52:2299–2316
- Greig SM, Sear DA, Carling PA (2005). The impact of fine sediment accumulation on the survival of incubating salmon progeny: Implications for sediment management. *Science of the Total Environment* 344:241–258
- Heppell CM, Wharton G, Cotton JA, Bass JAB, Roberts SE (2009). Sediment storage in the shallow hyporheic of lowland vegetated river reaches. *Hydrological Processes* 23:2239–2251
- Lambert CP, Walling DE (1988). Measurement of channel storage of suspended sediment in a gravel-bed river. *Catena* 15:65–80
- Lawler DM, Petts GE, Foster IDL, Harper S (2006). Turbidity dynamics during spring storm events in an urban headwater river system: The Upper Tame, West Midlands, UK. *Science of the Total Environment* 360:109–126
- López-Tarazón JA, Batalla RJ, Vericat D (2011). In-channel sediment storage in a highly erodible catchment: the River Isábena (Ebro Basin, Southern Pyrenees). *Zeitschrift für Geomorphologie* 55:365–382
- Marteau B, Batalla RJ, Vericat D, Gibbins CN (2017). The importance of a small ephemeral tributary for suspended sediment dynamics in a main-stem river. *River Research and Applications* 1–15
- Marteau B, Vericat D, Gibbins C, Batalla RJ, Green DR (2016). Application of Structure-from-Motion photogrammetry to river restoration. *Earth Surface Processes and Landforms* 42:503–515
- Marttila H, Kløve B (2014). Storage, properties and seasonal variations in fine-grained bed sediment within the main channel and headwaters of the River Sanginjoki, Finland.

Hydrological Processes 28:4756–4765

- Milhous RT (1973). Sediment transport in a gravel bottomed stream. Oregon State University
- Miller AJ, Shoemaker LL (1986). Channel storage of fine grained sediment in the Potomac River. In: Hadley RF (ed) *Drainage Basin Sediment Delivery*, IAHS Publi. IAHS Press, Wallingford, pp 287–303
- Montgomery DR (2007). Soil erosion and agricultural sustainability. *Proceedings of the National Academy of Sciences of the USA* 104:13268–72
- Navratil O, Legout C, Gateuille D, Esteves M, Liebault F (2010). Assessment of intermediate fine sediment storage in a braided river reach (southern French Prealps). *Hydrological Processes* 24:1318–1332
- O’Leary D (2013). Pearls in Peril LIFE+ GB - Action A3: Conservation Actions for the Freshwater Pearl Mussel in the River Ehen, Cumbria. Report LIFE 11 NAT/UK/383. West Cumbria River Trust, UK: 45p.
- Österling ME, Arvidsson BL, Greenberg LA (2010). Habitat degradation and the decline of the threatened mussel *Margaritifera margaritifera*: influence of turbidity and sedimentation on the mussel and its host. *Journal of Applied Ecology* 47:759–768
- Owens PN, Batalla RJ, Collins AJ, Gomez B, Hicks DM, Horowitz AJ, Kondolf GM, Marden M, Page MJ, Peacock DH, Petticrew EL, Salomons W, Trustrum NA (2005). Fine-grained sediment in river systems: environmental significance and management issues. *River Research and Applications* 21:693–717
- Owens PN, Walling DE, Leeks GJL (1999). Deposition and storage of fine-grained sediment within the main channel system of the River Tweed, Scotland. *Earth Surface Processes and Landforms* 24:1061–1076
- Petticrew EL, Krein A, Walling DE (2007). Evaluating fine sediment mobilization and storage in a gravel-bed river using controlled reservoir releases. *Hydrological Processes* 21:198–210
- Piqué G, López-Tarazón JA, Batalla RJ (2014). Variability of in-channel sediment storage in a river draining highly erodible areas (the Isábena, Ebro Basin). *Journal of Soils and Sediments* 14:2031–2044
- Quinlan E, Gibbins CN, Batalla RJ, Vericat D (2015a). Impacts of Small Scale Flow Regulation on Sediment Dynamics in an Ecologically Important Upland River. *Environmental Management* 55:671–686
- Quinlan E, Gibbins CN, Malcolm I, Batalla RJ, Vericat D, Hastie L (2015b). A review of the physical habitat requirements and research priorities needed to underpin conservation of the endangered freshwater pearl mussel *Margaritifera margaritifera*. *Aquatic Conservation: Marine and Freshwater Ecosystems* 124:107–124
- R Core Team (2017). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria
- Reid LM, Dunne T (1996). Rapid evaluation of sediment budgets. Catena Verlag GMBH, Reiskirchen, Germany
- Sauer VB, Meyer RW (1992). Determination of error in individual discharge measurements. United States Geol. Surv. Open - File Rep. 92: 1–21p.

- Smith BPG, Naden PS, Leeks GJL, Wass PD (2003). Characterising the fine sediment budget of a reach of the River Swale, Yorkshire, U.K. during the 1994 to 1995 winter season. *Hydrobiologia* 494:135–143
- Smith HG, Dragovich D (2008). Sediment budget analysis of slope-channel coupling and in-channel sediment storage in an upland catchment, southeastern Australia. *Geomorphology* 101:643–654
- Soulsby C, Youngson AF, Moir HJ, Malcolm IA (2001). Fine sediment influence on salmonid spawning habitat in a lowland agricultural stream: A preliminary assessment. *Science of the Total Environment* 265:295–307
- Tarr EC (2008). The population structure and habitat requirements of the freshwater pearl mussel, *Margaritifera margaritifera*, in Scotland. PhD thesis, University of Aberdeen, Scotland
- Trimble SW (1983). A sediment budget for Coon Creek basin in the Driftless Area, Wisconsin, 1853-1977. *American Journal of Science* 283:454–474
- Walling DE, Amos CM (1999). Source, storage and mobilisation of fine sediment in a chalk stream system. *Hydrological Processes* 13:323–340
- Walling DE, Collins AL, Jones PA, Leeks GJL, Old G (2006). Establishing fine-grained sediment budgets for the Pang and Lambourn LOCAR catchments, UK. *Journal of Hydrology* 330:126–141
- Walling DE, Owens PN, Carter J, Leeks GJL, Lewis S, Meharg AA, Wright J (2003). Storage of sediment-associated nutrients and contaminants in river channel and floodplain systems. *Applied Geochemistry* 18:195–220
- Walling DE, Owens PN, Leeks GJL (1998). The role of channel and floodplain storage in the suspended sediment budget of the River Ouse, Yorkshire, UK. *Geomorphology* 22:225–242
- Walling DE, Quine TA (1993). Using Chernobyl-derived fallout radionuclides to investigate the role of downstream conveyance losses in the suspended sediment budget of the River Severn, United Kingdom. *Physical Geography* 14:239–253
- Walling DE, Russell MA, Hodgkinson RA, Zhang Y (2002). Establishing sediment budgets for two small lowland agricultural catchments in the UK. *Catena* 47:323–353
- Wilson AJ, Walling DE, Leeks GJL (2004). In-channel storage of fine sediment in rivers of southwest England. In: Golosov V, Belyaev V, Walling DE (eds) *Sediment transfer through the fluvial system*. IAHS Publication, pp 291–199
- Wood PJ, Armitage PD (1997). Biological Effects of Fine Sediment in the Lotic Environment. *Environmental Management* 21:203–217
- Worrall F, Burt TP, Howden NJK (2013). The flux of suspended sediment from the UK 1974 to 2010. *Journal of Hydrology* 504:29–39
- Young MR, Cosgrove PJ, Hastie LC (2001). The extent of, and causes for, the decline of a highly threatened Naiad: *Margaritifera margaritifera*. In: Bauer G, Wächtler K (eds) *Ecology and Evolution of the Freshwater Mussels Unionoida*, Springer-V. pp 337–357

CHAPTER 5.

GEOMORPHOLOGICAL ADJUSTMENTS IN RESPONSE TO SYSTEM-SCALE RESTORATION

Baptiste Marteau, Chris Gibbins, Damià Vericat and Ramon J. Batalla.



*Development of a gravel bar in the River Ehen.
Photo: Baptiste Marteau, May 2016.*

Paper intended for submission to journal *Geomorphology*

CHAPTER 5. GEOMORPHOLOGICAL ADJUSTMENTS IN RESPONSE TO SYSTEM-SCALE RESTORATION

5.1. ABSTRACT

Alteration of sediment connectivity has consequences for fluvial processes and dynamics. The recognition of issues stemming from sediment starvation and resulting geomorphic adjustments have contributed to the development of river restoration and rehabilitation initiatives in many parts of the world. Evaluating the results of such initiatives requires years of post-restoration monitoring since the achievement of a new equilibrium is not immediate; hence, in the initial period following actions, the river may initially be considered in a transient, adjustment phase). However, even early-stage analysis can provide useful insights into the processes acting for ecosystem recovery. Within this context, we monitored the River Ehen following the reconnection of its headwater tributary in 2014, to assess geomorphic adjustments of an armoured channel in response to a “natural gravel augmentation”. The effects of the renewed supply of coarse sediment in the main-stem were studied by analysing bed surface grain size distribution (GSD), particle mobility (tracers) and cross-sectional topography within in a 300-m section downstream from the tributary confluence. Two years after the reconnection, these main-stem effects remain limited to localised deposition and scour. A new lateral bar is developing in one of the morphological units, with an overall fining of the GSDs. Surface particle mobility has increased since the reconnection in the two most active morphological units. Few comparable field studies exist, though results are in line with flume studies that have explored the geomorphic response of armoured channel to the addition of sediments. Channel complexity is increasing in places, although this remains limited to more active areas. Results indicate that the rate of adjustments in the main-stem are much less than the rate of changes in the tributary, due to the confluence bar temporarily storing an estimated 75% of the coarse sediment exported from Ben Gill. While geomorphic adjustments are anticipated to continue with the continued delivery of sediment from the tributary, potential benefits for the river’s biota are constrained by the impacts that this reconnection is having on fine sediment dynamics.

Key words: river restoration and rehabilitation, reconnection, coarse sediment supply, confluence bar, geomorphic adjustments, fluvial processes, River Ehen.

5.2. INTRODUCTION

The decoupling of rivers from their sediment sources affects the transport capacity of downstream river reaches. For instance, dams are capable of trapping virtually all of the coarse sediment transported by rivers (Williams and Wolman 1984; Vericat et al. 2006; Batalla and Vericat 2011; Tena et al. 2012). Instream gravel mining (Kondolf 1994) and changes in land-use and land cover (e.g. afforestation, Buendía et al. 2016) can also alter sediment supply, with the latter influencing transport capacity due to changes in runoff. Small scale flow regulation, including the construction of weirs and the diversion or disconnection of tributaries, can also affect sediment dynamics in main-stem rivers (Quinlan et al. 2015). The consequences of this for fluvial dynamics in downstream river reaches have been studied extensively, although less so for small dams (e.g. “run-of-river” impoundments, Csiki and Rhoads 2010)- and depend on a variety of factors, including dam operation, the magnitude of changes in the flow regime, and channel characteristics (Kondolf 1997). They result in adjustments to geomorphic conditions that usually include incision, armouring, vegetation encroachment and simplification of channel morphology; such adjustments have been observed in regulated rivers around the world (e.g. Church 1995; Sear 1995; Kondolf 1997; Pitlick and Wilcock 2001; Batalla and Vericat 2011). In addition, aggradation can be observed in rivers where flow regimes have been reduced to the point that they can no longer carry the sediment supplied by tributaries (Kondolf et al. 2012), or when this sediment is coarser than what is normally transported by the receiving system (Ferguson et al. 2006).

Recognition of the problems of sediment starvation and fluvial adjustment has led to widespread river restoration or rehabilitation efforts. Frequently these aim to improve habitat for aquatic organisms, most notably fish species (Pasternack 2008; Smith et al. 2014) although a growing number of other issues are being tackled through river restoration (e.g. catchment-scale objectives, Hillman and Brierley 2005; restoration of river-floodplain connectivity, Clilverd et al. 2013; prevention of channel incision, Irstea 2015). There are two ways that sedimentary activity can be re-instated: by feeding the river artificially (e.g. gravel augmentation), or by restoring altered connectivity pathways (e.g. dam removal).

Gravel augmentation has become a widespread and common practice to mitigate the total blockage of upstream sediment supply (Habersack and Piégay 2008; Gaeuman 2012; Kondolf et al. 2014) and is most often applied in upland rivers where coarse sediment is a critical

component of the habitat of commercially, economically and culturally important salmonid fish. However due to (a) the high cost of such artificial augmentation, and (b) the fact that benefits may be short-lived (Harvey et al. 2005), other options are needed.

Potentially more desirable as a long-term solution is to reconnect the affected river with its natural source(s) of sediment, allowing material to be delivered at times and in quantities that are controlled by natural processes. A full reconnection between a river and its upper (or sub-) catchment not only implies a change in the mass balance of the system, but also in the energy balance, with the inherent variability in flow and sediment processes. Dam removal, for instance, recreates conditions in which both water and sediment fluxes are restored -provided that alterations upstream are limited. The reconnection of a sub-catchment has the potential, just as can be observed at tributary junctions and confluences in natural systems, to change sediment transport dynamics of the receiving system. Effects may be further enhanced by the degree of alteration caused by the disconnection of the sediment sources (e.g. degree of armouring, Parker et al. 1982a). Thus, this type of restoration is consistent with the ecosystem-based approach and more sustainable than artificial augmentation, with geomorphological adjustments resulting from the restoration differing from those associated with dam removal.

Along with logistical and economic issues, project designers are faced with several challenges and uncertainties related to the geomorphic aspects of gravel augmentation. Channel conditions (geometry, slope, degree of armouring, grain size distribution) as well as hydrological factors (availability of flows to mobilise added gravel) have to be taken into account in the project design (Pasternack et al. 2004). Additionally, the volume of gravel to be injected, the grain size distribution of the sediments, the timing and frequency of augmentation, and the location of the injection (Bunte 2004; Gaeuman 2012) all have to be decided upon. All these elements are key to ensure that the temporal and spatial extent beneficial changes are correctly predicted (Wheaton et al. 2004). In this regard, reconnecting a long-lost tributary may seem more straightforward solution, as the volume of material, the size of sediments and the frequency of gravel injections are controlled naturally by the system itself. Finally, the provision of material is likely to be sustained for a very long time and generate long-lasting geomorphological adjustments.

The River Ehen restoration project offers the possibility to study such geomorphological adjustments in response to such tributary reconnection.

In previous chapters, we have demonstrated how a small increase in catchment size (1.2%) contributes to a 65% increase in main-stem suspended sediment yield (Chapter 3). Here we quantify the amount of bed material that is being supplied after the re-connection, and how this new situation affects main-stem morpho-dynamics; the overarching goal is to understand how this type of reconnection, as distinct from mere artificial gravel augmentation in a given time and point, influences fluvial processes and geomorphic conditions. Specific objectives are: (i) to assess the volumes and temporal dynamics of coarse sediment delivered from the reconnected sub-catchment, and particularly how a confluence bar mediates the interaction between this sub-catchment and its mainstem, (ii) to quantify adjustments to mainstem bed material dynamics (particle mobility) and sedimentary conditions (bed grain-size distributions), and (iii) describe the nature and magnitude of topographic changes in the mainstem. Observed changes are used as a basis for discussing adjustments to geomorphic processes and the potential longer-term implications of the reconnection of the sub-catchment for riverbed mobility and channel dynamics.

Previous chapters have provided information on the Ehen, Ben Gill and the restoration initiative. This information is not repeated here. Results are presented in an order that reflects the interactions between system components in relation to the specific objectives listed above; changes in Ben Gill are described first, followed by resulting changes at the confluence and then, finally, responses in the Ehen.

5.3. STUDY CONTEXT AND AREA

The study section is situated in the upper River Ehen, downstream from Ennerdale Water (Figure 5.1). The Ehen is gauged by the Environment Agency at Bleach Green gauging station (550 m downstream from the lake outlet).

The new Ben Gill channel was opened on 3 October 2014, and the first flows occurred the following day. As the impoundment of the upper part of the basin remained unchanged, changes in the main-stem of the Ehen are attributed to the re-connection of Ben Gill.

Suspended loads have increased markedly following the reconnection (Marteau et al. 2017b), with the fate of this material (whether it conveyed immediately downstream or settles locally) being dictated by the magnitude and degree of synchronicity between flows in the Ehen and Ben Gill (Marteau et al. 2017a).

Although there is no data about the rate of coarse material export from Ben Gill prior to its diversion, several pieces of evidence exist to help build an image of its geomorphic activity. Aerial images from 1970 (before its disconnection) show the marked extent of the depositional bar at the confluence (Plate 5.1). Since the disconnection of the lower part of Ben Gill, coarse material has regularly been removed from the diversion grid (at the fan apex) by locals and used either as building material or spread in the field downstream from this grid (United Utilities 2012). Based on this, preliminary studies have estimated that an average of 100 m³ of coarse material was prevented from discharging in the Ehen every year (Brown et al. 2008; United Utilities 2012). In addition, Ben Gill material is generally coarser than that found in the Ehen (median particle size (D_{50}) is 77 mm in Ben Gill, and between 36 and 55 in the Ehen, while larger sizes (e.g. D_{84}) reach 149 mm in Ben Gill, and between 59 and 103 in the Ehen; Quinlan 2014). The stream power required to move these particles reflects the potential activity of Ben Gill. Finally, the presence of old pearl mussel individuals in the receiving River Ehen (over 100 years old, Killeen and Oliver 1997) indicates that habitat conditions must have been adequate for the survival and recruitment of mussels prior to the disconnection. This is not the case anymore (Killeen and Moorkens 2013; O’Leary 2013) and can be at least partly attributed to shortage of coarse sediment availability and lack of geomorphic activity (Quinlan 2014; Quinlan et al. 2015).



Plate 5.1. Aerial photos of the confluence of Ben Gill with the River Ehen, at the outlet of Ennerdale Water. Flow direction in the main-stem Ehen is from left to right. Arrows 1 & 2 refer to morphological features of interest.

(Credit: 1970, Environment Agency [Penrith]; 2003, Google Maps; 2016, Jason Hagon on the account of the University of Aberdeen)

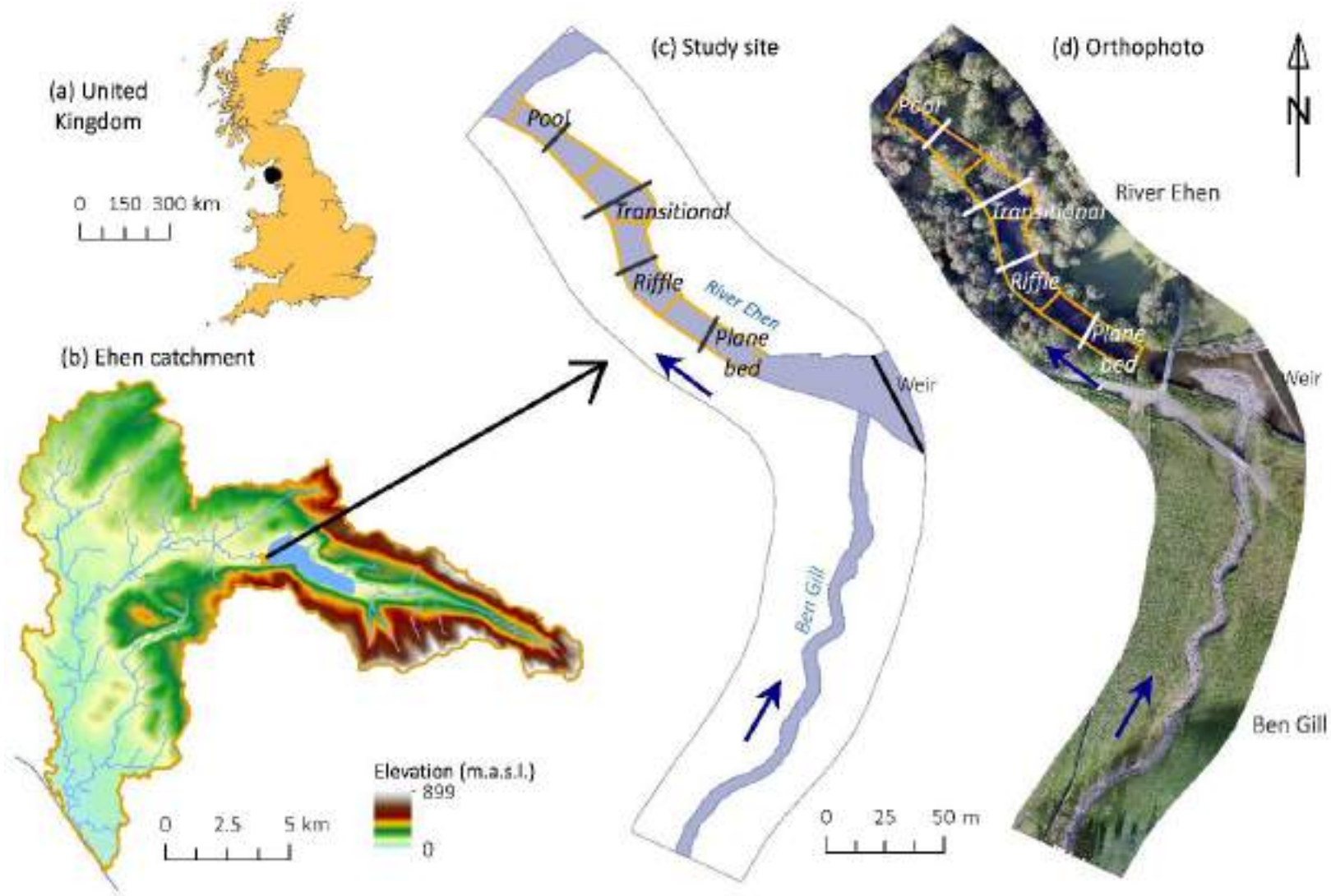


Figure 5.1. Details of the study catchment and site. (a) location of the catchment within the United Kingdom. (b) the River Ehen and its catchment. (c) Plan view and (d) aerial orthophoto of the study site. Morphological units are delimited in orange, and colours

5.4. MATERIALS AND METHODS

This study builds on results from Quinlan (2014) and Quinlan et al. (2015a), who studied the state of the River Ehen prior to the reconnection of its headwater sub-catchment. Current (post-reconnection) bed stability and texture are compared to these studies.

5.4.1. Hydrological context

The Ehen is gauged by the Environment Agency 550 m downstream from the lake outlet. The gauging weir records discharge at 15-min intervals and these data are used to characterise the hydrological regime of the Ehen during the current study period (July 2014 until October 2016; i.e. 2 months prior to and 24 months following the reconnection). Mean daily discharges for the 1974-2016 are also available, and used here for longer-term contextualisation of the study.

Ben Gill is not gauged but was estimated to flow approximately 1/5 of the time (Quinlan et al. 2015; Marteau et al. 2017a). Information on flow conditions in Ben Gill in the present study were collated from different sources, including field notes and observations, until the installation of a time-lapse camera facing the confluence in June 2015 (see Marteau et al. (2017a) for more details). Flow events in Ben Gill are characterised using the images acquired by the camera at 1h interval. These photos were used in a previous study to assess the implications of asynchronicity of flows in the Ehen and those in Ben Gill for fine sediment transport and storage (Marteau et al. 2017a). Data are used here as a proxy for discharge in Ben Gill.

5.4.2. Coarse sediment supply

5.4.2.1. Post-reconnection surveys

Ben Gill and the confluence bar were surveyed separately and topographic changes between successive surveys were computed for the two features, providing insights into the minimum volume of material entering in the main-stem (sediment exported from the active channel of Ben Gill) and the role of passive transient storage played by the confluence bar, respectively.

Multi-temporal topographic point clouds and orthophotomaps were obtained using Structure-from-Motion (SfM) photogrammetry, based on digital images collected from an Unmanned Aerial Vehicle (UAV). Digital Elevation Models (DEMs) were produced from 3D point-clouds,

errors of DEMs was assessed and, finally, successive DEMs were compared (i.e. DEMs of Difference; DoDs) to monitor topographic changes and quantify the net volume of change. Specific details of the general workflow used to acquire and process SfM photogrammetry data can be found in Marteau et al. (2016) (see especially the schematic of the workflow in Figure 2.3, Chapter 2). A summary of the main steps is given below.

Data acquisition. A total of 196 fixed Ground Control Points (GCPs) were installed around the 300-m long channel of Ben Gill and surveyed with a Leica Viva[®] GNSS (Leica Geosystems) differential rtk-GPS. The 3D quality of the coordinates oscillated between 0.009 and 0.024 m. Flights were undertaken along three lines (both banks, then along the channel centreline) to yield appropriate overlap. Over 1000 images were captured per survey. A total of 8 surveys were conducted between October 2014 and October 2016 (Figure 5.2). Flight altitude remained constantly between 10 and 20 m above ground, which was targeted as optimum given the characteristics of the equipment used (Marteau et al. 2016).

Photogrammetry. Aerial pictures were processed using AgiSoft[®] PhotoScan Professional (Version 1.2.6) (AgiSoft LLC 2015). Images from each survey were selected based on (i) sharpness, (ii) over-exposure to light, (iii) graininess due to high ISO values, (iv) the presence of obstruction of features of interest (e.g. legs of the UAV) and (v) avoiding unnecessary overlap between images (i.e. when the UAV was static). The remaining images (< 500) were aligned, with the centre of the GCPs identified and adjusted manually.

Error analysis. The assessment of model accuracy was based on information obtained from the GCPs (e.g. Brasington et al. 2000). This involved using some GCPs as markers (i.e. to georeference and register the model) and the remainder as 'check points' (ChP; to assess accuracy and precision of the model). Accuracy is then determined as the mean distance of the real location of the ChPs to their projection in the georeferenced model (i.e. residual), while precision is provided the standard deviation of the residuals. Here, instead of selecting a proportion of GCPs as ChP in a static manner, a bootstrapping algorithm was used to run this random selection 1000 times, generating a value of registration error, precision and accuracy for each GCP. Model precision was used to determine a minimum level of detection (minLoD, Brasington et al. 2003) by calculating the spatial distribution of *t*-scores (Lane et al. 2003), which defines the probability of the change observed in each cell to be 'certain' (confidence interval used here = 80%).

Outputs. The photogrammetry software generates aerial orthophotos in addition to 3D point-clouds. Both of these were used complementarily. Dense point-clouds (1800 observations on average) were decimated using ToPCAT (Brasington et al. 2012) to generate regularised point-clouds representing the minimum observation within a 0.05 by 0.05 m cell (ToPCAT is available from the GCD software, available as an ArcMap tool, see <http://gcd.joewheaton.org/> or Wheaton et al. 2010 to see the methodological development). Triangulated Irregular Networks (TINs) were computed from these, before the creation of DEMs (at 0.05 m cell size). Orthophotos (at 0.025 m resolution) were used for image classification in order to differentiate vegetation (potentially wrongly interpreted as topographic changes due to episodes of growth and decay) from the riverbed. Thresholded topographic changes were calculated for every successive DEM by the production of DoDs, taking into account only changes considered certain at the 80% CI (i.e. changes above the minLoD). A total of 7 DoDs provided insights into the volumes of erosion and deposition in the channel over the study period (Figure 5.2), as well as an estimate of the minimum volume of sediment exported from the channel between successive surveys (net change). Similar information was computed for the deposition bar developing at the confluence with the Ehen, although some specific details needed to be considered here.

Specific methods and considerations for the confluence bar. The application of photogrammetry remains challenging for submerged areas (Lane 2000; Westaway et al. 2000). The ephemeral nature of Ben Gill rendered easy the survey of its main channel. However, modelling topography of the confluence bar was constrained by water surface elevation in the Ehen and the amount turbulences at the outlet of the lake (e.g. Woodget et al. 2014). Using the orthophotos, submerged areas were identified and DEMs were corrected following the procedure by Westaway et al. (2001) and Woodget et al. (2014). Underwater topography was corrected by the refractive index of clear water (1.34) applied to water depth. DEM error also increases with depth (Woodget et al. 2014), so values of model accuracy were adapted accordingly. In the absence of field data to create our own model of error for submerged areas, level of thresholding was multiplied by 2 in shallow areas (> 10 cm) and 4 in deeper areas, which can be considered as being conservative relative to other studies (e.g. Westaway et al. 2001; Woodget et al. 2014). Areas of high water surface turbulence were excluded altogether. As a consequence, one of the surveys (i.e. November 2015) had to be removed from the analysis because of low bar exposure and high surface water turbulence.

5.4.2.2. Pre-reconnection survey

The initial plan was to undertake a pre-reconnection aerial survey of the whole of the new channel as soon as all the engineering work was completed and the machinery and related construction equipment was removed. This survey was scheduled for the first day after the opening. However, heavy rains and high flow in the channel prevented this survey going ahead. Engineering contractors (those constructing the new channel) carried out a conventional topographic survey of the channel (using an rtk-GPS) two days prior to channel opening. This survey was composed of 37 cross-sections and is used here to represent the channel baseline state. Although the spatial extent of this survey is somewhat less than achieved during the post-reconnection ones (see 5.4.2.1), it allows assessment of change in the short period between channel completion and the first aerial survey.

Topographic changes between the pre-reconnection and the first post-reconnection surveys were computed based on cross-sectional changes (1D). Each point of each cross-section of the initial GPS survey was intersected with the first SfM-derived DEM (October 2014). Elevation of the October 2014 DEM was extracted for each of these cross-sections and subsequently used to provide cross-sectional topography data. Thus, both sets of data share the same extension and density of points. The difference in cross-sectional area was divided between positive (elevation gain) and negative (elevation loss) difference (i.e. deposition and erosion respectively). Total areas of erosion and sedimentation were divided by the width of the cross-section (i.e. weighted cross-sectional change), and then extrapolated between cross-sections to determine the volumetric changes associated with the period between the two surveys:

$$\Delta V_{a[e;d]} = AC_{i[e;d]} \cdot \left(\frac{1}{2} \cdot A_{i-1|i} + \frac{1}{2} \cdot A_{i|i+1} \right) \quad (5.1)$$

where $\Delta V_{a[e;d]}$ is the volume of change (m^3) associated with channel segment a , for erosion (e) and deposition (d), channel segment a is defined by the sum of half of the area between cross-section $i-1$ and i ($A_{i-1|i}$) and half the area between cross-sections i and $i+1$ ($A_{i|i+1}$), and $AC_{i[e;d]}$ is the weighted cross-sectional area difference (m^2/m) in cross-section i for erosion and deposition. Total volume of change (V_c) for a channel segment a was then calculated as:

$$V_{c(a)} = \sum [\Delta V_{a[e]} + \Delta V_{a[d]}] \quad (5.2)$$

The sum of the volume of changes for each individual segment represents the total volume of change of the reach (37 segments, covering a 250-m long reach). Uncertainties associated with

this method are multiple (Arnaud et al. 2017). Although the complete assessment of uncertainties is out of the scope of this paper, the calculation of errors is necessary to determine the confidence in estimates of geomorphic changes as considered in section 3.2.1. In order to compare results for period A (Figure 5.2) with successive SfM-derived DoDs, a threshold of minimum level of detection at the cross-sectional area of difference ($minLoD^2$) was applied as follows:

$$minLoD^2 = \sqrt{\varepsilon_{GPS}^2 + \varepsilon_{DEM}^2} \cdot \left(\frac{w_i}{p_i - 1} \right) \quad (5.3)$$

where ε_{GPS} and ε_{DEM} are the potential errors associated with each survey considered here, w_i is the width of cross-section i , p_i is the number of points on cross-section i . Area of difference for each cross-section was estimated as uncertain if lower than this $minLoD^2$.

No geomorphic feature existed at the confluence prior to the opening of Ben Gill channel. As no topographic survey of the confluence was undertaken prior to the first deposition of gravel, the volume of deposition was estimated using the SfM-derived point cloud from October 2014. Using CloudCompare® (Version 2.8.1), the volume of the gravel bar was estimated from a theoretical plan surface simulating the original bed. This did not allow for proper estimation of errors but helped to provide an estimate of the sediment export associated with this first period.

5.4.3. Assessment of sedimentary changes in the Ehen

The assessment of sedimentary adjustments in the River Ehen downstream the confluence of Ben Gill was based on changes in surface grain size distributions, bed mobility and channel topography. Full details of the methods are provided in the sections below.

5.4.3.1. Surface grain size distributions

Bed surface texture was monitored in the Ehen by assessing the grain size distribution (GSD) using the Wolman pebble count method (Wolman 1954). This technique is suitable for wadable streams, and involves walking along imaginary lines, zigzagging across the channel and blind picking a pebble every step, covering the entire study area evenly (Bunte and Abt 2001). Each particle was measured along its b -axis. The lower limit of this technique is considered at around 8 mm, while all larger sizes are sampled. The three morphological units were sampled independently on 7 occasions (Figure 5.2), with 200 particles collected in plane bed and riffle,

and 300 in the pool (see Figure 5.1c & d for the location of morphological units). In addition, data collected by (Quinlan et al. 2015) in 2011-2012 was used as pre-reconnection reference. They sampled the same morphological units, although only 100 particles per site were collected.

No attempt was made to sample subsurface material due to (i) the absence of exposed areas, even at low flows (because of the very simple geometry of the channel), and (ii) the risks associated with subsurface sampling and the release of fine sediments in a mussel river.

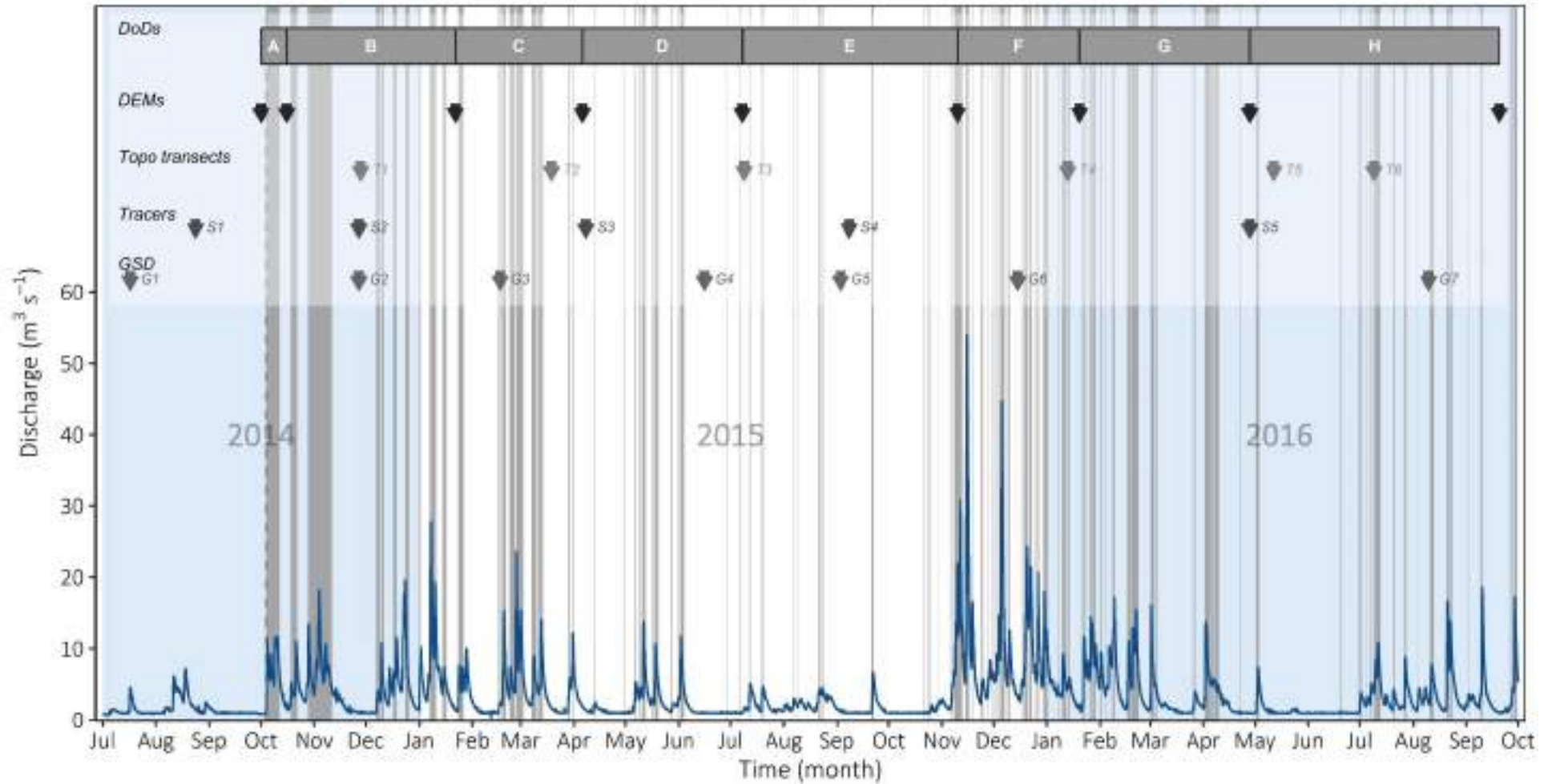


Figure 5.2. Hydrograph of the River Ehen (at Bleach Green gauging station), timing of flows in Ben Gill (grey bars) and frequency of the different field surveys undertaken for the study period (arrows). The dashed vertical line shows the day of the reconnection.

5.4.3.2. Bed surface mobility

The movement of particles was monitored in the Ehen using painted tracers. Each morphological unit was seeded with 100 particles placed in lines of 5 to 7 tracers, perpendicular to the flow, and spread over the entire unit (Plate 5.2). Size of tracers covered the whole range of particles found in the bed of respective units and ranged between 8 and 181 mm (in *b*-axis) in the plane bed and the pool, and 8 and 256 mm and the riffle. Tracers were seeded on 31 July 2014 and resurveyed on 5 occasions (Figure 5.2). The study design was selected to match that of Quinlan et al. (2015). Their results, collected from 2 resurveys under medium flows (return periods of 1.4 and 1.8 years), are used for comparison between pre- and post-reconnection mobility conditions and to study potential changes in mobility patterns. Due to missing data and lack of confidence in some of the records in the pool, only mobility data for the riffle and the plane bed were extracted from Quinlan's dataset. Because these units are expected to be the most active ones, and since they are the closest to the confluence, the lack of data in the pool does not impede the study of bed surface mobility evolution following the reconnection of Ben Gill.

5.4.4. Changes in bed topography

Bed topography across a fixed control transect was surveyed in each morphological unit in the Ehen (Figure 5.1c & d) over the course of the study using an Acoustic Doppler Current Profiler (ADCP) (StreamPro, Teletyne RD Instruments®). Only one survey per unit was used to assess topographic changes, given that the study reach showed little geomorphic complexity. A single cross-section was expected to provide enough information on the main process (erosion/sedimentation) acting in the reach (unit-scale changes in topography) throughout the study period. Surveys were performed on 6 occasions (Figure 5.2). The bankside areas were surveyed with a Leica Viva® GNSS differential rtk-GPS on the first occasion, while only areas here deposition would prevent access of the ADCP were re-surveyed manually. No other changes to the banks were observed throughout the study.



Plate 5.2. Photographs of the three morphological units; (a) plane bed, (b) riffle, and (c) pool. Photographs taken facing downstream. (Photos: Baptiste Marteau, March 2016).

For each sampling occasion, surveys were replicated between 2 and 4 repeat runs were carried out per transect (apart from survey #3 that only 1 run was available). Data of all replicates were pooled together and used to determine the average bed elevation of the cross-section and a measure of uncertainty (i.e. standard deviation of bed elevation) at a spacing of 0.2 m ($> D_{84}$ of coarsest unit). Similarly to the procedure used to determine the minLoD for successive DEMs (see section 3.2. above), difference in elevation was defined as certain only if the change was higher than

$$t \cdot \sqrt{SD_i^2 + SD_{i+1}^2} \quad (5.4)$$

with SD_i and SD_{i+1} the standard deviation of surveys i and $i+1$ respectively, and $t = 1$.

5.4.5. Flow Hydraulics

Key parameters to describe flow hydraulics were computed for each morphological unit from 1D modelling using WinXSPRO[®] (Version 3.0, 2005, USDA Forest Service). The hydraulic model was built with bed topography and the D_{84} to determine roughness (Thorne & Zevenbergen method, Hardy et al. 2005). Results were validated with field observations on the day the surveys were performed and flow data from the gauging station, located c. 500 meters downstream the study reach. Modelling was repeated for each series of topographic surveys in each unit. The discharge-shear stress (Q - τ) relationship was examined to compare flow hydraulics in relation to potential changes in topography. Because differences between successive models were not significant (further details provided in the results section), using a single model per morphological unit was suitable. Model outputs were used to calculate discharge-related stream power (ω), using Bagnold's (1966) formula:

$$\omega = \frac{\rho_w \cdot g \cdot Q \cdot S}{w} \quad (5.5)$$

where ω is stream power ($W m^{-2}$), ρ_w is the density of water ($kg m^{-3}$), g is the gravitational acceleration ($m s^{-2}$), Q is discharge ($m^3 s^{-1}$), S is local slope ($m m^{-1}$) and w is the channel width at bankfull discharge. Once a Q - ω was defined, discharge data were used to compute time series of ω at 15-min intervals.

The relationship between maximum stream power recorded over a given period (ω_{max}) and the size of mobilised particles (in b -axis) was used to develop sediment mobility models for each morphological unit. These models yielded information on the minimum stream power required

to displace a given particle (i.e. critical stream power (ω_{ci})). Then, following Hassan and Zimmerman (2012), ω_{ci} was used to calculate total excess of stream power during a given period (ω_e):

$$\omega_e = \sum(\omega - \omega_{ci}) \text{ when } \omega > \omega_{ci} \quad (5.6)$$

Values of ω_e were used to compare particle mobility before and after reconnection. Direct comparison of the distance moved by tracers is not possible given the differences in conditions experienced by the tracers in both studies. Instead, total displacement of moved and recovered particles was divided by the total ω_e experienced by the tracers, and plotted against their b -axis. This provided an estimate of the distance travelled per unit of ω_e for a particle of a given size.

5.4.1. Data analysis

Hydraulics

In order to determine if topographic changes had an impact of flow hydraulics, i.e. if a single 1-D modelling exercise of flow hydraulics was suitable for the entire study period, changes in the Q- τ relationship over time were assessed. To do so, the power-law regression of Q- τ relationship was tested using ANCOVAs.

DEMs of Differences (DoDs)

As indicated above, full details of the analysis of geomorphic change detection from SfM photogrammetry can be found in Marteau et al. (2016). Only thresholded volumes of change from all DoDs are reported here, so the volumes exclude the amounts considered uncertain (as per the reported error analyses). All these analyses were run using the GCD tool.

Grain Size Distributions

Differences in bed sediment grain size distributions were analysed using χ^2 -homogeneity test. This test allows the comparison of entire distributions, rather than simply testing for differences in summary statistics (e.g. mean particle size, sorting, skewness). It performs well for sampled particle size distributions of arbitrary shape and is suitable for comparing distributions of different size (Scheibelhofer et al. 2016).

Bed mobility

Mobility models based on tracer and hydraulic data were expressed in the form $\omega_{ci} = a \cdot D_i^b$. Bagnold's (1980) formulation of

$$\omega_{ci} = 0.0971(D_i)^{1.5} \cdot \log(1200d/D_i) \quad (5.7)$$

led Costa (1983) to model particle mobility from a power regression of the form $a \cdot D_i^b$. Several authors have also applied regressions of this form for different types of river (Williams 1983; Ferguson 2005; Petit et al. 2005) and the same form of equation was used in this study.

Tracer data were further investigated using limiting response (LR) regression models. LR models allow for heterogeneity in values of Y across the range of the X variable (something which would violate assumptions of standard, central response regression modelling) but they also allow for a focus on upper and lower limits of observed responses. The relationships between flow characteristics (e.g. peak discharge, ω_{max} , ω_e), particle displacement, and the size of particles mobilised typically shows great scatter. This scatter can be explained by numerous factors controlling particle mobility, such as hiding effect (Parker et al. 1982b; Andrews 1983), local variability in near-bed velocity and depth (Bagnold 1980), possible particle imbrication (Parker et al. 2011) or local topography (Petit et al. 2005; Parker et al. 2011). However, by looking at the upper limit, we can infer the potential maximum distance that a given particle can travel.

The nature of the scatter in the Ehen tracer data meant that central response models were inappropriate, and so LR ones were used. These provided insights into the maximum response in distance travelled that could be expected for a given value of particle size. The upper limit (T = 0.95) was modelled using Quantile Regression (QR); this models a line for which 95% of points sit below. To describe the general trend, QR was fit to the T = 0.5 (the line fit such that 50% of points sit above and below). The upper limit of the distribution can show the constraints imposed by the measured limiting factor.

Scatter plots of pre- and post-reconnection data were fitted separately with QR. The aim was to understand the potential displacement per unit of ω_e for a particle of a given size. The median shows a central tendency and the 0.95 QR explains the upper limit of particle displacement. Additionally, comparing conditions pre- and post-reconnection can tell whether conditions of mobility have changed. Among the different regression models tested, the power

model $y = e^{a \cdot x} \cdot e^b$ (i.e. $\log_{10}(y) = a \cdot x + b$) provided the best fit for both levels of T (based on AIC values).

All statistical test were performed in R (R Core Team 2017).

5.5. RESULTS

5.5.1. Hydrological context

The hydrological regime of the Ehen reflects typical patterns for the NW of England. The river experiences low flows in the summer and higher flows in the winter, with some high flow events observed intermittently in late spring. Despite the regulation by Ennerdale Water and its associated weir, the hydrological regime of the River Ehen remains relatively flashy and variable. Flows for the study period ranged from $0.31 \text{ m}^3 \text{ s}^{-1}$ (11/02/2015) to $54.0 \text{ m}^3 \text{ s}^{-1}$ (15/11/2015). Mean and median discharges ($3.50 \text{ m}^3 \text{ s}^{-1}$ and $1.99 \text{ m}^3 \text{ s}^{-1}$, respectively) are slightly higher than long-term respective values ($2.72 \text{ m}^3 \text{ s}^{-1}$ and $1.38 \text{ m}^3 \text{ s}^{-1}$, 1974-2016). Flows in November and December 2015 were particularly high, with a maximum discharge of $54.0 \text{ m}^3 \text{ s}^{-1}$; this magnitude of event has a return period of 30 years.

Flow in Ben Gill was recorded approximately 19.4% of the time, with a total of 112 flow events over the study period (Table 5.1). The first event happened the day after the reconnection and was the longest recorded (8.2 days). Typically, flows responded rapidly to local rainfall events, and also recessed quickly; periods of flow lasted from just few hours to a few days. Table 5.2 summarises flow statistics for Ben Gill for the periods used for monitoring bed material fluxes from the tributary. The first event was unusually long compared to the ones observed in 2015 and 2016. The highest number of events was recorded in the 2 months separating the surveys used for DEM *F* (November 2015- January 2016), which corresponds to the period of high hydrological activity in the entire catchment (Figure 5.2). Activity in Ben Gill was lower during the summer months of 2015 and 2016.

Table 5.1. Summary table of flow statistics in Ben Gill associated with the DoDs.

Model	Period	Number of flow events	Total duration of flow	Average duration of flow event
			day	day
A	September 2014 – October 2014	1	8.2	8.2
B	October 2014 – January 2015	9	28.3	3.1
C	January 2015 – April 2015	10	20.9	2.1
D	April 2015 – July 2015	12	9.2	0.8
E	July 2015 – November 2015	16	11.6	0.7
F	November 2015 – January 2016	25	20.4	0.8
G	January 2016 – April 2016	19	24.4	1.3
H	April 2016 – October 2016	20	18.8	0.9

5.5.2. Flow Hydraulics in the Ehen

The τ - Q relationship for each morphological unit did not change significantly over time (ANCOVA test per unit, $p > 0.05$). Thus, a single model was created per unit. The overall Root Mean Square Error (RMSE) of all modelled (Q_{mod}) vs. observed (Q_{obs}) discharges was $0.41 \text{ m}^3 \text{ s}^{-1}$. (Figure 5.3). Given the negligible changes observed in flow hydraulics, the very stable nature of the riverbed and that no topography data were available for the 2011-2012 period of study, the model created was assumed suitable for the pre-reconnection period as well.

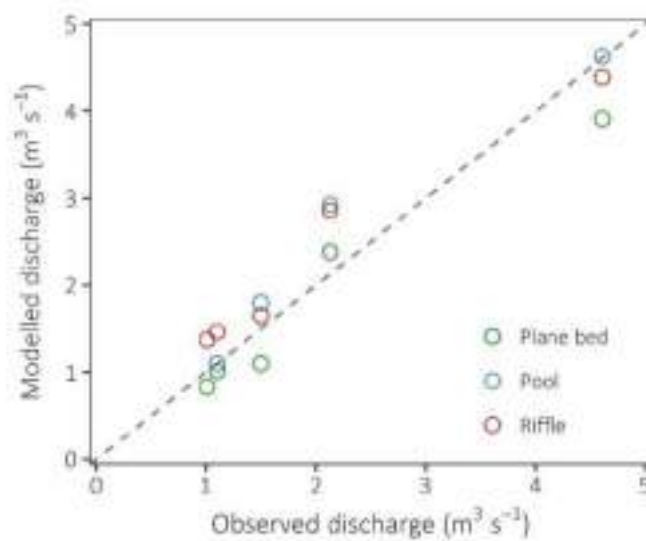


Figure 5.3. Observed and modelled discharge resulting from the 1D modelling (WinXSPro).

Stream power (ω) associated with flow magnitude was calculated using equation (4). ω was highest in the plane bed and lowest in the pool. ω_{max} calculated in the entire reach was 119 W m^{-2} and was observed post-reconnection during the 30-year flood of 2015 (S5 in Figure 5.2, Table 5.2). ω_{max} pre-reconnection was 48.2 W m^{-2} , significantly lower than these observed post-reconnection.

Table 5.2. Summary table of discharge and hydraulics associated with tracers surveys in the River Ehen.

Tracers survey	Discharge				Stream Power			Number of flood events
	Q_{mean}	Q_{max}	Q_{SD}	Return period of Q_{max}	<i>Plane Bed</i>	<i>Riffle</i>	<i>Pool</i>	
					ω_{max}	ω_{max}	ω_{max}	
	$m^3 s^{-1}$		years	$W m^{-2}$	$W m^{-2}$	$W m^{-2}$		
S1	2.52	7.21	1.64	0.5	15.9	11.4	6.0	8
S2	3.28	18.20	3.12	1.3	40.3	28.8	15.3	14
S3	4.42	27.80	3.95	3.1	61.5	44.0	23.3	17
S4	2.07	13.70	1.62	0.9	30.3	21.7	11.5	11
S5	4.53	54.00	5.46	30	119.4	85.5	45.3	26

5.5.3. Bed material fluxes from Ben Gill

5.5.3.1. Errors and uncertainties

The 3D model accuracy of the successive point clouds was relatively high and constant (between 0.022 and 0.056 m, Table 5.3), allowing for the computation of high resolution DEMs and reliable estimates of topographic changes. It is worth mentioning that the accuracy of the DEMs is considered the same as these of the point clouds; therefore, errors associated to the generation of the DEM from the point cloud (interpolation) were not taken into account, given the high density of the clouds and the scope of this chapter.

Table 5.3. Summary table of statistics of the topography models obtained from SfM photogrammetry. The extension of these is limited to Ben Gill and its confluence to the Ehen.

Model	Number of images	Average flight altitude <i>m</i>	Average pixel resolution <i>cm²/pix</i>	Average point density <i>point/m²</i>	3D registration error ¹ <i>m</i>	3D model precision ² <i>m</i>	3D model accuracy ³ <i>m</i>
August 2014	448	10.7	0.0313	3210			
October 2014	500	13.1	0.0556	1790	0.050	0.025	0.044
January 2015	361	15.6	0.0729	1370	0.060	0.030	0.056
April 2015	475	12.4	0.0454	2210	0.039	0.017	0.035
July 2015	341	13.8	0.0590	1690	0.039	0.017	0.035
November 2015	399	12.4	0.0502	2000	0.073	0.048	0.047
January 2016	441	14.1	0.0590	1690	0.029	0.014	0.026
April 2016	526	19.7	0.1340	784	0.019	0.020	0.016
October 2016	367	15.1	0.0686	1460	0.011	0.011	0.022

¹Registration error: error of the GCPs after georeferencing the point cloud.

²Model precision: standard deviation of the ChP residuals.

³Model accuracy: mean value of the ChP residuals.

Uncertainties associated with the initial GPS survey (pre-reconnection) are unknown. However, due to the simplified structure of the channel at the time of survey (pre-reconnection) and the quality of most GPS equipment nowadays, an error of 0.1 m was assumed. This error is also in agreement to the largest clasts found in the channel; therefore, it accounts for the uncertainties associated with GPS operation (e.g. recording the top or the bottom of a clast as the ground elevation). By comparison, model accuracy of the first SfM-derived DEM (for October 2014) was 0.044 m (Table 5.3)

5.5.3.2. Bed material fluxes

Ben Gill channel experienced marked erosion following the reconnection to its main-stem (Figure 5.4). Erosion was always the dominant process (between 66 and 91% of the volume of all changes), with up to 1.66 m of scour observed in some places for model F (Figure 5.4). Histograms on the bottom of Figure 5.4 show the distribution of the elevation changes and the associated volumes for each DoD. These diagrams show that patterns of both erosional and depositional processes varied over time, although greater differences can be observed for erosion. For instance, the histogram for period D is bimodal for erosion, probably indicating two separate processes: a first ‘peak’ driven by a massive by localised erosion (-1 m) (e.g. bank erosion), and a second ‘peak’ (around -0.5 m) mainly representing small but frequent processes acting at the bottom the channel. Deposition was mostly observed in the vicinity of the bridge, i.e. in the lower part of the channel. Positive topographic changes were generally of lower

intensity than negative ones, although they covered similar areas; mean thickness of topographic change was always higher for erosion than deposition.

The total estimated net export of sediment from Ben Gill over the study period was to 412 m³ (Erosion = 665 m³, Deposition = 253 m³). This equates to approximately 1.4 m³ for every metre of channel length. This only represents the minimum flux transferred to the Ehen since the supply from upstream the reach is not directly considered in this assessment. Therefore, the nature of the monitoring means that estimates of volumetric change represents a minimum volume, and potentially an underestimation of the true geomorphic adjustment in the channel.

Bed material fluxes calculated from the DoDs for individual periods varied between 3.8 and 108 m³ of sediment, and were greatest in period C (January – April 2015) and lowest in period F (November 2015 – January 2016, Figure 5.5a). However, the latter period still experienced high topographic changes; the volumes of deposition were the highest recorded (83 m³), indicating the active internal turnover of sediment despite the little export suggested by the net flux values. Topographic changes for period A were assessed from cross-sections. The estimated sediment flux from Ben Gill for this period was c. 57 m³. Figure 5.5a shows the evolution of erosion, deposition and net change for the entire study period.

5.5.4. Evolution of the confluence bar

Topographic changes captured at the confluence bar were mainly depositional (Figure 5.6). Periods A and C experienced only deposition, with A being the largest episode of deposition experienced over a short period of time (c. 90 m³ over 2 weeks). The highest proportion of erosion (52%) was observed over period G, although net topographic changes were negligible (total change of -0.18 m³, see Figure 5.5b). Unfortunately, high water levels and turbulences at the confluence during the flight survey of November 2015 prevented the use of this DEM for geomorphic change detection (Figure 5.6). The total estimated storage of sediment at the confluence over the entire study period was 283 m³ (Erosion = 24 m³, Deposition = 307 m³).

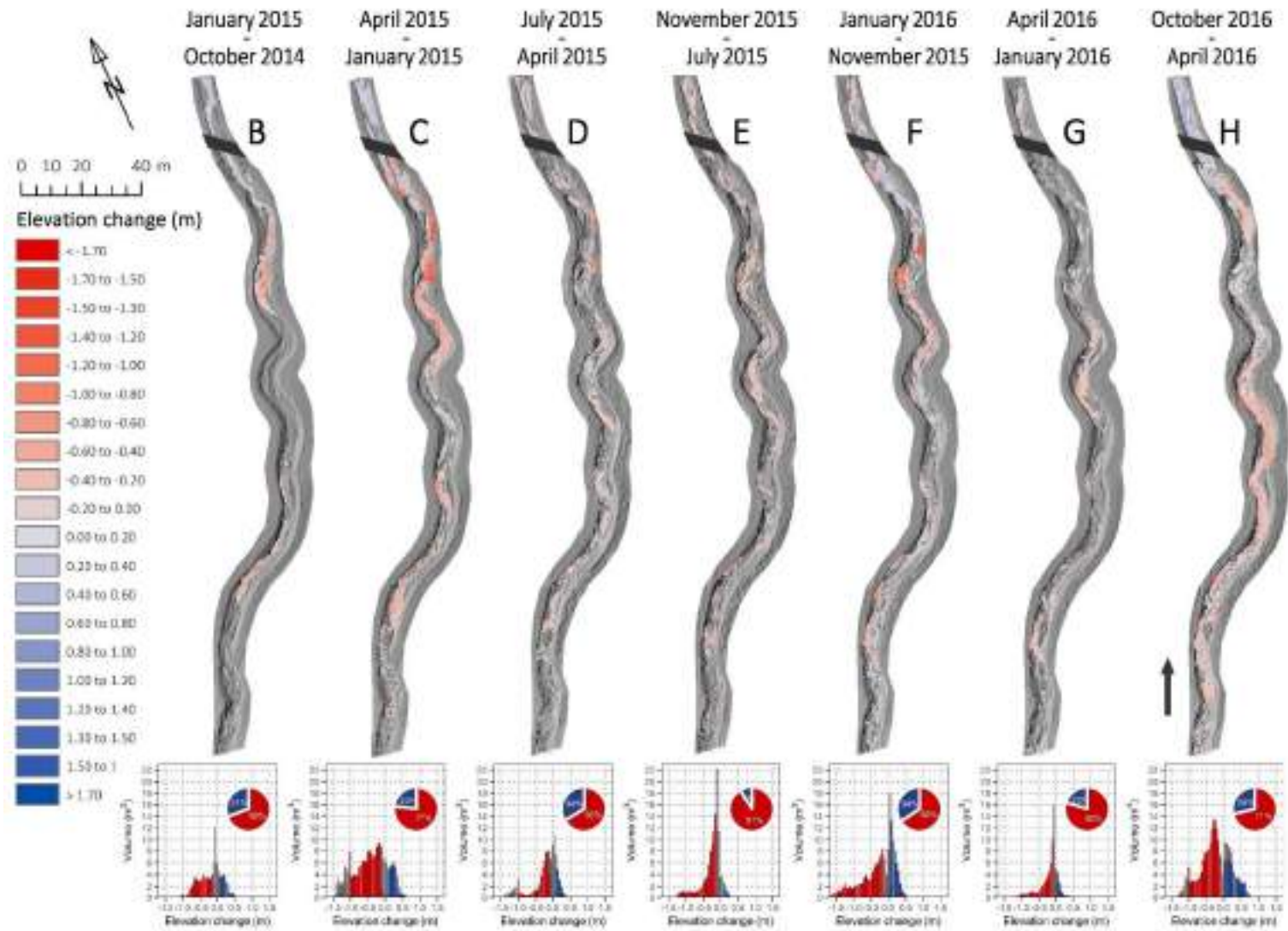


Figure 5.4. Topographic changes (DoDs) and associated histograms in Ben Gill channel. Letters refer to the different periods (see Figure 5.2).

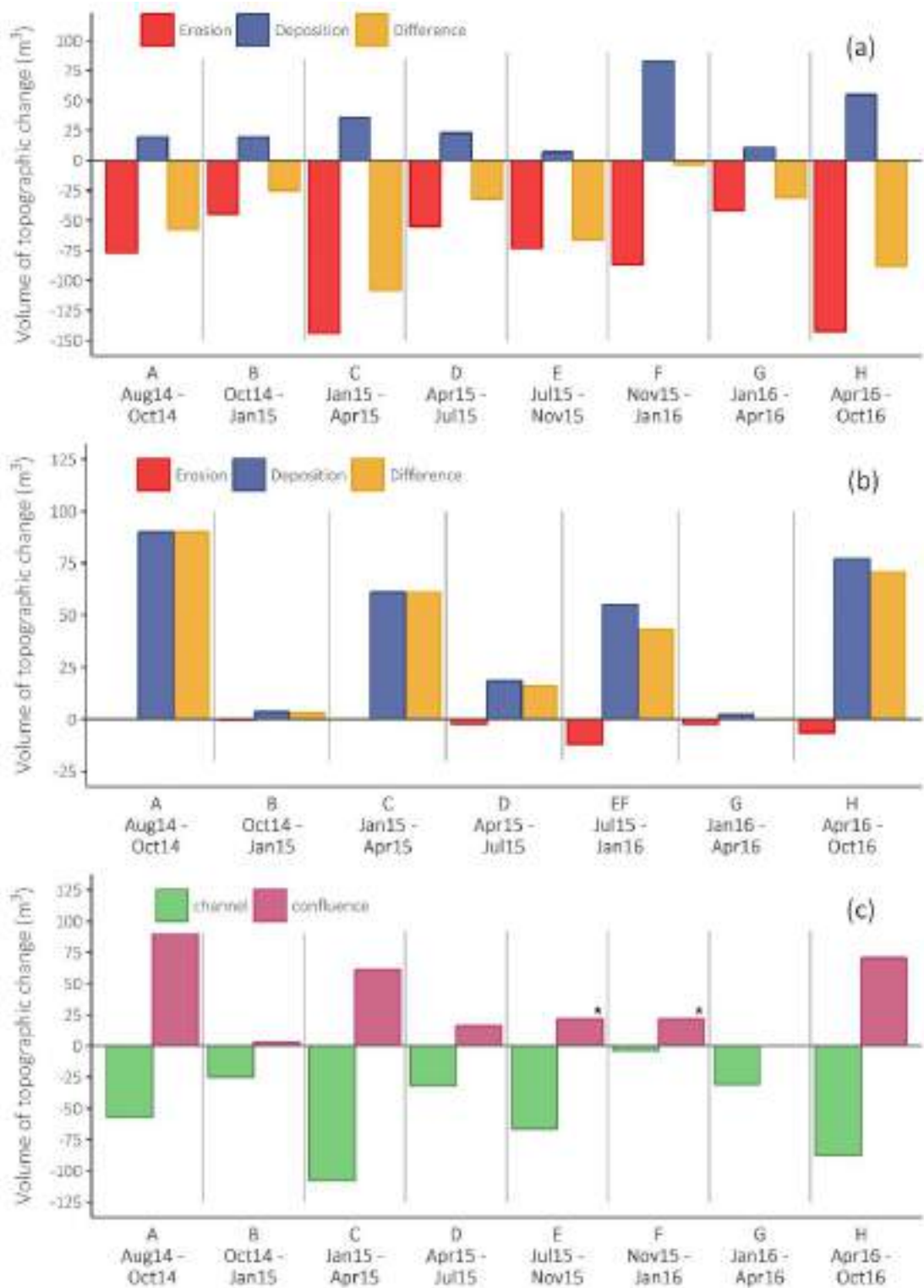


Figure 5.5. Volumes of topographic change: (a) in Ben Gill channel and (b) at the confluence. No data was available for periods E and F at the confluence bar. Instead, changes captured between E and F are pooled together (labelled 'EF'). (c) Total volume of topographic changes in Ben Gill channel and the confluence.

*Volume of change from DoD EF (confluence bar) was divided equally between E and F.

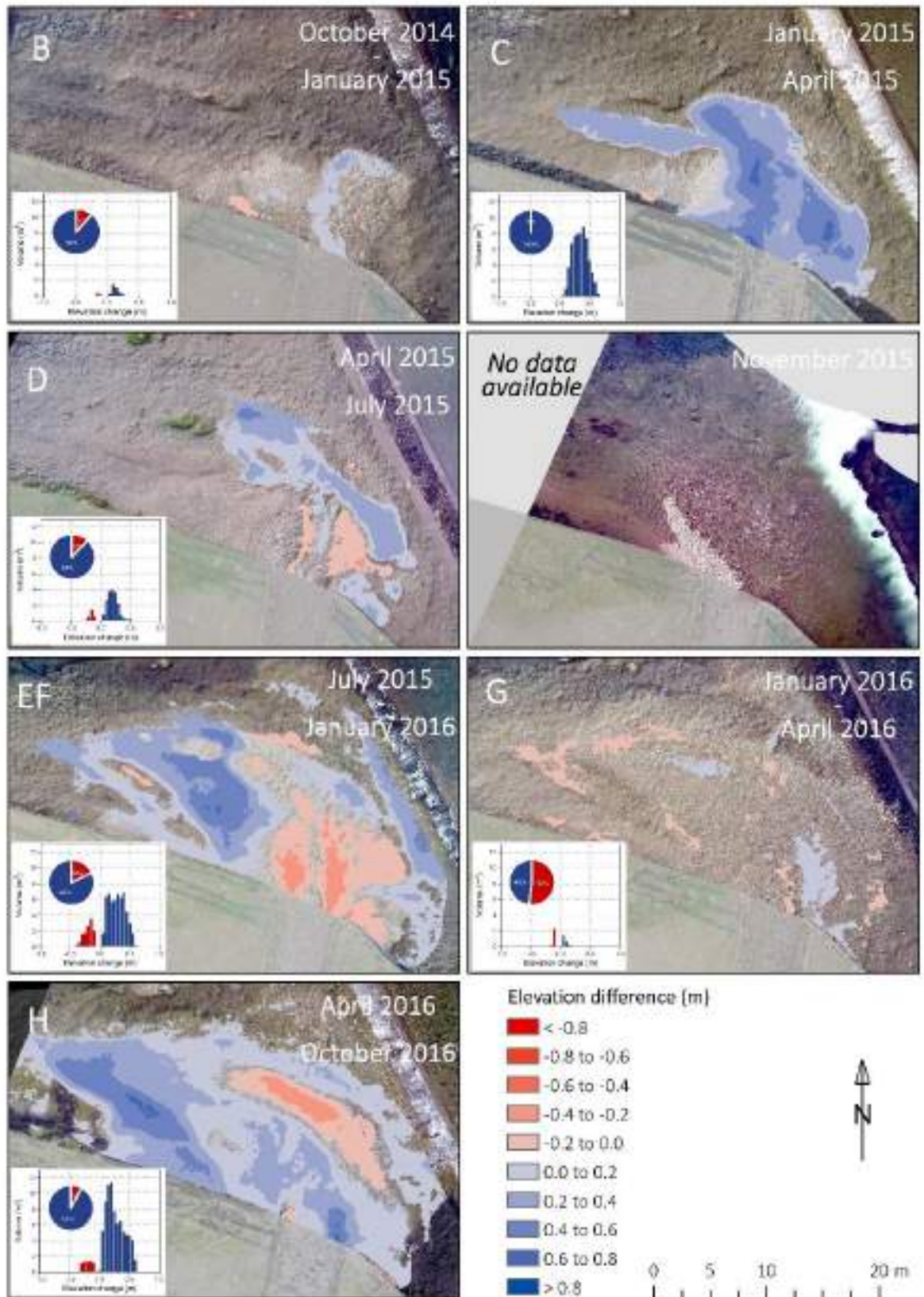


Figure 5.6. Topographic change (DoDs) and associated histograms for the confluence (except for E and F, see text and Figure 5.5 for details).

The relative geomorphic changes in Ben Gill and the confluence bar show that not all material eroded from the channel was deposited at the confluence (Figure 5.5c); rather, some material is progressively being conveyed down the main-stem Ehen. Exceptionally, in period A the net volume exported from Ben Gill represents the only occasion where export from the channel was lower than deposition at the confluence (c. 90 m³, Figure 5.5c). Although this could be related to the 'snapshot' nature of geomorphic change detection, or a large input of sediment from upstream compensating for internal erosion, we consider that this reversal of the normal patterns primarily stems from the coarse resolution of the initial GPS-based survey (especially because much visible erosion was observed following the extremely high flow on the first day of the reopening).

The confluence bar continues to grow in size (continual positive geomorphic change) at a rate which is underestimated due to issues related to detection of changes underwater. Comparing the total export of material from Ben Gill (c. 412 m³) and the total storage at the confluence (c. 307 m³), we can estimate a minimum volume of sediment effectively available in the Ehen of 105 m³ (c. 25% of the exported material, with this being a conservative estimate).

5.5.5. Changes in bed surface grain size distributions in the Ehen

In total, 7 GSD surveys were undertaken. First, no significant difference was found between the GSD reported by Quinlan et al. (2015) and that at G1 (χ^2 test, p -values: plane bed = 0.35, riffle = 0.28, pool = 0.24). GSD did not differ in the pool following the reconnection (Table 5.4). In the plane bed, only G2 was significantly different from G1 (χ^2 , $p < 0.05$). The riffle is the morphological unit where GSD was most variable over time, with G1 to G4 each significantly different from their preceding sampling occasion. Here, successive GSDs post-reconnection remained constantly different from G1, suggesting an effect of Ben Gill that persisted during the whole of the study period.

Table 5.4. Results of the χ^2 test of homogeneity used for the comparison of bed texture.

Plane Bed	G1	G2	G3	G4	G5	G6	G7
G1	-	*	**	NS	NS	NS	NS
G2		-	NS	NS	NS	NS	NS
G3			-	NS	*	NS	**
G4				-	NS	NS	NS
G5					-	NS	*
G6						-	NS
G7							-
$\chi^2 = 71.42, df = 48, p = 0.0158$							
Riffle	G1	G2	G3	G4	G5	G6	G7
G1	-	*	*	***	**	**	*
G2		-	***	NS	NS	NS	NS
G3			-	**	***	***	**
G4				-	NS	NS	NS
G5					-	NS	NS
G6						-	NS
G7							-
$\chi^2 = 77.45, df = 36, p = 7.32e-05$							
Pool	G1	G2	G3	G4	G5	G6	G7
G1	-		NS	NS	NS	NS	NS
G2		-					
G3			-	NS	NS	NS	NS
G4				-	NS	NS	NS
G5					-	NS	NS
G6						-	NS
G7							-
$\chi^2 = 45.75, df = 40, p = 0.2456$							
***	$p < 0.001$						
**	$p < 0.01$						
*	$p < 0.05$						
NS	Not Significant						

Figure 5.7a shows the average GSD over the study period for each morphological unit. These appear to be clearly different (details of all percentiles per each sampling occasion can be found in Table 5.5). Mean median particle size varies between 33.5 and 67.0 mm (for the pool and the plane bed, respectively). Some changes are also evident through time, after the re-connection. The change between G1 and G2 in the plane bed is towards an overall flattening of the GSD, apart from the sediment class 90.5-181 mm (Figure 5.7b). The proportion of grains smaller than 11.3 mm also increased. In the riffle, the proportion of particles between 8 and 22.6 mm generally increased from G1 to G4 (Figure 5.7c). The proportion of coarse particles (> 128 mm) did not change appreciably, but changes were observed in the proportion of material between 22.6 and 128 mm. The GSD at G4, from which successive surveys were not significantly different, shows a higher sorting than G1, with more of the finer fraction (< 22.6 mm) and less of the coarser. Similarly, the percentage of particles <8 mm increased in all morphological units

following the reconnection (Table 5.5) and tended to decrease over time and return to levels similar to pre-reconnection by G7.

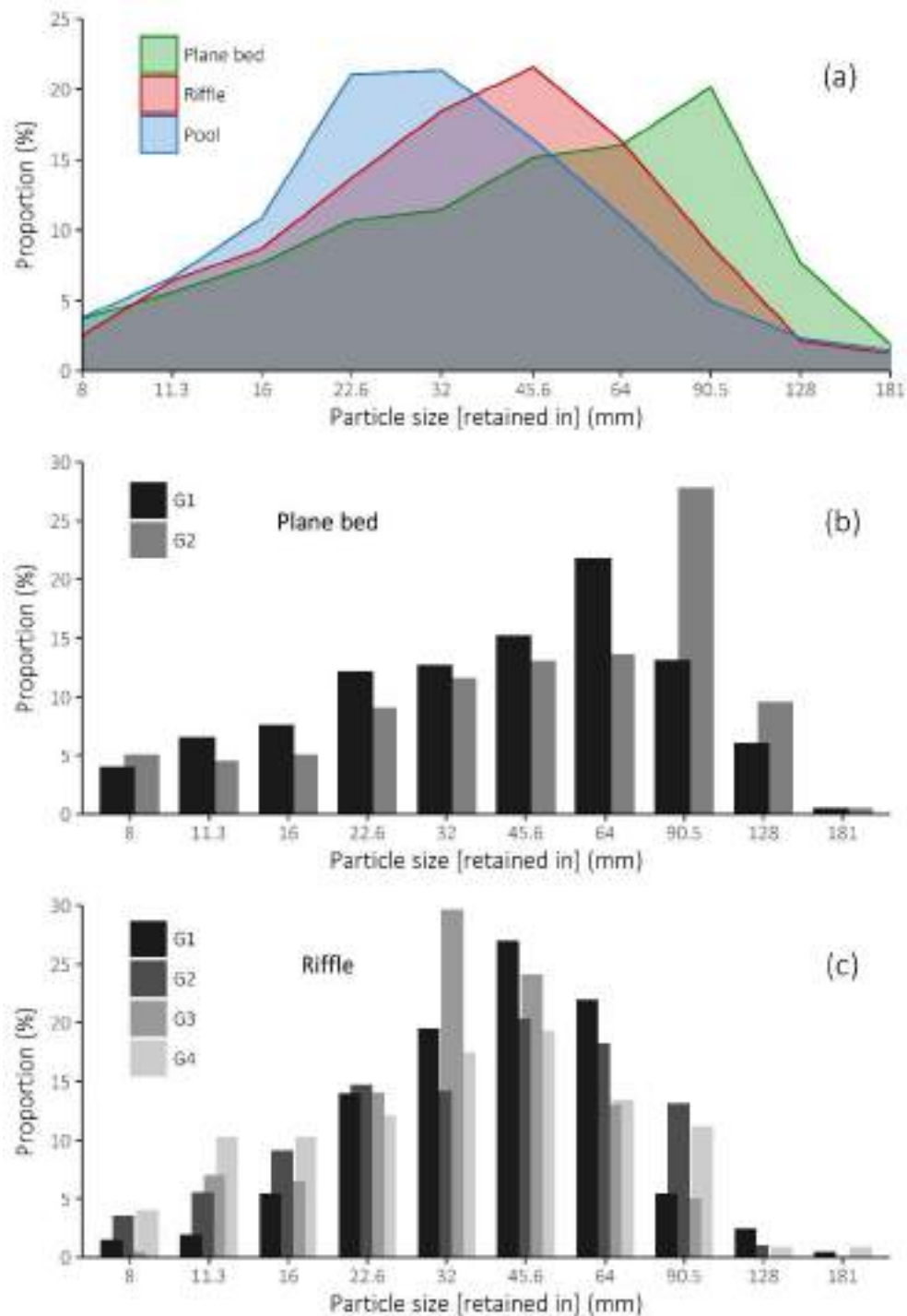


Figure 5.7. Histograms of GSD per morphological unit. (a) Average distributions for the entire study period. Changes on GSD fractions for the (b) plane bed and (c) riffle morphologies. Only GSD at sampling occasions that were found to be statistically different (χ^2).

Geomorphological adjustments in response to system-scale restoration

Table 5.5. Summary table of the main grain size distribution statistics, from the Wolman pebble counts, in each morphological unit.

Metric	Plane bed								Riffle								Pool							
	<i>P1</i>	<i>G1</i>	<i>G2</i>	<i>G3</i>	<i>G4</i>	<i>G5</i>	<i>G6</i>	<i>G7</i>	<i>P1</i>	<i>G1</i>	<i>G2</i>	<i>G3</i>	<i>G4</i>	<i>G5</i>	<i>G6</i>	<i>G7</i>	<i>P1</i>	<i>G1</i>	<i>G2</i>	<i>G3</i>	<i>G4</i>	<i>G5</i>	<i>G6</i>	<i>G7</i>
D₁₆	26.5	20.0	23.0	19.9	18.0	21.0	23.7	25.8	24.3	27.8	21.0	23.0	17.7	20.0	18.0	22.0	18.9	20.8		19.8	20.0	22.0	17.0	20.0
D₂₅	33.7	27.8	33.8	27.8	26.5	26.0	30.0	35.8	31.2	33.0	26.5	28.0	22.8	26.0	25.0	30.0	24.5	27.0		23.5	24.0	27.5	20.0	24.0
D₅₀	55.4	53.0	67.0	55.0	57.0	57.5	56.0	62.5	52.9	50.0	48.0	43.0	40.5	50.0	44.0	47.0	38.1	37.0		34.0	36.0	40.0	33.5	38.0
D₇₅	86.5	85.0	105.0	105.3	94.5	98.8	98.0	96.3	78.2	73.0	74.5	56.0	66.0	75.5	66.0	77.0	54.4	59.0		54.0	59.5	60.5	53.5	57.0
D₈₄	102.6	99.2	115.0	125.0	112.0	112.8	117.0	113.0	88.5	84.2	85.3	66.0	81.3	92.0	82.7	94.3	62.6	73.2		65.2	72.0	73.7	67.0	72.0
D₉₀	115.6	116.0	128.8	137.4	125.0	125.0	130.6	122.1	108.0	90.0	96.2	75.0	96.0	105.8	98.0	114.2	74.6	92.2		75.0	83.0	84.6	82.0	90.0
% <8mm	0.00	5.74	8.76	8.04	9.73	7.83	4.33	1.97	3.80	0.99	8.80	2.93	4.29	3.37	3.79	2.94	3.40	3.23		7.79	6.12	7.69	6.71	2.28
Arithmetic sorting <i>Folk & Ward 1957</i>	-0.93	-1.13	-1.16	-1.27	-1.19	-1.09	-1.11	-1.02	-1.04	-0.80	-0.98	-0.77	-1.04	-1.02	-1.10	-1.01	-0.87	-0.93		-0.92	-0.95	-0.91	-1.01	-0.97
Arithmetic Mean <i>Folk & Ward 1957</i>	-5.73	-5.56	-5.81	-5.69	-5.60	-5.69	-5.75	-5.83	-5.60	-5.61	-5.46	-5.33	-5.28	-5.50	-5.33	-5.52	-5.15	-5.26		-5.14	-5.22	-5.33	-5.07	-5.25
Arithmetic Skewness <i>Folk & Ward 1957</i>	-0.13	-0.24	-0.34	-0.17	-0.24	-0.21	-0.11	-0.22	-0.16	-0.06	-0.23	-0.18	-0.09	-0.19	-0.13	-0.04	-0.17	0.13		0.04	0.05	-0.01	0.03	0.04
Arithmetic kurtosis <i>Folk & Ward 1957</i>	0.88	0.92	0.96	0.85	0.78	0.67	0.84	0.92	1.17	0.95	0.86	1.06	0.86	0.83	1.06	0.96	1.04	1.15		1.09	1.01	1.12	0.97	1.11

D_i represent the *i*th percentile of the grain-size distribution

5.5.6. Particle mobility in the Ehen

5.5.6.1. Distance and grain size distribution of mobilised material

Of the 300 tracers seeded, 31% were recovered at the end of the study (Table 5.6). The periods between the 5 resurveys encompassed different values of peak flow (see Figure 5.2), ranging between 7.2 and 54 m³ s⁻¹. Recovery rates were very high for the first two surveys (88-98%; Table 5.6). Over the whole period, the pool showed the highest recovery rates (100% at S1 to 43% at S5) while the riffle showed the lowest ones (97% at S1 to 21% at S5). Recovery dropped markedly when preceded by high flows. Particles that were not recovered were not used for further analysis. No systematic data on particle burial were collected, although tracers were found under small gravel accumulations on numerous occasions. Only 2 surveys were carried out by Quinlan et al. (2015a) prior to the reconnection, capturing movement associated with peak flows of 21.8 and 18.6 m³ s⁻¹. Recovery rates were lower in their study for P1 (56%) but almost all of these were subsequently recovered (98%, P2).

Longest displacements of particles were observed in the plane bed (53.8 m, Figure 5.8a), with particles up to 150 mm moved. However, as this corresponds to the largest seeded particle (reflecting local GSDs), it is possible that larger material may also have been mobilised. The largest particle moved was found in the riffle (235 mm, Figure 5.8b), which also corresponds to the largest clast seeded. Mobility patterns in the pool showed lower displacement than in the plane bed but also smaller size of tracers displaced (Figure 5.8c). In general, largest displacements were observed in S5, when the highest peak flow was observed (30-year flood, Table 5.6).

Mobility of tracers in relation to the GSD of each unit shows that most flow events were not able to mobilise a distribution of particle sizes coarser than the bed (Figure 5.9). The survey S3 had a maximum associated discharge of *c.* 28 m³ s⁻¹ and was only capable of moving a distribution of particles within the envelop of GSD for the lower range of sizes (8 – 22.6 mm) in the plane bed (Figure 5.9a) and the pool (Figure 5.9c). Only flows associated with S5 ($Q_{\max} = 54$ m³ s⁻¹, 30-year flood) were able to mobilise particles over a distribution coarser than the respective unit GSDs. When excluding the pool, patterns were different prior to the reconnection (surveys “P”, Figure 5.9). Mobility patterns in the plane bed and riffle are rather similar to the ones observed for S3, with a maximum discharge (27 m³ s⁻¹) slightly higher than these recorded at P1 and P2 (21.8 and 18.6 m³ s⁻¹ respectively).

Geomorphological adjustments in response to system-scale restoration

Table 5.6. Summary table of tracers mobility surveys and flow hydraulics in the Ehen, prior to and after the reconnection.

Survey	Morphological unit	Average steplength <i>m</i>	Maximum steplength <i>m</i>	% recovered (from total)	% recovered (from previous survey)	% moved (from previous survey)	Size of largest particle moved <i>mm</i>	Displacement of largest particle <i>m</i>	Q_{mean} $\text{m}^3 \text{s}^{-1}$	Q_{max} $\text{m}^3 \text{s}^{-1}$	Q_{SD} $\text{m}^3 \text{s}^{-1}$	ω_{max} W m^{-2}	ω_e W m^{-2}
P1*	Plane Bed	1.75	5.14	44%	-	88.5%	100	2.01	4.49	21.80	2.96	48.2	15827
	Riffle	0.76	3.72	71%	-	56.3%	110	0.78				34.5	9992
	Pool	-	-	-	-	-	-	-				18.3	937
	Entire reach	1.91	15.02	56%	-	69.2%	110	0.78				48.2	15827
P2*	Plane Bed	1.61	14.95	44%	100%	100%	100	0.08	2.40	18.60	2.70	41.8	1951
	Riffle	0.57	6.26	68%	95.2%	87.1%	190	0.16				29.9	1149
	Pool	-	-	-	-	-	-	-				15.9	67
	Entire reach	1.82	29.78	55%	98.0%	95.7%	190	0.16				41.8	1951
S1	Plane Bed	0.28	1.13	97%	-	18.6%	107	0.14	2.52	7.21	1.64	15.9	0
	Riffle	0.28	0.73	97%	-	13.4%	102	0.16				11.4	0
	Pool	0.18	0.34	100%	-	7.0%	48	0.14				6.0	0
	Entire reach	0.26	1.13	98%	-	12.7%	107	0.14				15.9	0
S2	Plane Bed	1.19	10.66	85%	87.6%	41.2%	125	0.33	3.28	18.20	3.12	40.3	1473
	Riffle	0.85	3.44	84%	86.6%	26.8%	111	0.39				28.8	784
	Pool	0.39	1.08	94%	94.0%	20.0%	109	0.32				23.3	45
	Entire reach	0.90	10.66	88%	89.5%	28.7%	125	0.33				40.3	1473
S3	Plane Bed	8.09	43.33	62%	72.9%	63.5%	125	0.24	4.42	27.80	3.95	61.5	8866
	Riffle	1.17	12.71	64%	76.2%	63.1%	135	1.93				44.0	5548
	Pool	1.11	5.64	79%	84.0%	66.0%	90	0.15				23.3	938
	Entire reach	3.07	43.33	68%	77.9%	56.3%	135	1.93				61.5	8866
S4	Plane Bed	6.31	11.11	53%	85.5%	22.6%	36	3.51	2.07	13.70	1.62	30.3	272
	Riffle	0.35	1.97	50%	78.1%	43.8%	205	0.14				21.7	119
	Pool	0.00	0.00	76%	96.2%	3.8%	-	-				11.5	0
	Entire reach	1.92	11.11	60%	87.3%	15.0%	205	0.14				30.3	272
S5	Plane Bed	11.72	53.81	28%	52.8%	90.6%	142	0.59	4.53	54.00	5.46	119.4	36094
	Riffle	5.07	14.35	21%	42.0%	82.0%	235	0.39				85.5	23583
	Pool	7.77	30.25	43%	56.6%	78.9%	95	0.61				11.5	6681
	Entire reach	8.71	53.81	31%	51.4%	49.7%	235	0.39				119.4	36094

*P1 and P2 are pre-reconnection data from Quinlan et al. (2015).

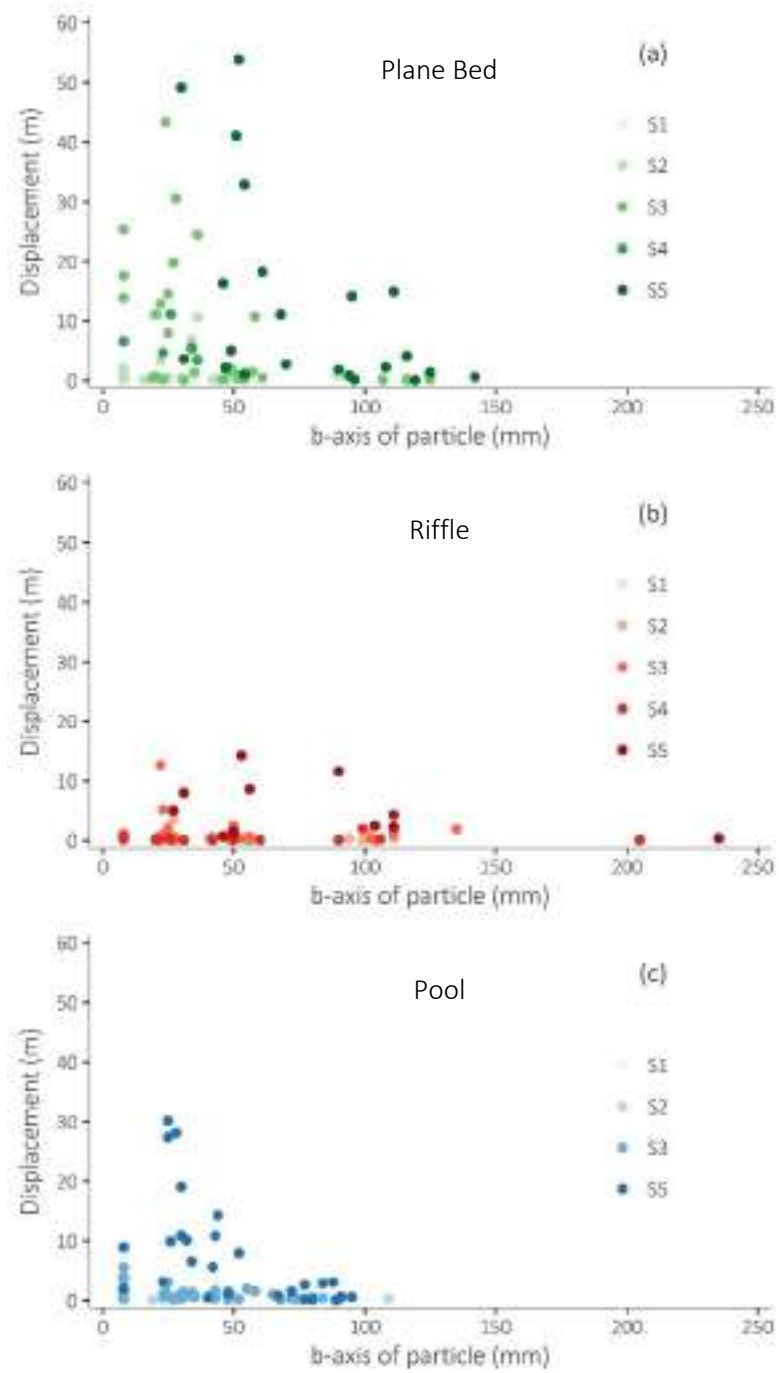


Figure 5.8. Displacement (m) against the b-axis of all tracers recovered for each survey (S1 to S5): (a) in the Plane Bed, (b) in the Riffle and (c) in the Pool. See table 5.6 for the hydraulic data associated to each period.

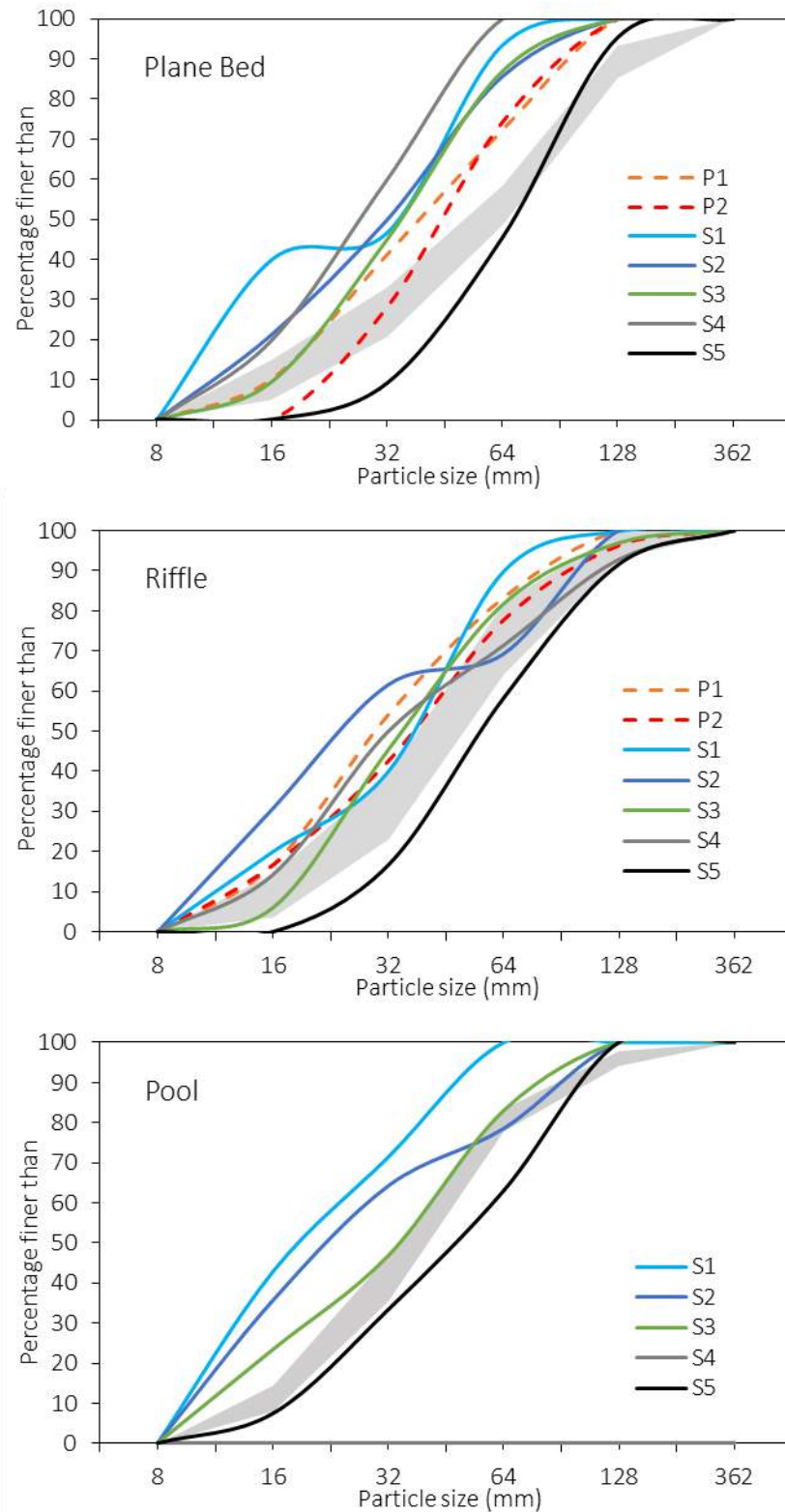


Figure 5.9. Grain size distribution of the mobilised tracers for each survey of this study (S1 to S5) and these from Quinlan et al. (2015, P1 & P2): (a) plane bed, (b) riffle and (c) pool. The bed grain size distribution envelope from the different GSDs sampled in this study is shown as grey areas. No data was used for the pool from Quinlan et al. (2015, P1 & P2).

5.5.6.2. Particle mobility models

In order to identify the minimum ω required to entrain particles (i.e. critical stream power, ω_{ci}), the relationship between several particle size statistics (i.e. D_{max} , D_{mean} , D_{84}) and ω_{max} , determined from the associated Q_{max} experienced prior to the resurvey of tracers, was analysed (Figure 5.10a). The maximum particle size mobilised in the plane bed and the riffle were the largest tracers available (Figure 5.8), restricting the use of D_{max} to understand particle mobility in the Ehen and creating a rather weak relationship with ω_{max} (Figure 5.10a). Using D_{mean} offered the best fit (Figure 5.10b) but is of limited utility to estimate ω_{ci} since it smoothes the relationship and underestimates the critical value. The choice was made to use the relationship between D_{84} and ω_{ci} for the analysis (Figure 5.10c); D_{84} has been used in previous studies (e.g. Petit et al. 2005). The mobility model produced sits within other models found in the literature (Figure 5.10d).

5.5.6.3. Excess of stream power and mobility

Using equation (5.5), excess stream power (ω_e) was computed for each survey period at 15-min intervals (Table 5.6). The registered flow data indicate that ω did not reach ω_{ci} prior to S1 in any morphological unit. ω_e was also 0 in the pool during S4, which coincides with the very limited movement observed in this unit during this period. Maximum ω_e was experienced during S5 throughout the entire reach, which can be explained partly by the length of time between S4 and S5, but also by the long-lasting periods where ω was above ω_{ci} . ω_e experienced during the study by Quinlan et al. (2015) was relatively high at P1 and lower at P2, and no episode where $\omega_e = 0$ was observed then.

The nature of the scatter in the points representing the relationship between particle size of recovered tracers and displacement relative to ω_e showed a typical limiting response form (Figure 5.11), with high variability for some b -axis values (small particles) and low variability for others (large particles). In general (i.e. $T = 0.5$), for the same relative level of ω_e , smaller particles were capable of travelling longer distances than larger ones. The upper bounds of the response ($T = 0.95$) fell sharply across the particle size range, with much lower maximum displacements for larger particles than smaller ones. This fall across particle size range was much steeper for the upper limit than the general relationship represented by the median response ($T = 0.5$).

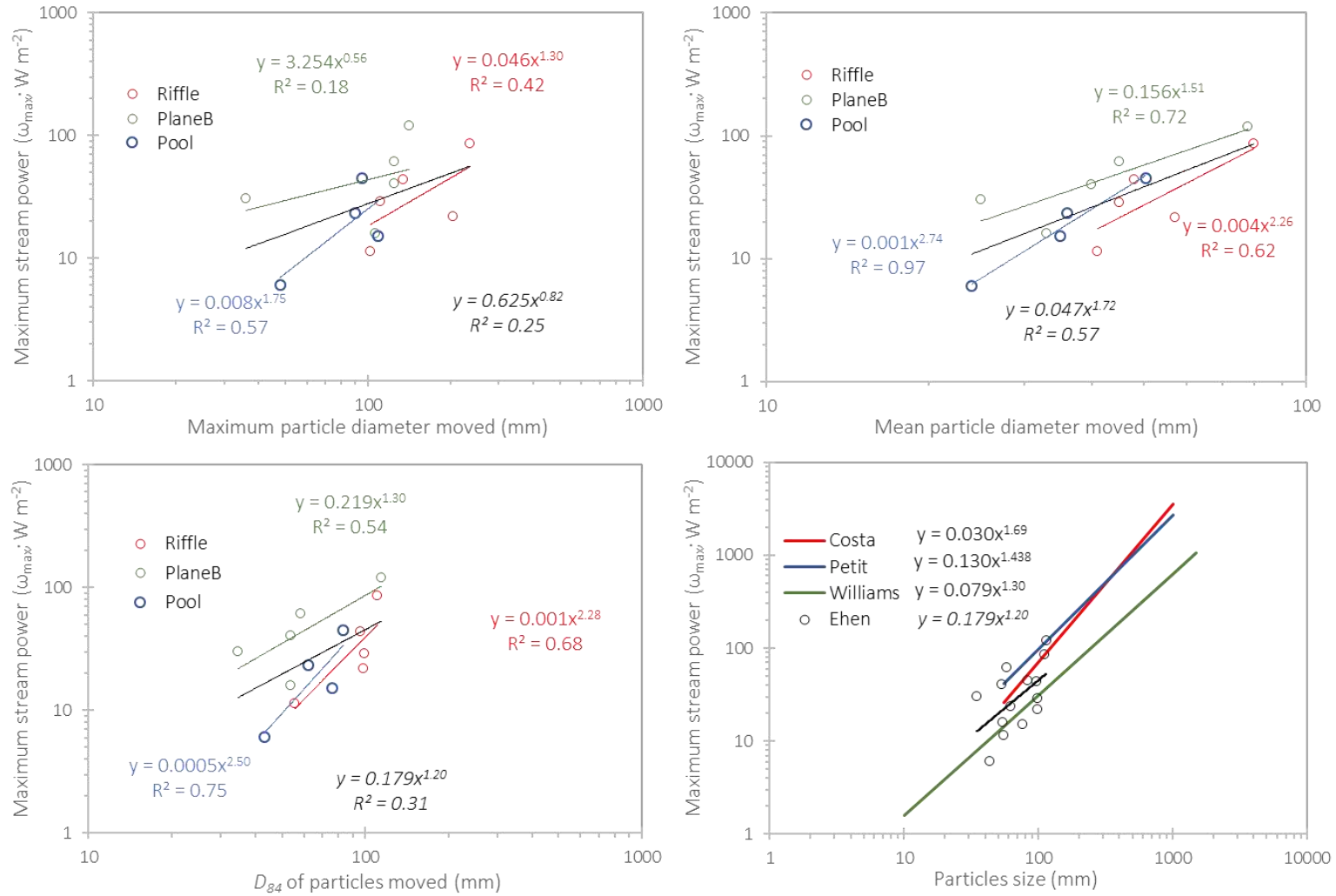


Figure 5.10. Relationship between maximum stream power (ω_{max}) and different statistics of particle size: (a) maximum, (b) mean and (c) D_{84} of grain size distribution. (d) mobility model for this study (from D_{84} data) compared to formulae found in the literature (Costa, 1983; Williams, 1983; Petit et al. 2005).

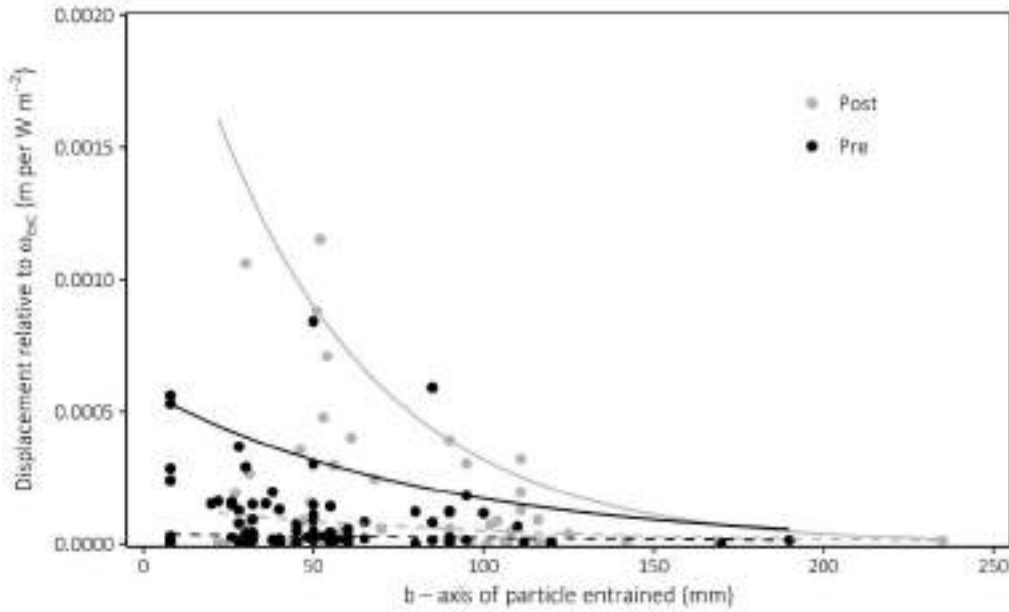


Figure 5.11. Particle displacement relative to the excess stream power they experienced (all successive surveys and morphological units Plane Bed and Riffle merged together), in relation to the b -axis of particles, in the River Ehen, pre- (black dots) and post-reconnection (grey dots). Note that the straight and dashed lines represent the 0.95 and 0.50 quantile regression models, respectively.

Models were fit separately to data for the post-reconnection period (current study) and the pre-reconnection period covered by Quinlan et al. (2015). The $T = 0.95$ model fits for both periods were significant ($p < 0.005$) but the $T = 0.5$ fit was significant only for the post-reconnection model period. Analysis of the model coefficients (especially b) showed that the upper limit of the responses differed significantly between the periods (Table 5.7). Thus, the upper limit of the response is significant in determining the maximum potential distance travelled by a particle under similar ω_e conditions, and is now higher than it was previously. Overall, particle mobility in the riffle and the plane bed has increased since the reconnection.

Table 5.7. Summary of quantile regressions fitted on tracers data (See Figure 5.11). Values in bold are significantly different ($\alpha = 0.05$). a : coefficient; b : intercept. Models of the form $y = a \cdot e^x + b$.

T	Pre-reconnection			Post-reconnection			
	coefficients	lower bound	upper bound	Coefficients	lower bound	upper bound	
0.95	b	-3.23	-3.48	-2.76	-2.60	-2.79	-2.37
	a	-0.0053	-0.0079	0.0039	-0.0090	-0.0103	0.0295

5.5.7. Reach-scale topographic changes at the River Ehen

The pool experienced little topographic change compared to the other morphological units (Figure 5.12). Overall geomorphic changes in the plane bed were negative, with the floods of winter 2015 playing a significant role in generating an overall deepening of this unit. The limited deposition of gravel that occurred in the plane bed between T4 and T5 was insufficient to compensate for erosion at T4. Deposition happened in the riffle between T1 and T2 (c. 22 m³), and corresponds to the observed development of a gravel bar along the right bank (Plate 5.2). The large floods of winter 2015 (between T2 and T4) generated loss of material from this unit. Further accumulation in the riffle happened between T4 and T5, and the erosion observed between T5 and T6 can be identified as a deepening of the channel along the bank opposite to the gravel accumulation. The transitional area, only surveyed for topography, experienced mostly erosion (c. 10 m³).



Figure 5.12. Topographic changes (net) in the upper River Ehen, extrapolated from changes in cross-sectional area (only changes above the minimum level of detection have been considered, see methods). See Figure 5.1 for details on the morphological units. Note that there was no suitable topography data for T3 at the riffle, therefore for T2-T3 and T3-T4: the value of T2-T4 is divided between the two (Indicated with *).



Plate 5.3. Photographic evidence of the development of a gravel bar in the riffle. (a) first signs of deposition (April 2015, $Q = 1.0 \text{ m}^3 \text{ s}^{-1}$). (b) further development of the deposition (January 2016, $Q = 1.4 \text{ m}^3 \text{ s}^{-1}$).

5.6. DISCUSSION

5.6.1. Context

Part of the success of a restoration project relies on the appropriate post-restoration evaluation and monitoring (Bradshaw 1996; England et al. 2008). Given the need to consider the slow rate of environmental responses when evaluating river restoration efforts (see Chapter 1) and the relative decrease in pace with increasing scale (Petts 1987), limited conclusions can be drawn from only 2 years of post-restoration monitoring in a system-scale restoration initiative. Nevertheless, early monitoring was required because of the sensitivity of the freshwater pearl mussel to changes in geomorphic and sedimentary conditions. In addition, past evidence of its former geomorphic activity resulted in the expectation that geomorphic activity would be

triggered as soon as the channel was offered the opportunity to recover its naturalness. The degree of this activity, however, has proven to be greater than all expectations.

Just as expressed by Petts and Gurnell (2005) in relation to the fluvial metamorphosis in response to dam closure, the reactivation of sediment connectivity is likely to generate a series of phases, from an accommodated regime state towards another, new regime state, possibly (and ideally) closer to the natural one. Moving from one state to another the system will progress along the relaxation path, at a pace that will depend on the river characteristics (e.g. degree of energy, sensitivity to changes, hydrologic regime), the degree of alteration compared to its (estimated) “natural” state (e.g. shift in river type, degree of armouring and stabilisation) and how much of the altered processes are being restored. From the physical adjustment of channel forms to changes of flow and sediment regime will depend the ecological response, which is usually slower and may span through several phases (Petts 1987; Petts and Gurnell 2005).

The reconnection of Ben Gill to its sediment-starved and regulated main-stem Ehen offers a unique opportunity to observe the geomorphic adjustments during the adjustment phase that result from a renewed delivery of material. The system-scale nature of this restoration exercise, to reconnect two hitherto isolated system components (sub- and main-stem catchments), has implications for the mass and energy balances of the system. Predicting trajectories of evolution of the system are complicated by the ongoing adjustments experienced by the tributary, which is now the main source of sediment and the main factor controlling the timing and frequency of sediment delivery.

5.6.1. Key findings

5.6.1.1. Fluxes of coarse material from Ben Gill

Results from the application of SfM photogrammetry suggest that Ben Gill is exporting sediment at an estimated minimum rate of just over 200 m³ y⁻¹. Erosion is still the dominant process observed in the lower part of the channel 2 years after its reconnection. Different mechanisms of channel adjustment can be identified, based on the spatial patterns of erosion and their magnitude. These are not constant through time, as indicated by the shape of the frequency distribution of erosion (Figure 5.4). High magnitude changes are driven mainly by bank erosion, while the bottom of the bed still undergoes local degradation; this process is of

lower magnitude but extends over larger areas. Although part of this eroded material is composed of fine particles, the development of a gravel bar at the confluence proves that this delivery also concerns coarser material. This was clearly reflected in the magnitude of changes following the first rainfall event, which was of exceptional intensity (i.e. highest 24h precipitation ever recorded at local weather station). In addition to the large release of fine sediment transported in suspension (> 35 t, 14% of the annual load; Marteau et al. 2017b), a minimum of 90 m³ of coarse material was deposited at the confluence (eroded from the new Ben Gill channel, and/or potentially transferred from its upper catchment). Because it is not gauged, no data are available that might be used to statistically assess relations between flow and erosion. Nevertheless, it is likely that geomorphic activity in Ben Gill is controlled by the magnitude of the events more than their duration or frequency. A higher internal reworking of sediment was identified for period F, with larger volumes of deposition compared to other periods. This could be related to the regular rainfall events generated by the two successive storms of winter 2015, during which a total of 25 events were recorded that are likely to have been short (mean duration = 0.8 days) but intense.

Although the channel was designed to follow the original (pre-diversion) course of the stream, it will need some time (i.e. adjustment period) to reach a new 'dynamic equilibrium', with adjustments in slope, channel geometry, flow intensity, sinuosity, bed configuration and sediment supply. To date, Ben Gill shows no signs of decrease in activity and continues to supply large volumes of sediment, some of which remains stored in the confluence bar. Volumes of erosion estimated from indirect assessments (i.e. SfM) are twice those anticipated from preliminary studies (c. 100 m³ per year, United Utilities 2012). This difference reflects the rather high activity observed in the channel within the first 2 years post-reconnection.

5.6.1.2. The mediation role of the confluence bar

Very limited erosion was captured on the confluence bar during this study (total erosion = 8.4% of changes at the confluence), despite the high flows of winter 2015 (maximum discharge = 30-year return period flood) and the evidence of fresh gravel deposits in the mainstem. This means that the Ehen is not capable of transporting all the coarse material delivered by the tributary. Because the confluence bar continues to grow, with little signs of erosion, it is likely that the material identified as 'exported' has had virtually no transient period in the bar. The behaviour of particles reaching the confluence can thus be described as binary: when a particle is eroded

from Ben Gill, it is either retained in the bar or transported directly towards the main-stem. Particles that are stopped at the confluence have limited chances of reaching the main-stem under ambient conditions; they will remain stored there until at least one of the factors controlling the growth and erosion of the confluence bar changes.

Two main factors controlling the changes on the confluence bar can be identified. The first factor is the unexpectedly and relatively high sediment supply from Ben Gill. It is a very dynamic headwater stream whose ephemeral activity contrasts with the regulated River Ehen. However, it is likely that its activity will quasi-stabilise in the future as Ben Gill tends towards a dynamic equilibrium; adjustments in the slope and sinuosity of the channel will reduce local erosion (i.e. in the lower end of the channel) and the system will mostly export material produced in the upper part of the catchment. Inherent features related to the old alluvial fan sedimentology may also play a role in this; e.g. rocky outcrops may act as knickpoints, cohesive material may prevent lateral erosion, etc. With this in mind, and given the stochastic nature of the stream, the time required to reach such equilibrium is difficult to assess, but an estimation of years to decades can be hypothesised. The second factor controlling the behaviour of the confluence bar is the transport capacity of the Ehen. This has been altered by flow regulation (lake and weir), but also by the proximity of the confluence bar to the weir. As visible on the aerial photographs (Figure 5.6), the bar now extends more or less all the way to the weir and the fish-pass. Because the weir is rather wide (60 m), the energy applied by the water when flow rises over the weir is dissipated over a large area. Additionally, now that the confluence bar has expanded, the distance available between the weir and the bar for the water to gain momentum (i.e. energy) is limited. When the water hits the bar, it has gained little kinetic energy and has very limited competence.

5.6.1.3. Geomorphic adjustments in the Ehen

Prior to the reconnection, the study reach of the River Ehen displayed signs of a very stable channel (Quinlan et al. 2015). When armouring prevents further channel degradation, the energy available is dissipated through bank erosion, leading to a simplification of channel morphology (Church 1995; Pitlick and Wilcock 2001) and channel widening (Xu 1996). This is what was observed in the Ehen; channel geometry was very simple, with no geomorphic features (such as gravel bars) but with a wide and uniform armoured channel. Armour layers can be observed in those natural systems where sediment supply exceeds or falls well below

transport capacity (e.g. Dietrich et al. 1989; Lisle and Madej 1992). However, the degree of armouring can be exacerbated by impoundments and the associated disruption of sediment fluxes, and leading to pavement where bed mobility is marginal.

Despite the regulation (partly natural, related to the presence of a post-glacial lake, and partly enhanced by the weir), the river has retained some hydrologic dynamism and flashiness (Figure 5.2). The degree of armouring in the Ehen and the absence of apparent changes in topography lead Marteau et al. (2017) to described the armour surface layer as pavement. Whether a coarse surface layer is termed 'armour' or 'pavement' (sensu Sutherland 1987) depends mainly on its frequency of movement. An armour layer develops in rivers where frequently occurring flows still have competence to entrain the larger particles present. Conversely, a pavement refers to more static conditions under which the largest particles remain immobile (Bunte and Abt 2001). Parker et al. (1982a) additionally distinguished mobile from static armours found in rivers with an important sediment deficit, such as observed downstream from dams. Here we refer to armour to the situation in which the bed is frequently entrained, while pavement is used to represent more static conditions (Sutherland 1987). The pavement observed in the River Ehen is more likely a result of sediment starvation (downstream winnowing of fines without replacement from upstream due to the weir and the dis-connection of Ben Gill) than a lack of competent flows (following Bunte and Abt 2001). In this case, restoring a more natural (dynamic) provision of sediment can help restore some habitat heterogeneity and potentially, in the long run, contribute to the (partial) breakup of the pavement and limit localised bank erosion or other impacts on channel morphology.

Analysis of the movement of painted tracers revealed that patterns of transport were different in the present study period compared to that of Quinlan et al. (2015). Limited knowledge was gained about mobility in the pool due to issues with part of the data. In the present study, greatest mobility was witnessed in the plane bed. The largest particle moved was found in the riffle, but no clear difference in maximum size could be seen between the plane bed and the pool. Additionally, the riffle showed similar frequency of larger particles being displaced (when compared to results of Quinlan et al. 2015), although not over long distances. In the current study, more particles were displaced in the plane bed over longer distances compared to the riffle, where coarser particles were moved but mean travel distances were shorter. However, estimates of mobility in the riffle are probably biased by the low recovery rate for smaller particles (i.e. no measurement of displacement). The riffle experienced important deposition

of gravel after S2, with the development of a gravel bar along the right bank as can be observed in Plate 5.2. Numerous tracers are likely to have been buried and trapped under the bar, hence the apparent lower records of displacement (average step-length at highest peak flow = 5.5 m) and recovery rate (final survey = 21%). The displacement of particles in the pool was much lower than reported by Quinlan et al. (2015), with no movement at all observed on one occasion (S4).

Overall, particle mobility is higher since the reconnection, with a lower amount of energy required to move particles of the same size. Comparison of the relative size of mobilised particles to the surface GSD confirms the low mobility experienced in the River Ehen, even after the reconnection, with only high magnitude flood events (e.g. return period of 30 years) capable of transporting particles that encompassed the entire surface GSD. Even though the confluence bar retains a large fraction of the sediments delivered by Ben Gill, part of this material is carried downstream (approximately $50 \text{ m}^3 \text{ y}^{-1}$), a situation that the river has not experienced for 40 years.

Signs of change were also observed in surface GSDs, especially in the riffle, with variable changes at the beginning but a general fining of the bed surface latterly. No change was found in the pool, although field observations suggest that this could be missed by the method used to sample GSD. Local pockets of sand and fine gravel were identified in areas of preferential deposition (e.g. behind boulders, along the banks) but failed to be captured by the Wolman pebble count which only accounts for particles $> 8 \text{ mm}$. These observations, together with the fining trends identified in the riffle, support the hypothesis that only the smaller fraction of the material supplied by Ben Gill is transported downstream under the existing hydrological regime. It is also supported by the relatively fine size of the gravel forming the new bar feature in the riffle (Plate 5.2).

Part of the coarse material delivered by Ben Gill is being dispersed downstream, although the impact on channel topography and geometry remains limited. Overall topographic changes throughout the study were close to 0, with only the riffle showing clear signs of deposition, and the plane bed, signs of erosion. Deposition was expected in this part of the section (riffle) as it presented attributes of an old pre-existing gravel bar. Increase in depth in the plane bed was associated with the succession of very high discharges (winter 2015).

At this time, the confluence bar was already well developed and forced most of the flow to one side of the channel. Despite the magnitude of the floods, the gravel bar showed limited signs of erosion -in fact, it kept on growing in size due to the continued supply of material from Ben Gill. It is probable that flow constriction applied by the confluence bar forced most of the flow over a limited width of the plane bed, situated just downstream from the confluence, generating higher velocities and shear stress and resulting in local erosion.

Flume experiments have confirmed field observations that a reduction in sediment supply results in an increase in the D_{50} (Dietrich et al. 1989; Lisle et al. 1993, 2000; Buffington and Montgomery 1999) and the surface layer becomes immobile (Dietrich et al. 1989; Nelson et al. 2009). Conversely, the addition of material to an armoured channel tends to increase bed surface mobility (Sklar et al. 2009; Koll et al. 2010; Venditti et al. 2010) and decrease bed surface particle size (Sklar et al. 2009). Despite the limited extent of this study (in space and time), the geomorphic adjustments reported here are in line with the conclusions from flume experiments. The renewed provision of coarse material from Ben Gill has reactivated part of the lost geomorphic processes - material is being carried downstream and is starting to affect particle mobility and bed texture. The dispersion of coarse material is likely to be further enhanced once channel complexity is significantly improved (e.g. Lisle et al. 2001).

Limitations exist to the use of flume experiments to interpret field observations. In some instances, the injection of sediment was capable of mobilising part of the bed surface (e.g. Koll et al. 2010; Venditti et al. 2010), opening the possibility of seeing the armour layer of the River Ehen (partly) entrained as more sediment is moved on top of it over time. However, most flume studies are undertaken over a freshly created armour layer, where the movement of particles is not impeded by biological activity (e.g. macroinvertebrates; Johnson et al. 2009; biofilm; Piqué et al. 2016) or imbrication and compactness (Houbrechts et al. 2012). The riverbed of the Ehen has shown little sign of mobility since the study of Quinlan et al. (2015a) (starting in 2011), displayed a very high compactness and the presence of macroinvertebrates and biofilm (Quinlan 2014). Thus, it is likely that conditions for a partial mobilisation of the pavement will require more time and/or more sediment and/or coarser particles which, due to the dominant dispersive nature of displacement behaviour of mixed sediment (Lisle et al. 2001; Sklar et al. 2009), may require longer than the timeframe of this study to be captured.

5.6.1.4. What future for the Ehen?

The riffle and downstream pool-riffle transitional area are separated by a hydraulic jump (c. 0.5 m), which plays a role in trapping gravel in the riffle and generating higher velocity directly downstream from the jump. Early signs of break-up of the pavement have been observed most recently, downstream from this jump, with new sediment being deposited in its stead (Plate 5.3). This is evidence that the system has retained some potential for recovery, but also that this will only be achieved if specific conditions are met, i.e. increased morphological complexity (e.g. hydraulic jumps) and high discharges (e.g. >25-year return period floods). Increase in morphological complexity will result from the transport of material away from the confluence bar.

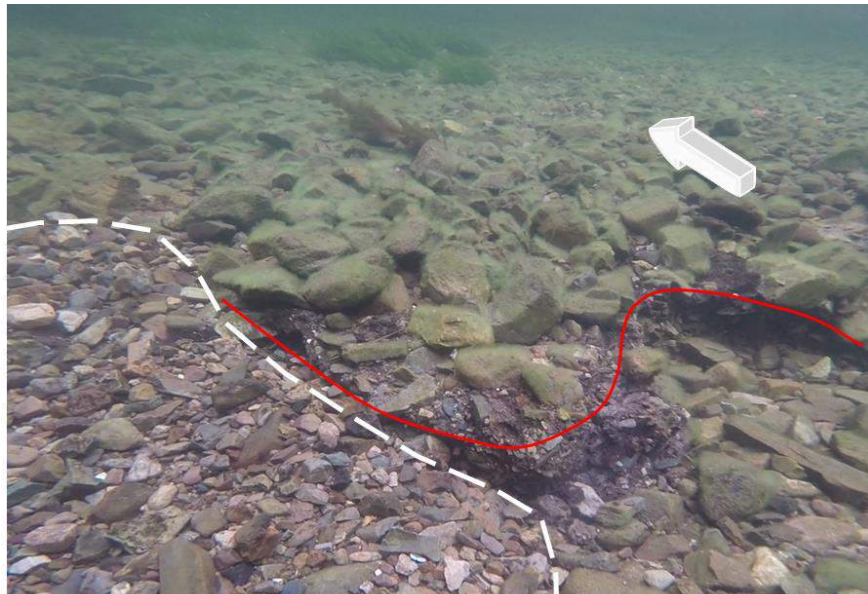


Plate 5.4. Photographic evidence of early signs of break-up of the pavement, just downstream from the hydraulic jump (separating riffle and transitional area). The red line shows limit of the break-up. White dashed line shows fresh material deposits, potentially originating from Ben Gill. Arrow shows flow direction. The pavement is characterised by large particles covered with biofilm, underlined by a matrix of very cohesive sediments and fine gravels.

The effects expected from gravel augmentation (e.g. bed fining, enhanced bed mobility) are most beneficial when they persist over a long period of time and affect long sections of river channel (Bunte 2004; Harvey et al. 2005). Given that particle size and excess shear stress (reflected in changes in bedforms) adjust to both flow intensity and sediment supply (Buffington and Montgomery 1999), and since Ben Gill shows no sign of reduction in its sedimentary activity, geomorphological and sedimentary adjustments in the upper Ehen are likely to continue over long periods of time. In the absence of blocking features (e.g. large

boulders, large woody debris), as is the case in the River Ehen, a moderate sediment supply (along with a moderate transport capacity) has the potential to generate a high habitat heterogeneity (Yarnell et al. 2006). We have demonstrated that part of the sediment delivered by Ben Gill (minimum of 25%) is transported downstream in the Ehen. To date, topographic adjustments in the Ehen in response to this material remain limited but should increase as more sediment is dispersed.

Overall, the signs suggest that the River Ehen is slowly adjusting to the renewed delivery of coarse material. Despite the large volumes provided by the sub-catchment, the Ehen struggles to carry all the material downstream so deposition within the study reach remains limited. The scale of changes observed in Ben Gill is not yet matched with geomorphic adjustments of the same order in the Ehen. We hypothesise that further “improvement” in bed conditions should follow, providing that flows are capable of moving material away from the confluence bar.

5.6.2. Methodological issues

5.6.2.1. Monitoring in Ben Gill

The fact that Ben Gill is an ephemeral stream has raised a number of issues. Most notably, the intense but short-lived activity in the channel has made it impossible to properly measure its discharge and necessitated the use of alternative methods to characterise flows (i.e. time-lapse photography). However, its ephemeral nature made possible the use of SfM photogrammetry without the need to deal with surface water reflection (at least in the channel). This was key for the accurate estimation of (minimum) sediment fluxes as was shown by the mismatch observed between export from the channel and deposition at the confluence for the period A, when only GPS cross-sectional topographic data was available. This high-resolution surveying technique provides an opportunity for better estimates of sediment fluxes since it is capable of capturing changes at the grain-size scale (as recently reviewed by Vericat et al. 2017). It is also a useful tool to understand the geomorphic processes responsible for the changes observed. The quality of the results also benefited from the combination of both SfM outputs (i.e. point-cloud and orthophotos) to identify potential artefacts (vegetation, silt fences) and an ability to blank these areas out of the analysis. Finally, the design of appropriate survey methods to match the equipment used was crucial to successfully capture geomorphic changes within a SfM photogrammetric framework (as reported by Marteau et al. 2016).

5.6.2.2. Monitoring in the River Ehen

The full assessment of mobility patterns was constrained by the fact that the coarsest seeded tracers moved in 2 of the 3 morphological units. The use of D_{max} is common practice in the literature (e.g. Lobera et al. 2017), although some authors have used other percentiles (e.g. Petit et al. 2005). The use of D_{84} when we could not justify the use of D_{max} yielded a poorer fit but an equation that matched those found in the literature. In the absence of better data, this approach is estimated as appropriate when the purpose remains of studying patterns within the same river. Extrapolating such results elsewhere is not recommended.

Capturing topographic changes in the Ehen remained limited to a series of 4 transects. Although channel geometry was relatively simple at the beginning of the study, it is acknowledged that changes may have been missed or overestimated. Nevertheless, the results presented here are coherent with what was observed on site throughout the study.

The use of the χ^2 homogeneity test for assessing changes in GSD was successful in detecting differences where other tests, such as the comparison of usual statistics (D_{50} , sorting, skewness, etc.) failed. Similarly, the application of LR models to data on particle mobility in relation to the relative ω_e proved to be helpful in interpreting changes in particle mobility. These tools are not commonly used in fluvial geomorphology but may provide important insights in some situations; for instance, when the upper but not lower bounds of the response in a dependent variable (e.g. sediment transport rate) is influenced by values of an independent variable (e.g. hydraulic variable). In the present study, the LR models allowed statistically robust interpretation of the relation between mobilised particle size and stream power.

5.7. FINAL REMARKS

Small sub-catchments can be significant sediment sources to main-stem systems (Rice 1998). Ben Gill has proven to be a non-negligible source of fine material, with suspended sediment load having increased by 65% after reconnection (Marteau et al. 2017b) and, as shown here, exerts an important control on coarse sediment supply and dynamics. Within the adjustment phase, effects of this renewed sedimentary activity in downstream reaches of the Ehen remain limited to localised deposition and scour in morphological units that are close to the confluence and where flow hydraulics are most diverse. The bed presents signs of increased mobility, with bedload (particularly the finer fraction) carried downstream as a sediment carpet and

overpassing the stable paved layer of coarser material. It is likely that more time is needed for the coarse sediment supplied by Ben Gill to disperse further downstream and interact with the pavement; this may be considered a point at which the river will reach its new equilibrium state. However, the pearl mussel might benefit from this rather slow process, since it can be sensitive to abrupt changes in habitat and excessive disturbance of the riverbed. Further monitoring of the speed and the extent at which the Ehen recovers, along with surveys of mussel juveniles, will be necessary to ensure that these early signs of improvement are turned into a restoration success.

5.8. REFERENCE LIST

- AgiSoft LLC (2015). Agisoft PhotoScan Professional Edition. Version 1.2.3.
- Andrews ED (1983). Entrainment of gravel from naturally sorted riverbed material. *Geological Society of America Bulletin* 91:1225–1231
- Arnaud F, Piégay H, Béal D, Collery P, Vaudor L, Rollet AJ (2017). Monitoring gravel augmentation in a large regulated river and implications for process-based restoration. *Earth Surface Processes and Landforms* 42:2147–2166
- Bagnold RA (1966). An Approach to the Sediment Transport Problem from General Physics. USGS Professional Paper 422-I
- Bagnold RA (1980). An Empirical Correlation of Bedload Transport Rates in Flumes and Natural Rivers. *Proceedings of the Royal Society of London A Mathematical and Physical Sciences* 372:453–473
- Batalla RJ, Vericat D (2011). A review of sediment quantity issues: examples from the River Ebro and adjacent basins (Northeastern Spain). *Integrated environmental assessment and management* 7:256–68
- Bradshaw AD (1996). Underlying principles of restoration. *Canadian Journal of Fisheries and Aquatic Sciences* 53:3–9
- Brasington J, Langham J, Rumsby B (2003). Methodological sensitivity of morphometric estimates of coarse fluvial sediment transport. *Geomorphology* 53:299–316
- Brasington J, Rumsby BT, McVey RA (2000). Monitoring and modelling morphological change in a braided gravel-bed river using high resolution GPS-based survey. *Earth Surface Processes and Landforms* 25:973–990
- Brasington J, Vericat D, Rychkov I (2012). Modeling river bed morphology, roughness, and surface sedimentology using high resolution terrestrial laser scanning. *Water Resources Research* 48:1–18
- Brown D, Butterill G, Bayliss B (2008). Ben Ghyll Geomorphology report. Environment Agency, Version 2.0, Penrith, Cumbria
- Buendía C, Bussi G, Tuset J, Vericat D, Sabater S, Palau A, Batalla RJ (2016). Effects of afforestation on runoff and sediment load in an upland Mediterranean catchment. *Science of the Total Environment* 540:144–157
- Buffington JM, Montgomery DR (1999). Effects of sediment supply on surface textures of gravel-bed rivers. *Water Resources Research* 35:3523–3530
- Bunte K (2004). Gravel Mitigation and Augmentation Below Hydroelectric Dams: A Geomorphological Perspective. *Report to the Stream Systems Technology Center, Fort Collins, CO*
- Bunte K, Abt SR (2001). Sampling surface and subsurface particle-size distributions in wadable gravel- and cobble-bed streams for analyses in sediment transport, hydraulics, and streambed. Gen. Tech. Rep. RMRS-GTR-74. Fort Collins, CO: U.S.D.A., Forest Service, Rocky Mountain Research Station

- Church M (1995). Geomorphic Response to River Flow Regulation - Case-Studies and Time-Scales. *Regulated Rivers-Research & Management* 11:3–22
- Clilverd HM, Thompson JR, Heppell CM, Sayer CD, Axmacher JC (2013). River–floodplain hydrology of an embanked lowland Chalk river and initial response to embankment removal. *Hydrological Sciences Journal* 58:627–650
- Costa JE (1983). Paleohydraulic reconstruction of flash-flood peaks from boulder deposits in the Colorado Front Range. *Geological Society of America Bulletin* 94:986–1004
- Csiki S, Rhoads BL (2010). Hydraulic and geomorphological effects of run-of-river dams. *Progress in Physical Geography* 34:755–780
- Dietrich WE, Kirchner JW, Ikeda H, Iseya F (1989). Sediment supply and the development of the coarse surface layer in gravel-bedded rivers. *Nature* 340:215–217
- England J, Skinner KS, Carter MG (2008). Monitoring, river restoration and the Water Framework Directive. *Water and Environment Journal* 22:227–234
- Ferguson RI (2005). Estimating critical stream power for bedload transport calculations in gravel-bed rivers. *Geomorphology* 70:33–41
- Ferguson RI, Cudden JR, Hoey TB, Rice SP (2006). River system discontinuities due to lateral inputs: Generic styles and controls. *Earth Surface Processes and Landforms* 31:1149–1166
- Gaeuman D (2012). Mitigating downstream effects of dams. In: Church M, Roy AG, Biron PM (eds) *Gravel-bed Rivers: Processes, Tools, Environments*. John Wiley & Sons, Ltd., Chichester, UK,
- Habersack H, Piégay H (2008). River restoration in the Alps and their surroundings: past experience and future challenges. In: Habersack H, Piégay H, Rinaldi M (eds) *Gravel-Bed Rivers VI: From Process Understanding to River Restoration*. Elsevier, pp 703–735
- Hardy T, Panja P, Mathias D (2005). WinXSPRO, A Channel Cross Section Analyzer, User's Manual, Version 3.0. *Gen Tech Rep RMRSGTR147*
- Harvey B, McBain S, Reiser D, Rempel L, Sklar L (2005). Key Uncertainties in Gravel Augmentation: Geomorphological and Biological Research Needs for Effective River Restoration.
- Hassan MA, Zimmermann AE (2012). Channel response and recovery to changes in sediment supply. In: Church M, Biron PM, Roy AG (eds) *Gravel-bed Rivers: Processes, Tools, Environments*. John Wiley & Sons, Ltd., Chichester, UK, pp 464–473
- Hillman M, Brierley G (2005). A critical review of catchment-scale stream rehabilitation programmes. *Progress in Physical Geography* 29:50–76
- Houbrechts G, Van Campenhout J, Levecq Y, Hallot E, Peeters A, Petit F (2012). Comparison of methods for quantifying active layer dynamics and bedload discharge in armoured gravel-bed rivers. *Earth Surface Processes and Landforms* 37:1501–1517
- Irstea (2015). Technical note about the monitoring of hydromorphological restoration of the Upper Drac River (Hautes-Alpes, France). Grenoble, France
- Johnson MF, Reid I, Rice SP, Wood PJ (2009). Stabilization of fine gravels by net-spinning caddisfly larvae. *Earth Surface Processes and Landforms* 34:413–423

- Killeen I, Moorkens E (2013). Environmental Monitoring of the River Ehen freshwater pearl mussel population 2012: A report to United Utilities. Malacological Services, Dublin
- Killeen I, Oliver G (1997). The Freshwater Pearl Mussel (*Margaritifera margaritifera* [L. 1758]) in the River Ehen. Part 1. Report on 1996 Survey. Department of Zoology, National Museum of Wales, Cardiff: 24p.
- Koll K, Koll K, Dittrich A (2010). Sediment transport over static armour layers and its impact on bed stability. *International River Flow Conference - Braunschweig* 929–936
- Kondolf GM (1994). Geomorphic and environmental effects of instream gravel mining. *Landscape and Urban Planning* 28:225–243
- Kondolf GM (1997). Hungry Water: Effects of Dams and Gravel Mining on River Channels. *Environmental Management* 21:533–551
- Kondolf GM, Gao Y, Annandale GW, Morris Gregory L, Jiang E, Zhang J, Yongtao C, Carling P, Fu K, Guo Q, Hotchkiss R, Peteuil C, Sumi T, Wang H-W, Wang Z, Wei Z, Wu B, Wu C, Yang CT (2014). Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents. *Earth's Future* 2:256–280
- Kondolf GM, Podolak K, Grantham TE (2012). Restoring mediterranean-climate rivers. *Hydrobiologia* 719:527–545
- Lane SN (2000). The measurement of river channel morphology using digital photogrammetry. *Photogrammetric Record* 16:937–961
- Lane SN, Westaway RM, Hicks DM (2003). Estimation of erosion and deposition volumes in a large, gravel-bed, braided river using synoptic remote sensing. *Earth Surface Processes and Landforms* 28:249–271
- Lisle TE, Cui Y, Parker G, Pizzuto JE, Dodd AM (2001). The dominance of dispersion in the evolution of bed material waves in gravel-bed rivers. *Earth Surface Processes and Landforms* 26:1409–1420
- Lisle TE, Iseya F, Ikeda H (1993). Response of a channel with alternate bars to a decrease in supply of mixed-size bed load: A flume experiment. *Water Resources Research* 29:3623–3629
- Lisle TE, Madej MA (1992). Spatial variation in armouring in a channel with high sediment supply. In: Billi P, Hey RD, Thorne CR, Tacconi (eds) *Dynamics of Gravel-bed Rivers*. John Wiley & Sons, Ltd, Chichester, UK, pp 277–293
- Lisle TE, Nelson JM, Pitlick J, Madej MA, Barkett BL (2000). Variability of bed mobility in natural, gravel-bed channels and adjustments to sediment load at local and reach scales. *Water Resources Research* 36:3743–3755
- Lobera G, Andrés-Domenech I, López-Tarazón JA, Millán-Romero P, Vallés-Morán F, Vericat D, Batalla RJ (2017). Bed disturbance below dams: observations from two Mediterranean rivers. *Land Degradation and Development* 28:2493–2512
- Marteau B, Batalla RJ, Vericat D, Gibbins C (2017a). Asynchronicity of fine sediment supply and its effects on transport and storage in a regulated river. *Journal of Soils and Sediments*. doi: [in press]
- Marteau B, Batalla RJ, Vericat D, Gibbins CN (2017b). The importance of a small ephemeral

- tributary for suspended sediment dynamics in a main-stem river. *River Research and Applications* 33:1564–1574
- Marteau B, Vericat D, Gibbins C, Batalla RJ, Green DR (2016). Application of Structure-from-Motion photogrammetry to river restoration. *Earth Surface Processes and Landforms* 42:503–515
- Nelson PA, Venditti JG, Dietrich WE, Kirchner JW, Ikeda H, Iseya F, Sklar LS (2009). Response of bed surface patchiness to reductions in sediment supply. *Journal of Geophysical Research: Earth Surface* 114:1–18
- O’Leary D (2013). Pearls in Peril LIFE+ GB - Action A3: Conservation Actions for the Freshwater Pearl Mussel in the River Ehen, Cumbria. Report LIFE 11 NAT/UK/383. West Cumbria River Trust, UK: 45p.
- Parker C, Clifford NJ, Thorne CR (2011). Understanding the influence of slope on the threshold of coarse grain motion: Revisiting critical stream power. *Geomorphology* 126:51–65
- Parker G, Dhamotharan S, Stefan H (1982a). Model experiments on mobile, paved gravel-bed streams. *Water Resources Research* 18:1395–1408
- Parker G, Klingeman PC, McLean DG (1982b). Bedload and size distribution in paved gravel-bed streams. In: *Paved Gravel-Bed Streams*. pp 544–571
- Pasternack GB (2008). Spawning habitat rehabilitation: Advances in analysis tools. In: Sear DA, DeVries P, Greig S (eds) *Salmonid spawning habitat in rivers: physical controls, biological responses, and approaches to remediation. Symposium 65, American Fisheries Society*. Bethesda, MD, pp 321–348
- Pasternack GB, Wang CL, Merz JE (2004). Application of a 2D hydrodynamic model to design of reach-scale spawning gravel replenishment on the Mokelumne River, California. *River Research and Applications* 20:205–225
- Petit F, Gob F, Houbrechts G, Assani AA (2005). Critical specific stream power in gravel-bed rivers. *Geomorphology* 69:92–101
- Petts GE (1987). Time Scales for Ecological Change in Regulated Rivers. In: Craig JF, Kemper JB (eds) *Regulated Streams - Advances in Ecology*. Plenum Press, New York, NY, pp 257–266
- Petts GE, Gurnell AM (2005). Dams and geomorphology: Research progress and future directions. *Geomorphology* 71:27–47
- Piqué G, Vericat D, Sabater S, Batalla RJ (2016). Effects of biofilm on river-bed scour. *Science of the Total Environment* 572:1033–1046
- Pitlick J, Wilcock P (2001). Relations Between Streamflow, Sediment Transport, and Aquatic Habitat in Regulated Rivers. *Water Science and Application* 4:185–198
- Quinlan E (2014). Ecogeomorphological dynamics of the River Ehen prior to its restoration. PhD thesis, University of Aberdeen, Scotland
- Quinlan E, Gibbins CN, Batalla RJ, Vericat D (2015). Impacts of Small Scale Flow Regulation on Sediment Dynamics in an Ecologically Important Upland River. *Environmental Management* 55:671–686
- R Core Team (2017). R: A language and environment for statistical computing. R Foundation for

Statistical Computing, Vienna, Austria

- Rice S (1998). Which tributaries disrupt downstream fining along gravel-bed rivers? *Geomorphology* 22:39–56
- Scheibelhofer O, Besenhard MO, Piller M, Khinast JG (2016). Comparing particle size distributions of an arbitrary shape. *Powder Technology* 294:134–145
- Sear DA (1995). Morphological and sedimentological changes in a gravel-bed river following 12 years of flow regulation for hydropower. *Regulated Rivers: Research & Management* 10:247–264
- Sklar LS, Fadde J, Venditti JG, Nelson P, Aleksandra Wydzga M, Cui Y, Dietrich WE (2009). Translation and dispersion of sediment pulses in flume experiments simulating gravel augmentation below dams. *Water Resources Research* 45:1–14
- Smith B, Clifford NJ, Mant J (2014). The changing nature of river restoration. *WIREs Water* 1:249–261
- Sutherland AJ (1987). Static armour layers by selective erosion. In: Thorne CR, Bathurst JC, Hey RD (eds) *Sediment Transfer in Gravel-Bed Rivers*. John Wiley & Sons, New York, Chichester, UK, pp 243–260
- Tena A, Batalla RJ, Vericat D (2012). Reach-scale suspended sediment balance downstream from dams in a large Mediterranean river. *Hydrological Sciences Journal* 57:831–849
- United Utilities (2012). Hydrodynamic and Sediment Transport Modelling Report - Project Name: Ennerdale and Ben Gill - Project No: 80020012.
- Venditti JG, Dietrich WE, Nelson PA, Wydzga MA, Fadde J, Sklar L (2010). Effect of sediment pulse grain size on sediment transport rates and bed mobility in gravel bed rivers. *Journal of Geophysical Research: Earth Surface* 115:1–19
- Vericat D, Batalla RJ, Garcia C (2006). Breakup and reestablishment of the armour layer in a large gravel-bed river below dams: The lower Ebro. *Geomorphology* 76:122–136
- Vericat D, Wheaton JM, Brasington J (2017). Revisiting the morphological approach: opportunities and challenges with repeat high resolution topography. In: Tsustumi D, Laronne JB (eds) *Gravel-Bed Rivers: Processes and Disasters*. Wiley, Tokyo, Japan, pp 121–158
- Westaway RM, Lane SN, Hicks DM (2000). The development of an automated correction procedure for digital photogrammetry for the study of wide, shallow, gravel-bed rivers. *Earth Surface Processes and Landforms* 25:209–226
- Westaway RM, Lane SN, Hicks MD (2001). Remote Sensing of Clear-Water, Shallow, Gravel-Bed Rivers Using Digital Photogrammetry. *Photogrammetric Engineering & Remote Sensing* 67:1271–1281
- Wheaton JM, Brasington J, Darby SE, Sear DA (2010). Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets. *Earth Surface Processes and Landforms* 35:136–156
- Wheaton JM, Pasternack GB, Merz JE (2004). Spawning habitat rehabilitation -I. Conceptual approach and methods. *International Journal of River Basin Management* 2:3–20

- Williams GP (1983). Paleohydrological methods and some examples from Swedish fluvial environments. I. Cobble and boulder deposits. *Geografiska Annaler Series A, Physical Geography* 65:227–243
- Williams GP, Wolman MG (1984). Downstream effects of dams on alluvial rivers. *US Geological Survey Professional paper* 1286:94
- Wolman MG (1954). A method of sampling coarse river-bed material. *Transactions, American Geophysical Union* 35:951–956
- Woodget AS, Carbonneau PE, Visser F, Maddock IP (2014). Quantifying submerged fluvial topography using hyperspatial resolution UAS imagery and structure from motion photogrammetry. *Earth Surface Processes and Landforms* 64:47–64
- Xu J (1996). Underlying gravel layers in a large sand bed river and their influence on downstream-dam channel adjustment. *Geomorphology* 17:351–359
- Yarnell SM, Mount JF, Larsen EW (2006). The influence of relative sediment supply on riverine habitat heterogeneity. *Geomorphology* 80:310–324

CHAPTER 6.

THE ECOLOGICAL CONSEQUENCES OF FLOW REGULATION IN THE EHEN: FLOW COMPETENCE, BED DISTURBANCE AND IMPLICATIONS FOR THE INTERACTION BETWEEN PRIMARY PRODUCERS AND GRAZERS

Baptiste Marteau, Chris Gibbins, Damià Vericat and Ramon J. Batalla.



*Adult mayfly from Croasdale Beck (left) | Juvenile freshwater pearl mussel from the River Ehen (right).
Photos: Baptiste Marteau, April 2016 (left) | May 2015 (right).*

A version of this paper will be submitted to *Freshwater Biology*, and will be co-authored by collaborators M. Kelly (Bowburn Consultancy), M. Snell (University of Lancaster) and B. Surridge (Lancaster Environmental Centre)

CHAPTER 6. THE ECOLOGICAL CONSEQUENCES OF FLOW REGULATION IN THE EHEN: FLOW COMPETENCE, BED DISTURBANCE AND IMPLICATIONS FOR THE INTERACTION BETWEEN PRIMARY PRODUCERS AND GRAZERS

6.1. ABSTRACT

Freshwater pearl mussels have demanding water quality requirements, and particularly for well-oxygenated interstitial water. Several factors may induce decrease in interstitial oxygen levels, including the clogging by fine sediment and the oxygen consumption of bacteria when degrading organic matter. The presence of algae may exacerbate these factors, hence impacting habitat suitability for pearl mussels. Such concerns have triggered the launch of routine monitoring of algal biomass and community composition in the River Ehen, which hosts the largest remaining population of freshwater pearl mussels in England. In parallel, work was carried out to understand the factors influencing algae, including flow competence, bed disturbance and water chemistry. The consequences of these factors on the interaction between algae and invertebrate grazers was also analysed. To do so, monthly samples were collected in the Ehen and a neighbouring unregulated and more dynamic stream. The results indicated that temperature/season was the strongest control on algae. Flow competence was responsible for most of the variation once seasonal factors were accounted for in the analysis. Ordination analyses revealed that the two rivers have different macroinvertebrate assemblages, which can be partly explained by the relative abundance of different feeding groups. Generalised Estimation Equations (GEEs) provided some evidence that grazers may have a subtle influence on algal biomass, but apparent effects depended on how grazers were represented in the models (e.g. total or relative abundance, all potential grazers or obligate grazers). It is suggested that the large floods experienced during the study had important effect on both algal and macroinvertebrate communities. However, the main differences between the two rivers are driven by bed disturbance and flow competence, which are limited in the Ehen due to river regulation and the diversion of its headwater tributary.

Key words: bed disturbance, flow competence, macroinvertebrate grazers, algal biomass, River Ehen.

6.2. INTRODUCTION

The natural functioning of rivers reflects the working of riverbed sediments by natural disturbances (e.g. flow variations) within imposed boundary conditions (i.e. valley settings, geology, climate, etc.) both of which dictate the diversity and distribution of biota. Periodic and episodic disturbance by hydrologic variability is important for the sustainability of rivers and their functions (Baron et al. 2002). Human alterations of river systems have many forms (e.g. damming, dredging, in-channel mining, abstraction) and strongly affect the physical conditions of rivers (Kondolf 1997). Consequences of the physical alteration of rivers, and particularly river regulation, affects all aspects of their ecology (e.g. invertebrates, Boon 1988; algae, Marks et al. 2000; fish, Allan and Castillo 2007) including processes and feedbacks (length of the food-chain, Wootton et al. 1996; food-web transfer of energy, Parker and Power 1997; nutrient processing, Abril et al. 2015). In turn, altered ecology and processes may worsen the physical conditions of rivers (e.g. Johnson et al. 2009 and references therein).

Higher rates of algal growth and accumulation are found in impounded systems (Lobera et al. 2016; Piqué et al. 2016), with increased bed stability and the regulation of flows have been cited as causes (Clausen and Biggs 1997). The distribution and persistence of algae is partly a consequence of the magnitude and frequency of sediment transport (Ponsatí et al. 2015) and associated bed disturbance (Piqué et al. 2016). The development and persistence of algae can contribute to further stabilisation of the riverbed (Ponsatí et al. 2015; Piqué et al. 2016). While benthic algae may be influenced by both flow velocity and bed disturbance, these two things are not always well correlated (Townsend et al. 1997a). And because algae sit at the base of river food-webs, alteration of algal abundance and diversity can affect the entire trophic structure of the system (Wootton et al. 1996; Parker and Power 1997).

Numerous experiments and field observations have revealed the strong control exerted by invertebrate grazers on the distribution and abundance of stream algae (Feminella and Hawkins 1995; Steinman 1996; Lange et al. 2011). Grazing by invertebrates is selective and reflects the structure of their mouthparts and the relative accessibility of species on which they can feed (De Nicola et al. 1990; Lawrence et al. 2002). Thus, although total algal biomass generally decreases in the presence of grazers (Feminella and Hawkins 1995; Steinman 1996), they can also control the abundance of a dominant taxa with the indirect effect of promoting an increase in biomass of other species within the algal community (Steinman 1996; Liess and Hillebrand 2004). Abundance of algae can also be affected by physical disturbances (Peterson 1996; Passy

2007) and flow velocity (Biggs et al. 1998; Opsahl et al. 2003). However, velocity has also been shown to affect the behaviour of grazers (Poff and Ward 1992; Palmer 1995). Effects of velocity on grazers can be direct (e.g. shear stress) or indirect (e.g. altered presence of predators). For instance, fast currents may cause heavy case-bearing animals (e.g. caddisfly *Glossosoma*) or vulnerable species (e.g. mayfly *Baetis*) to be less capable of accessing some food resources (Poff and Ward 1992; Peckarsky 1996). Interactions between primary producers and their consumers are complex (Lamberti et al. 2007), and changes in these interactions may also affect other organisms that are not directly part of this trophic food-chain.

Kelly et al. (2015) investigated the composition and abundance of benthic algal communities in the upper River Ehen (NW England). This river is of ecological importance due to the presence of the largest remaining population of the endangered freshwater pearl mussel (*M. margaritifera* L.) in England. Adults are regularly found in breeding condition in the river (Environment Agency 2014) and in relatively large numbers (Killeen 2006) but the population is threatened by poor recruitment and a lack of juveniles (Killeen and Moorkens 2013). This was thought to be caused by the poor quality of hydraulic and sedimentary habitat for mussels themselves (Quinlan et al. 2015), as well as their host - the Atlantic salmon (*Salmo salar* L., O'Leary 2013). Additionally, pearl mussels require high water quality, and particularly well-oxygenated interstitial water (Young 2005). Decreases in interstitial oxygen levels can be caused by the physical clogging of pore spaces (e.g. by fine sediment accumulation or the presence of an algal mat, Greig et al. 2007; Sear et al. 2016) and the biological processes associated with the degradation of organic compounds (i.e. higher biological oxygen demand, Greig et al. 2007). Issues associated with excessive algal biomass on pearl mussel beds in the Ehen, such as the clogging of interstitial pores by decaying organic matter (Kelly 2013), has raised concerns over the observed high algal biomass in recent years (Kelly et al. 2015).

Their conclusions were twofold. First, the composition of both the diatom and non-diatom components of the community were consistent with 'high ecological status', as stated by the European Water Framework Directive (WFD, European Union 2000). Second, algae appear to be present in excess for at least part of the year (the winter period), with maximum values comparable to local rivers with considerably higher levels of nutrients (Kelly et al. 2015). They also hypothesised that the unexpected seasonal variations suggest top-down control by invertebrate grazers, controlling biofilm growth in the summer (i.e. highest period of production) and allowing biomass to increase in late autumn when grazing pressure is reduced

(e.g. Underwood and Kromkamp 1999). However, variations could also be caused by the alteration of the flow regime (i.e. regulation by Ennerdale Water and its associated weir) and the lack of mobility of the riverbed (Chapter 5) and high degree of compactness (Quinlan et al. 2015) which potentially limit the scour and allow for longer periods of accrual (as hypothesised by Kelly et al. 2015).

The aim of this study is to test some of the hypotheses regarding the influence of flow competence, bed disturbance and invertebrate grazing pressure on biofilm abundance in the Ehen put forward by Kelly et al. (2015). It compares two sites in the Ehen with two in the neighbouring but unregulated Croasdale Beck, where parallel data were collected at monthly intervals over a 13-month period. The objectives of this chapter are: (i) to characterise the macro-invertebrate and benthic biofilm assemblages in both rivers, and (ii) to explore potential physical and ecological controls on algal biomass. Water chemistry is also important for algal growth, so data on some basic chemical determinants were also collected and used in the analyses. However, as a detailed analysis of relations between water chemistry and algae (especially the importance of short-lived 'pulses' of nutrients delivered to the river) is being undertaken by the Environment Agency, this chapter focuses mainly on the role of other factors.

The algal data used in this chapter were collected by Dr. Martyn Kelly (Bowburn consultancy), Dr. Maria Snell (University of Lancaster) and Dr. Ben SurrIDGE (Lancaster Environmental Centre) as part of their routine long-term monitoring of the Ehen. They kindly agreed to add the two Croasdale Beck sites to their surveys for the 13-month period of the present study and shared the data in order to permit the analysis presented here. They have not been involved at all in preparation of this chapter, although we have plans for a joint publication that will be based on the main results.

6.3. METHODS

6.3.1. Study area

The River Ehen drains a total catchment of 155.8 km², with the upper part of the catchment mainly represented by the River Liza and Ennerdale Water (Figure 6.1) and the lower part flowing through arable land to the Irish Sea. This study focuses on the upper Ehen, i.e. the first few kilometres downstream from the lake, where mussels were historically abundant. In order

to better understand algal and invertebrate composition as well as hydraulic conditions in the Ehen, a neighbouring stream, Croasdale Beck, was chosen as a comparison site. Croasdale Beck is a free-flowing tributary of the Ehen (it joins the Ehen downstream from Ennerdale Bridge). At their confluence, the Ehen has a catchment area of 47 km² while Croasdale has an area of 7.9 km². The two rivers differ in channel width (Ehen: 10 to 15 m, Croasdale Beck: 5 to 7 m) and mean slope (Ehen: 0.001 to 0.005 m m⁻¹; Croasdale: 0.015 to 0.026 m m⁻¹). Croasdale was chosen to provide a marked contrast to the Ehen: it was hoped that these different gradients would lead to very different hydraulic conditions and levels of bed stability that potentially would affect algal biomass.

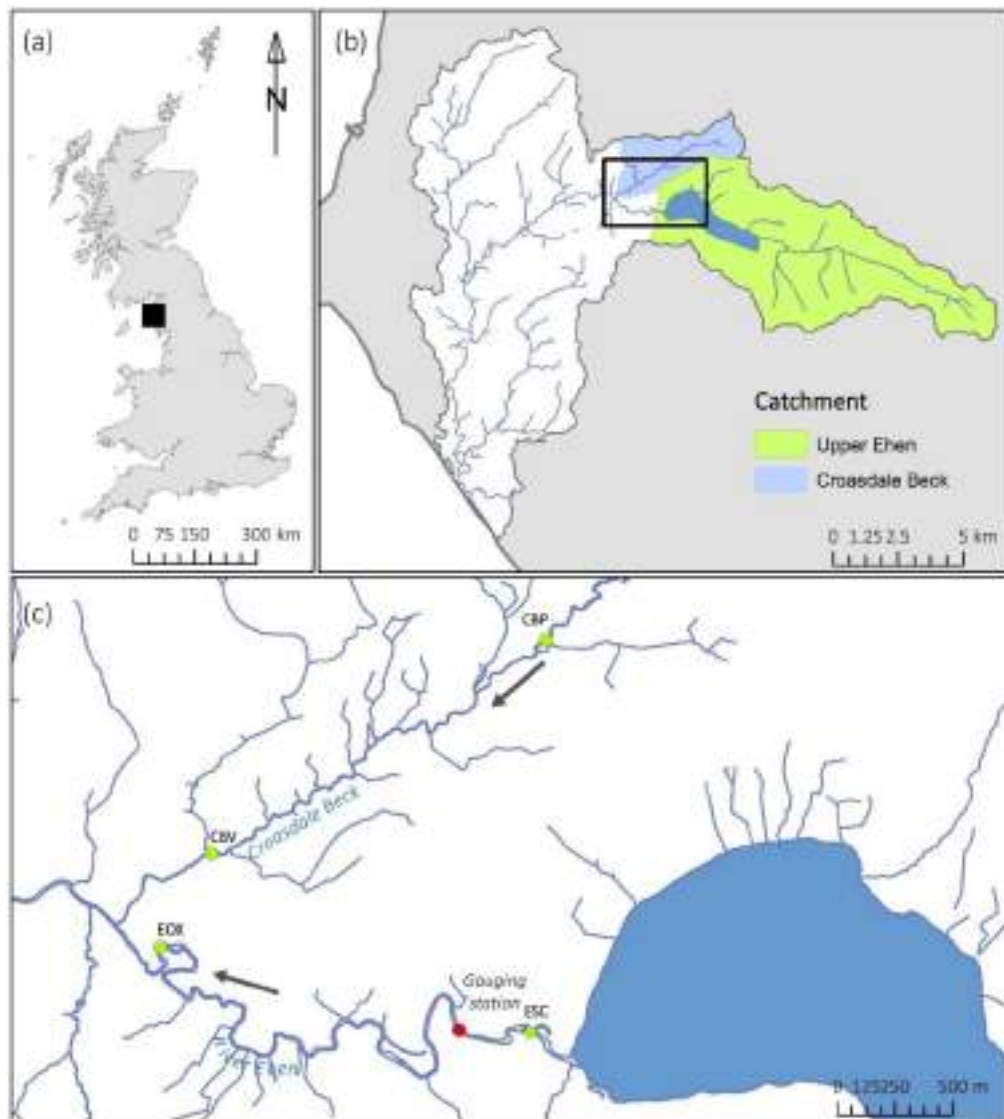


Figure 6.1. Map of location of the study sites. (a) Location of the Ehen catchment within the United Kingdom. (b) The Ehen catchment. The rectangle shows location of (c). (c) Location of the study sites, on the River Ehen and Croasdale Beck.

The upper part of the Ehen catchment drains through Silurian igneous rock similar to granite (i.e. Ennerdale Granophyre) while the western area is underlain by rock of the Skiddaw group, argillaceous rocks from the Ordovician age (Brown et al. 2008). Details of the nutrient status of Ennerdale Water and the Ehen can be found in Kelly et al. (2015). In short, Ennerdale Water suffered from slight acidification during the 20th century but pH remained higher than comparable lakes in the country, with little risks of further acidification. Additionally, although no formal classification was carried out, the upper Ehen would classify as oligotrophic and is most likely to be phosphorus-limited, rather than limited by nitrogen (Kelly et al. 2015).

Croasdale Beck drains a catchment composed of argillaceous sedimentary rocks covered by a mix of pastures, meadows and arable lands. Although it is more agricultural than the upper Ehen, the main difference in water quality resides in the higher alkalinity and conductivity resulting from the difference in geology. Limited pre-study data existed on water chemistry for Croasdale Beck partly due to the absence of strong human alteration over the course of the stream which limited the need for monitoring or assessment.

6.3.2. Sampling design

Samples of algae, invertebrates and water were collected on a monthly basis for 13 months (May 2015 – May 2016). All samples were collected on the same day when possible, with no more than a 2-day difference between macroinvertebrate and algal sampling. Scheduled samples dates sometimes had to be changed due to high flows, so sample intervals are not always identical.

6.3.2.1. Sampling locations

Samples were collected from paired sites on each river; the Scoutcamp (ESC) and Oxbow (EOX) in the River Ehen, and upstream (CBP) and downstream (CBV) sites in Croasdale (Figure 6.1). ESC was located approx. 300m downstream from the lake outlet, and is characterised by a rather uniform morphology and slow-flowing water (Table 6.1). EOX was located approx. 4 km from the lake, in a fast-flowing bend characterised by coarser material and higher mussel densities, and with both banks shaded by trees. CBP was located 0.5 km upstream from the confluence of Croasdale Beck with the Ehen. The section was generally rather straight although samples were collected at a point with a meander and associated pool-riffle morphology. CBV was 2.5 km upstream from the confluence and was more diverse, with a rapid succession of

fast and slower-flowing sections. Croasdale, rather than upstream of Ennerdale Water, was used as a reference due to the inaccessibility of the latter, but also because it allowed for paired sites at matching altitude and surrounding land use.

6.3.2.2. Discharge and flow hydraulics

The Ehen is gauged by the Environment Agency at Bleach Green (Figure 6.1) and records discharge at 15-min intervals. Catchment area at the gauging station is 44.5 km². Discharge in Croasdale Beck was recorded using a mini-diver® (VanWalt Technologies) located at CBV (Figure 6.1). Records of water pressure were corrected for air pressure and used to compute water levels at 15-min interval. Then, based on an empirical water level-discharge rating curve ($n=5$) and survey of local topography, a 1D hydraulic model was used to determine discharge at 15-min intervals for the entire study period.

The two sampling sites in the Ehen are only a few kilometres apart and with only a small increase in catchment area between the two, so discharge was not corrected for the relative difference in catchment size. Discharge at the upper site in Croasdale Beck (CBP) however was estimated based on relative catchment size compared to the downstream gauged site (CBV), as in relative terms catchment area increased appreciably between the two.

Time-series of discharge were used to compute several metrics of hydrological conditions over the 10-day period prior to sampling, i.e. maximum discharge (Q_{max}), mean discharge (Q_{mean}), number of flow events (nQ_p) and number of days since last event ($ndays$).

Flow competence was estimated using unit stream power, which was calculated for each site using Bagnold's (1966) formula:

$$\omega = \frac{\rho_w \cdot g \cdot Q \cdot S}{w} \quad (6.1)$$

where ω is stream power (W m⁻²), ρ_w is the density of water (kg m⁻³), g is the gravitational acceleration (m s⁻²), Q is discharge (m³ s⁻¹), S is local slope (m m⁻¹) and w is channel width at bankfull discharge. The term "unit" refers to the fact that ω is defined as the average over the width of the channel w . Using this Q - ω relationship, discharge data were used to compute time-series of ω at 15-min intervals. This allowed for the calculation, within the 10 days prior to each sampling occasions, of maximum unit stream power (ω_{max}) and unit excess of stream power (ω_e , Hassan and Zimmermann 2012). This metric represents the amount of energy experienced by the river over which ω was high enough to initiate entrainment of a given particle size. This

limit (i.e. critical stream power, ω_{ci}) can be determined using empirically-derived equations, mostly stemming from the work of Bagnold (1966, 1980). Ferguson (2005) proposes a reformulation of Bagnold's equation that allows the calculation of unit ω_{ci} without the need for critical water height:

$$\omega_{ci} = \tau_{ci} \cdot \left[\log \left(\frac{12 \cdot (\tau_{ci} / (\rho_w \cdot g \cdot S))}{D_i} \right) \right] \cdot \sqrt{\frac{\tau_{ci}}{\rho_w}} \cdot \frac{1}{w} \quad (6.2)$$

where ω_{ci} is unit critical stream power (W m^{-2}), τ_{ci} is critical shear stress ($\text{N kg}^{-1} \text{s}^{-1}$), ρ_w is the density of water (kg m^{-3}), g is the gravitational acceleration (m s^{-2}), S is local slope (m m^{-1}), D_i is particle size of interest (e.g. D_{50} , m) and w is channel width at bankfull (m). Critical shear stress can be determined from the Shield's [1936] equation:

$$\tau_{ci} = \theta_{ci} \cdot (\rho_s - \rho_w) \cdot g \cdot d_i \quad (6.3)$$

The dimensionless Shield criterion θ_{ci} varies appreciably depending on the type of river (Buffington and Montgomery 1997) but can be approximated based on local slope (Parker et al. 2011):

$$\theta_{ci} = 0.19 \cdot S^{0.28} \quad (6.4)$$

Finally, ω_e can be calculated as the sum, at 15-min interval, of $\omega - \omega_{ci}$ when $\omega > \omega_{ci}$.

6.3.3. Water chemistry

Water samples were collected from each site at the same time as invertebrates and used for chemical analysis. Dissolved oxygen (DO), conductivity (σ), pH and temperature were measured directly in the field on each date. Gran alkalinity was measured in the lab within a few days, from unfiltered water samples stored in a cool-box. Additionally, water was tested for nutrients - reactive orthophosphate (PO₄-P), reactive nitrate and nitrite (NO_x), and total organic carbon (TOC). Analyses were performed on unfiltered water, so the nutrient fractions are, technically, "reactive nutrients" rather than "soluble reactive nutrients". Samples were stored in a cool-box on site and frozen within a couple of hours, to be analysed together at the end of the study.

6.3.4. Bed disturbance

Bed surface grain size distribution (GSD) was assessed using the Wolman pebble count method (Wolman 1954) on one occasion. Two-hundred particles were collected and measured (for b -axis) in CBV and CBP, and 300 particles in ESC. No data was collected in EOX, as data were

already available from Moir et al. (2003) who performed series of GSD surveys throughout the entire River Ehen, using the same method. GSDs were simply used to compute the statistics (i.e. D_{50} , D_{70} and D_{90}) necessary to calculate metrics of bed disturbance at each of the sites.

Bed disturbance was assessed directly by means of painted tracers. Each site was seeded with 6 rows of 7 to 8 tracers, encompassing the whole range of clasts found from their respective GSD surveys. The movement of tracers was recorded on successive resurveys, and displaced particles were replaced. Bed movement was calculated based on particles coarser than the D_{50} of the site that had moved (Townsend et al. 1997b) and used as a metric of bed disturbance. Tracers have been used successfully in the past in this way (e.g. Death and Winterbourn 1994; Death and Zimmermann 2005; Schwendel et al. 2011; Lobera et al. 2016). Only the ‘intensity’ of disturbance was quantified using tracer data as it has been found to be highly correlated to other metrics of bed disturbance (e.g. frequency, magnitude; Townsend et al. 1997a).

Intensity of bed disturbance can be quantified using the total of tracer movement (TTM) approach from Schwendel et al. (2012), which they calculate as:

$$TTM = \left(D_{50} \cdot \frac{s_{50}}{n_{50}} + D_{70} \cdot \frac{s_{70}}{n_{70}} + D_{90} \cdot \frac{s_{90}}{n_{90}} \right) / (D_{50} + D_{70} + D_{90}) \quad (6.5)$$

where s_i is the sum of the moved distance of a size class, n_i is the number of stones recovered of that class and D_i is the geometric mean particle size of that class. Here, total distance of movement was not recorded but particle displacement was simply classified as (0) “unmoved”, (1) “moved out of line” (i.e. simply rolled or displaced < 0.2 m), (2) “moved within the reach”, or (3) “moved out of the reach or not recovered”. Sum of displacement s in the equation is replaced by the sum of classified values of displacement, and multiplied by the number of particles of size between D_i and D_j (e.g. between D_{50} and D_{70} , Lobera et al. 2016) that actually moved (not necessarily recovered). Values of D_i used are those computed from the GSD, and not the geometric mean of the class. This approach was chosen due to the low recovery rates (hence few measured distances available), especially in Croasdale Beck. When presenting this metric, Schwendel et al. (2012) suggested adding a value of distance for non-recovered tracers, based on the Q_{max} experienced by particles. One of the advantages of using a classified system is that there is no need to infer a travelled distance from Q hence limiting user-induced dependence between the two variables. Additionally, particles that are not recovered are assigned a level of 3, whether they are buried or have actually left the reach; bed disturbance

is considered maximal in both cases. This metric is later referred to as classified tracer movement (CTM).

6.3.5. Macroinvertebrates

Macroinvertebrates were sampled at each site on each date. Samples were scheduled monthly but some were moved by one or two days as required to ensure all samples were collected under similar low flow conditions. Five samples were collected at each site on each date, distributed from the downstream to the upstream end of the site, using a Surber sampler (0.09 m² sample area, mesh size = 500 µm). Samples were preserved in 70% ethanol on site for later analysis. In the laboratory, invertebrates were sorted and identified to species level for Plecoptera (Hynes 1993), Ephemeroptera (Elliott and Humpesch 2010) and Trichoptera (Wallace et al. 2003; Edington and Hildrew 2005), to genus level for Coleoptera (Nilsson 1996; Tachet et al. 2006) and Odonata (Tachet et al. 2006), and subfamily or tribe for Diptera and Oligochaeta (Tachet et al. 2006).

6.3.6. Benthic algal biomass

Abundance of the chlorophyll-*a* pigment within phytobenthos is commonly used as a proxy for total phytobenthos biomass (Kasprzak et al. 2008). Chlorophyll-*a* was determined based on *in situ* fluorometry (IFS), measured using a BenthosTorch® (bbe Moldaenke GmbH, Germany). ISF involves emitting light pulses on the algal mat, with different wavelengths (470, 525 and 610 nm) and recording the fluorescence response from the phytobenthos at 690 nm. An optical filter prevents excitation light from reaching the detector, which would otherwise cause an offset (Aberle et al. 2006). Additional excitation light at 700 nm is used to correct for fluorescence re-emitted by the substratum (Carpentier et al. 2013). Following calibration, the resulting signal can be decoupled into chlorophyll-*a* concentration associated with individual spectral groups. These groups are commonly interpreted as representing green algae, diatoms and cyanobacteria (Aberle et al. 2006). This method provides estimates of the biomass of individual components of the phytobenthic community, and can be summed up to provide a reliable estimate of total phytobenthos biomass.

On each sampling occasions, five submerged cobbles were removed from the bed at each site and phytobenthos biomass measured using ISF. Values reported here represent the average reading of the 5 samples.

6.3.7. Data analysis

6.3.7.1. Water chemistry

Correlations between components of water chemistry were analysed using Redundancy Analysis (RDA). The aim was to identify components with the highest explanatory power (to distinguish between sites) and to reduce the number of variables for later direct gradient analysis.

6.3.7.2. Bed disturbance

The suitability of using ω as a proxy for bed disturbance was analysed by looking at the relationship between bed disturbance (CTM), and ω_{max} and ω_e . Different regressions were fit to each site, with valid models taken as those with $p < 0.05$.

6.3.7.3. Invertebrate abundance and feeding groups

The potential influence of macroinvertebrate grazing pressure will differ between sites if macroinvertebrate assemblages are structurally different. To assess such differences in assemblages, a two-dimensional non-metric multidimensional scaling (NMDS, Kruskal 1964) was performed. This ordination technique calculates a distance matrix of all samples, which can be visualised in 2 (sometimes 3) dimensions. A measure of ‘stress’ is used to judge the goodness of fit, i.e. how well the ordination summarises distances between samples (rejected if > 0.2 ; McCune and Mefford 2016). NMDS has the advantage of making few assumptions about the nature of the data and allows for the use of any measure of distance (McCune and Mefford 2016). Site dissimilarity for the Ehen and Croasdale data was quantified using Sørensen’s distances on presence-absence of taxa (Heino et al. 2003).

The functional feeding groups of all invertebrate samples was defined using information from Tachet et al. (2006). A fuzzy coding procedure (Chevenet et al. 1994) was used to determine the affinity of each taxon to the different “functional feeding groups”. Affinity scores ranged from 0 to 3 (i.e. no to strong affinity) and group-wide averages were used for taxa identified at coarser level (e.g. family). Scores were then rescaled to proportions, to sum to 1 (Dolédec and Statzner 2008). Rescaled affinity scores were multiplied by the abundance of each taxon for each sample to create a sample x ‘feeding group’ abundance matrix (similar to Larsen and Ormerod 2010; Feio and Dolédec 2012; Buendía et al. 2013).

Abundance of macroinvertebrates is commonly $\log(x+1)$ transformed to reduce the influence of abundant taxa (Larsen and Ormerod 2010; Buendía et al. 2014). However, since the aim of this study is to characterise the role played by invertebrate grazers on algal biomass, reducing the influence of abundant taxa, which could feed totally or partially on phytobenthos, may result in underestimation of their grazing pressure. Thus, invertebrate abundance was kept as raw values for the ordinations.

6.3.7.4. Multivariate analysis of controls on algal abundance

Both macroinvertebrates and algae are likely subject to common environmental controls (e.g. flows, disturbance, water chemistry). Initially, the co-linearity between invertebrate and algal abundance (and hence the inference of common environmental controls on the two) was assessed by creating a correlation matrix. Several metrics were used to represent the grazer assemblage, such as the abundance of grazer generalists (i.e. taxa with the category “scrapper-grazer” >0), the weight of the category “scrapper-grazer” in the total abundance, the specific richness in taxa presenting the trait ‘grazing’ and the abundance of grazer specialists (i.e. with a value of the category “scrapper-grazer” >0.5).

In order to determine if invertebrate grazers have an influence on algae (the hypothesis put forward by Kelly et al. (2015)), the relationship between chlorophyll-*a* abundance and the different metrics of invertebrate grazing were tested using Generalised Estimating Equations (GEEs). GEEs are an extension of Generalised Linear Models, but allow the analysis of data that are not independent, such as samples collected from a single site on repeated occasions or sites that are geographically clustered (both of which apply here). GEEs models are valuable to analyse spatially or temporally correlated data in ecology (Vaughan et al. 2007). They allowed a single model representing grazer vs chlorophyll-*a* relations to be fit to data from all four sites.

Additional exploration of the environmental controls on algal composition (i.e. relative abundance of green algae, diatoms and cyanobacteria) was undertaken using RDA. This used the chemical selected from the early RDA ordination, and all bed disturbance data, as well as using invertebrate grazers as a pseudo-environmental variable. Prior to RDA, preliminary Detrended Correspondence Analysis (DCA) was used to define the length the first ordination gradient, which led to the choice of a RDA (rather than CCA). Forward selection was used to identify the most important influences on algal composition.

All analyses were performed in R (R Core Team 2017) using different packages; ‘vegan 2.4-3’ (Oksanen et al. 2017) for DCA, RDA and PCA, and ‘geepack’ (Højsgaard et al. 2006) for GEEs.

6.4. RESULTS

6.4.1. Hydrology and stream power

Discharge in the Ehen is considered rather flashy and responsive, despite being regulated by Ennerdale Water and its associated weir (Quinlan et al. 2015; Marteau et al. 2017). In terms of the timing of events, Croasdale showed a broadly similar flow regime, although some events were relatively high (e.g. 1 June 2015) and often showed more rapidly rising and falling limbs (e.g. late Sept 2015 and April 2016) (Figure 6.2).

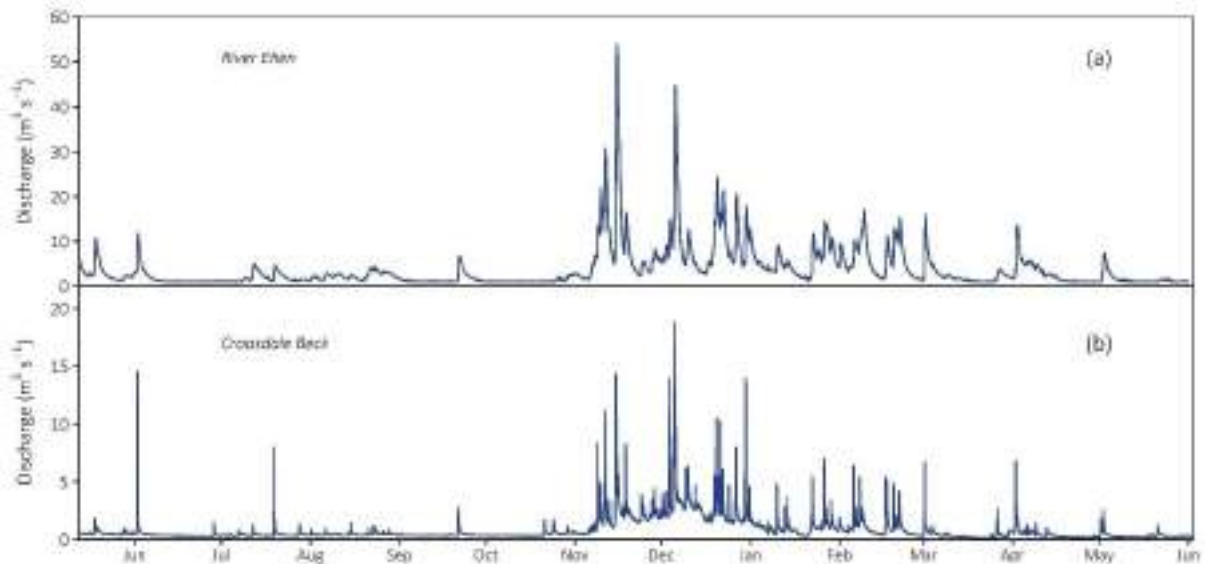


Figure 6.2. Discharge (a) in the Ehen (at gauging station) and (b) in Croasdale Beck (near catchment outlet).

Discharge in the Ehen varied between 0.92 and 54.0 m³ s⁻¹, with mean and median discharges of 3.66 and 1.91 m³ s⁻¹ respectively. This maximum discharge recorded represents a 30-year return period flood. No historical information on discharge in Croasdale Beck is available, which was only gauged for the period of this study. Nevertheless, given the shape of the hydrograph, the occurrence of several events around 15 m³ s⁻¹ during the study (Figure 6.2) and the comparison between the two hydrographs, the return period of the largest flood is unlikely to

be as important as the one recorded in the Ehen. Discharge over the 13 months ranged from 0.1 to 18.84 m³ s⁻¹ at site CBV and from 0.05 to 9.46 m³ s⁻¹ at CBP. Flows remained high for prolonged periods of time between November and January (Figure 6.2) and were higher than Q_{mean} for 30% of the time in the Ehen, and 25% in Croasdale Beck. These high flows created the potential for bed disturbance and associated changes in algal and invertebrate communities in both water courses.

Calculated values of ω indicated the higher flow competence of Croasdale Beck (Table 6.1). Maximum ω_e in ESC was 1 order of magnitude lower than both CBV and CBP, highlighting the large difference between the two systems. This can be argued to be explained by the absence of regulation (i.e. no high flow truncation) and the higher mean local bed slopes (Figure 6.3). The highest ω_{max} values were observed in CBV (600 W m⁻²), and the lowest in ESC (45.3 W m⁻²). Interestingly, although the two streams are neighbours, they did not experience their maximum ω during the same period (i.e. survey 7 in the Ehen, survey 8 in Croasdale). Similarly, the highest ω_e were recorded in CBV and CBP during the period preceding survey H. In the Ehen, both ESC and EOX experienced their highest ω_e during the period preceding survey G.

The ecological consequences of flow regulation in the Ehen

Table 6.1. Discharge and stream power statistics for each site (EOX & ESC = Ehen, CBV & CBP = Croasdale Beck). 'Number of days' is the number of days between successive sampling dates. However, flow statistics reported in the table represent conditions for the 10 days prior to sampling only.

Survey no.	Date	Number of days	EOX							ESC							CBV							CBP						
			Q _{max}	Q _{mean}	Q _{min}	Q _{sd}	W _{max}	W _e	Q _{max}	Q _{mean}	Q _{min}	Q _{sd}	W _{max}	W _e	Q _{max}	Q _{mean}	Q _{min}	Q _{sd}	W _{max}	W _e	Q _{max}	Q _{mean}	Q _{min}	Q _{sd}	W _{max}	W _e				
			m ³ s ⁻¹			W m ⁻²				m ³ s ⁻¹			W m ⁻²				m ³ s ⁻¹			W m ⁻²				m ³ s ⁻¹			W m ⁻²			
A	13/05/2015	-	13.70	2.15	0.95	2.27	48.0	4967	13.70	2.15	0.95	2.27	11.5	592	0.63	0.60	0.58	0.01	20.1	0	0.32	0.30	0.29	0.01	13.4	0				
B	04/06/2015	22	11.80	3.42	1.12	2.39	41.3	6948	11.80	3.42	1.12	2.39	9.9	866	14.57	0.66	0.38	0.97	464.1	6093	7.32	0.33	0.19	0.49	310.9	4287				
C	02/07/2015	28	3.98	1.21	0.93	0.52	13.9	64	3.98	1.21	0.93	0.52	3.3	0	1.48	0.35	0.27	0.09	47.2	4	0.74	0.18	0.14	0.04	31.6	11				
D	12/08/2015	41	5.08	1.93	0.92	0.93	17.8	1193	5.08	1.93	0.92	0.93	4.3	0	7.95	0.43	0.28	0.27	253.1	1213	3.99	0.21	0.14	0.14	169.6	890				
E	09/09/2015	28	4.55	2.09	0.98	0.97	15.9	820	4.55	2.09	0.98	0.97	3.8	0	1.40	0.44	0.32	0.13	44.7	1	0.70	0.22	0.16	0.06	29.9	8				
F	07/10/2015	28	6.73	1.51	0.95	1.16	23.6	1342	6.73	1.51	0.95	1.16	5.6	81	2.75	0.39	0.30	0.20	87.5	601	1.38	0.20	0.15	0.10	58.6	499				
G	21/11/2015	45	54.00	5.63	0.95	8.69	189.1	55313	54.00	5.63	0.95	8.69	45.3	11067	14.33	1.14	0.30	1.55	456.5	56680	7.20	0.57	0.15	0.78	305.9	41085				
H	14/12/2015	23	44.70	8.09	2.22	7.23	156.6	37954	44.70	8.09	2.22	7.23	37.5	6334	18.84	2.94	1.45	1.93	600.0	110764	9.46	1.47	0.73	0.97	402.0	80578				
I	12/01/2016	29	24.30	7.96	2.54	4.92	85.1	46317	24.30	7.96	2.54	4.92	20.4	7677	13.98	1.95	0.42	1.48	445.3	64875	7.02	0.98	0.21	0.75	298.4	49088				
J	12/02/2016	31	17.20	6.38	1.17	3.49	60.2	35287	17.20	6.38	1.17	3.49	14.4	5136	7.00	1.13	0.27	0.79	223.0	17438	3.52	0.57	0.14	0.40	149.4	13809				
K	08/03/2016	25	16.10	4.99	1.29	3.77	56.4	19289	16.10	4.99	1.29	3.77	13.5	2989	6.67	0.88	0.30	0.94	212.4	14797	3.35	0.44	0.15	0.47	142.3	10802				
L	13/04/2016	36	13.70	2.83	0.97	2.40	48.0	8994	13.70	2.83	0.97	2.40	11.5	945	6.77	0.45	0.10	0.54	215.5	4732	3.40	0.23	0.05	0.27	144.4	3516				
M	10/05/2016	27	7.39	1.72	0.96	1.24	25.9	1483	7.39	1.72	0.96	1.24	6.2	114	2.50	0.31	0.12	0.25	79.7	473	1.26	0.15	0.06	0.12	53.4	437				

6.4.2. Bed disturbance, GSDs and relationships with stream power

Bed grain-size distribution differed between sites within streams as much as between streams (Figure 6.3). The D_{50} was smallest in ESC and largest in EOX (35.9 and 56.5 mm respectively) although values for EOX should be used with care given that they were collected by a different operator at a different time (i.e. Moir et al. 2003). The D_{50} in Croasdale Beck was 54.6 mm in CBP and 43.5 mm in CBV. Other grain size statistics showed similar patterns between sites on respective rivers (inset in Figure 6.3).

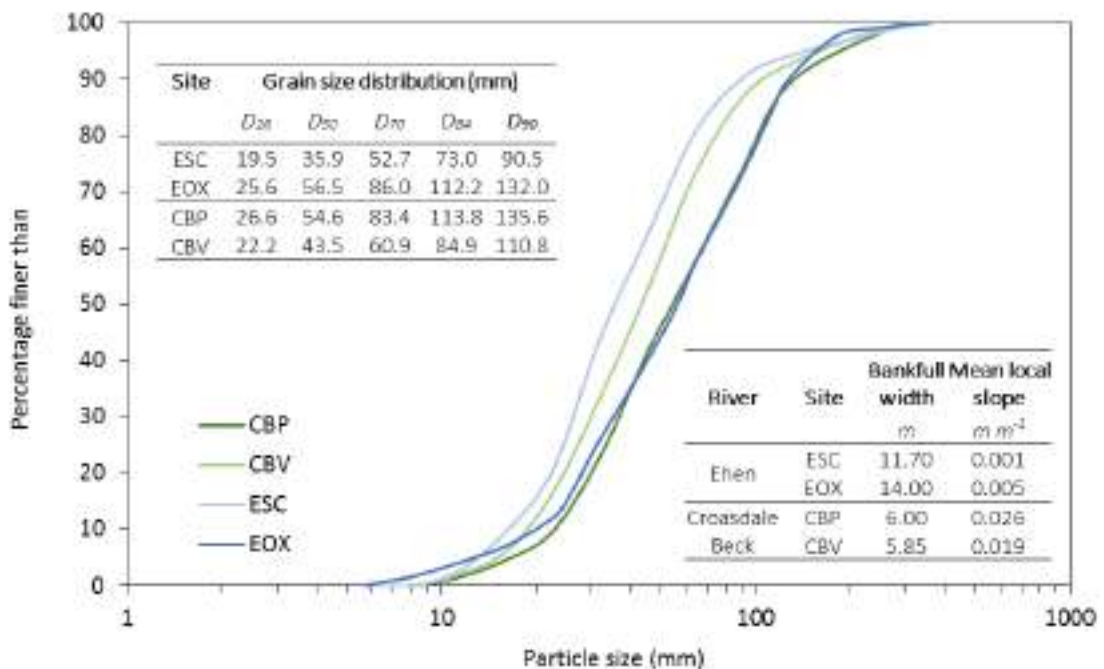


Figure 6.3. Grain size distribution (GSD) curves for each site. Inset tables show the main GSD statistics (top-left) and the main site characteristics (bottom-right).

Although the number of tracers used to compute bed disturbance over each period is limited (c. 20 per site) previous studies suggest that a meaningful estimate of bed disturbance can be obtained from the use of 15 stones or less (Death and Winterbourn 1994; Death and Zimmermann 2005). The relationship between CTM and both ω_{max} and ω_e was tested for each site (Figure 6.4). All relationships were significant (log regressions, $p < 0.05$) but were strongest in Croasdale Beck (CTM- ω_e ; r^2 ; CBV = 0.84, CBP = 0.75) than in the Ehen (CTM- ω_e ; r^2 ; EOX = 0.76, ESC = 0.66). This reflects the lower mobility observed in the Ehen, and particularly in ESC where values of CTM were the lowest.

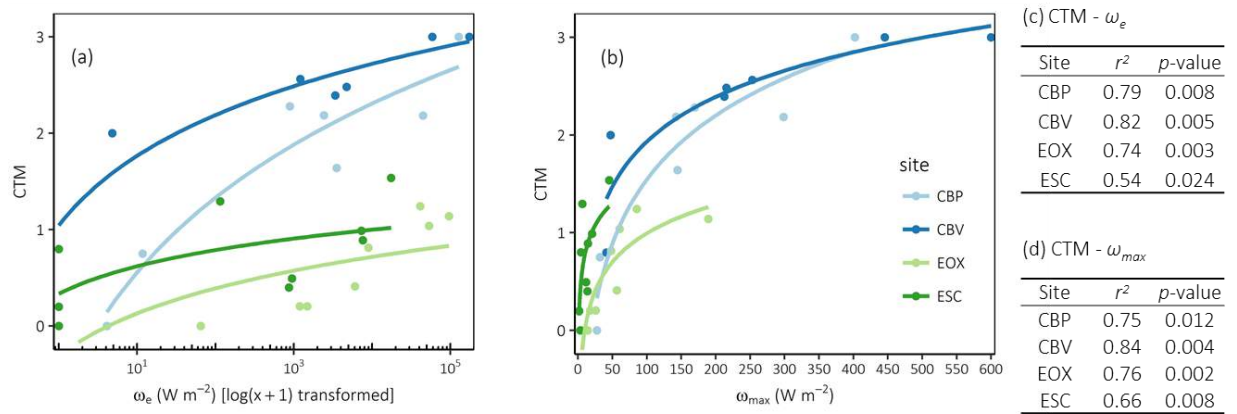


Figure 6.4. Relationship between bed disturbance (CTM) and flow competence. (a) Excess stream power and (b) maximum stream power. (c) coefficient of regression and p-value of the CTM- ω_e ($\log[x+1]$ transformed) relationship, and (d) for the CTM- ω_{max} relationship.

Values of CTM were constantly higher in Croasdale than in the Ehen, reaching the maximum possible value of 3 on several occasions (i.e. all tracers were moved out of the reach or buried between successive surveys). In contrast, maximum CTM was never reached in the Ehen and a total absence of movement was recorded at both ESC and EOX (occasion C). ESC showed higher bed stability (i.e. lower values of CTM) than EOX apart from occasion H, which represents the highest discharge (and ω_{max}) at which particle movement has been tracked. Maximum CTM in ESC was 1.5, and 1.2 in EOX.

6.4.1. Water chemistry

Time-series of water quality are shown in Figure 6.5. Issues with the DO sensor prevented the collection of data in for CBV in October and at all sites in November 2015. Additionally, the concentration of PO₄-P in November 2015 for CBV was measured at 1.6 mg l⁻¹, which is > 50 times the average of the other 12 samples. This measure was therefore dismissed. Missing values were filled with the average of concentrations measured at the previous and the following dates.

Results of the RDA (Figure 6.4) summarise and help highlight the differences in water chemistry between the two rivers and between the two Croasdale sites. Differences are related primarily to alkalinity, conductivity and NO_x. Values of alkalinity at CBV were constantly above 300 $\mu\text{eq l}^{-1}$ while they scarcely reached above 150 $\mu\text{eq l}^{-1}$ at the 3 other sites (Figure 6.5b). Conductivity showed similar patterns. All measured variables showed little seasonal patterns, apart from temperature. PO₄-P showed a decreasing trend throughout the study.

6.4.2. Abundance and composition of the algal community

Abundance and composition of the algal community differed through time and space (Figure 6.6). Abundance (as represented by chlorophyll-*a*) was highest in summer and lower in winter in Croasdale Beck, with virtually no algae found in November-December (Figure 6.6 a). Patterns in the Ehen were different, with high abundance in the summer, a sharp decrease in October-November, and high densities again in December through to February. Abundance was greatest in EOX but more constant over time in ECS.

Green algae were only found during the summer months (July to September, then return in April-May) but only dominated in July in Croasdale (Figure 6.6 b). Overall, diatoms represented the most abundant group. The relative community composition varied greatly in Croasdale Beck but was more stable in the Ehen, and particularly in ESC. Despite variations in abundance, the community structure showed limited variation in ESC compared to the other sites. The major peak in algae at EOX in Feb 2016 was driven by an increase in diatoms.

The ecological consequences of flow regulation in the Ehen

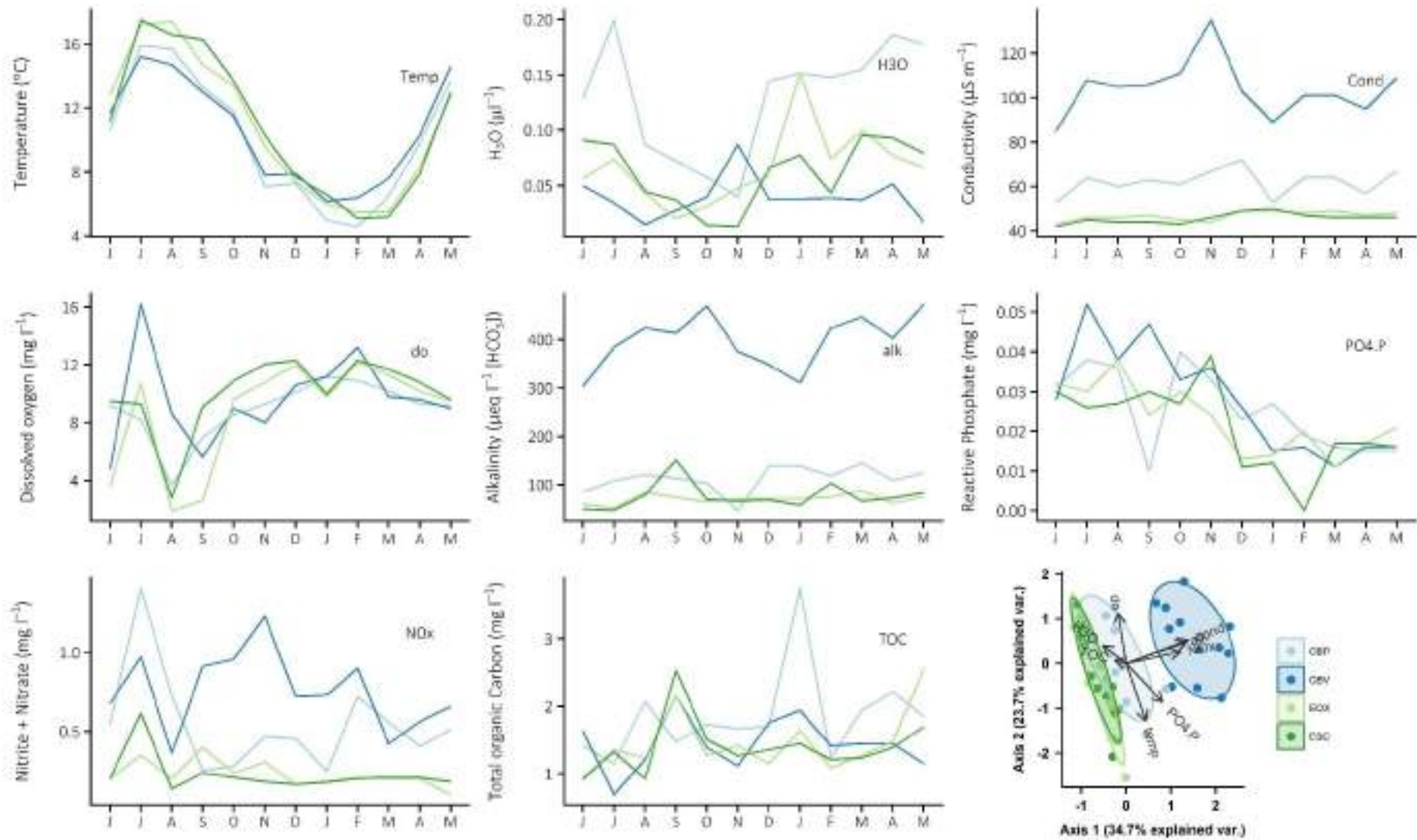


Figure 6.5. Time-series of water chemistry components, and RDA ordination showing differences in water chemistry between sites.

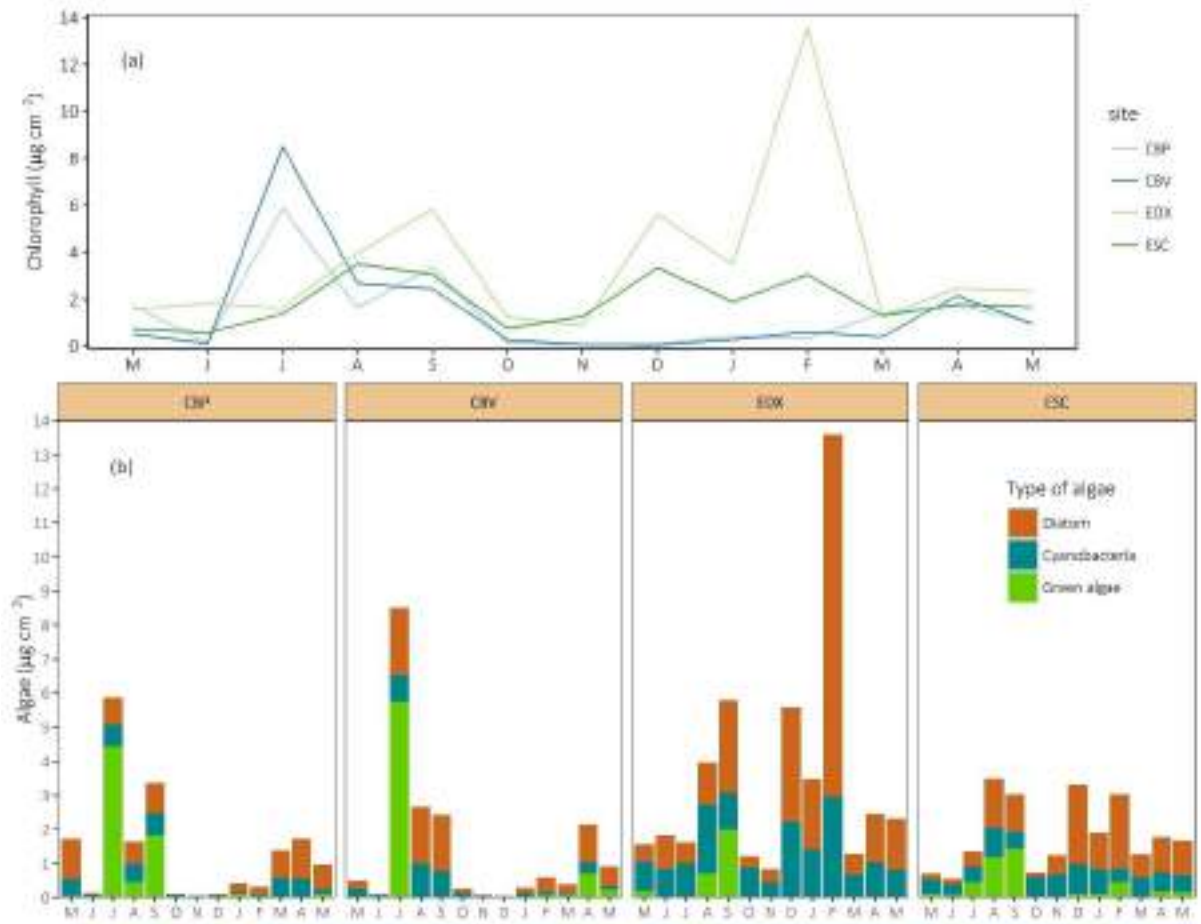


Figure 6.6. (a) Time-series of chlorophyll-a abundance for each site. (b) composition of the algal community over time (as BenthosTorch readings), for each site. Data provided by Kelly et al.

6.4.1. Macroinvertebrate assemblages and feeding groups

Results from the NMDS ordination (stress = 0.126) showed a clear distinction in macroinvertebrate assemblages between the two rivers (Figure 6.7). While the two sites in Croasdale Beck were clearly similar (great overlap between their 95% confidence ellipses), the two sites in the Ehen differed appreciably. This pattern is the opposite to that observed in the chemistry. Relative to the other sites, assemblages at ESC were homogeneous (i.e. little spatio-temporal variation on community composition), as indicated by the small size of the ellipse.

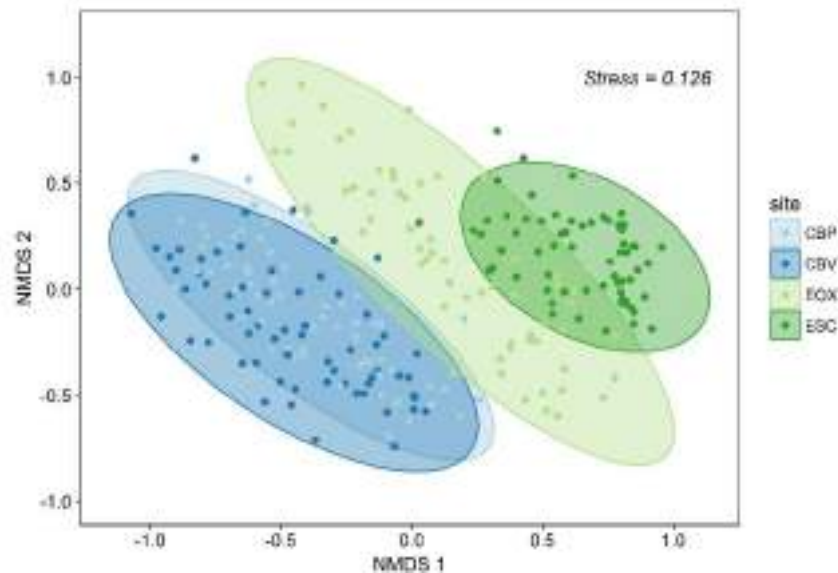


Figure 6.7. NMDS plot of macroinvertebrate assemblages dissimilarity using Sorensen's distance. Ellipses represent 95% confidence intervals.

Patterns shown by the PCA of feeding groups (Figure 6.8) may partly explain inter-site differences in community composition evident in the RDA. All sites overlap at the origin of the ordination, indicating that many samples were rather similar. However, in general the Ehen differed from Croasdale by having a greater abundance of shredders and piercers; conversely, Croasdale Beck had more filter-feeders and scraper-grazers. The length of all arrows is very similar, indicating that differences in community composition were not influenced disproportionately by any one feeding group.

There were no gross differences in overall densities of invertebrate between the four sites (Figure 6.9), with differences mainly related to seasonal patterns. Densities of macroinvertebrates were highest in late summer (August to October) and decreased sharply in winter (January onwards). The proportion of grazers differed markedly between sites (as per the PCA; Figure 6.8), although their relative proportion within a site remained rather constant through time. Filter-feeders dominated in CBV during the summer, while EOX and ESC had higher densities of deposit-feeders at that time. Predators were mostly present in the summer and almost disappeared in the winter. ESC showed the most stable assemblages over time, with proportions of each feeding group represented approximately equally on all sampling occasions. This is also the only site where piercers were found in great numbers.

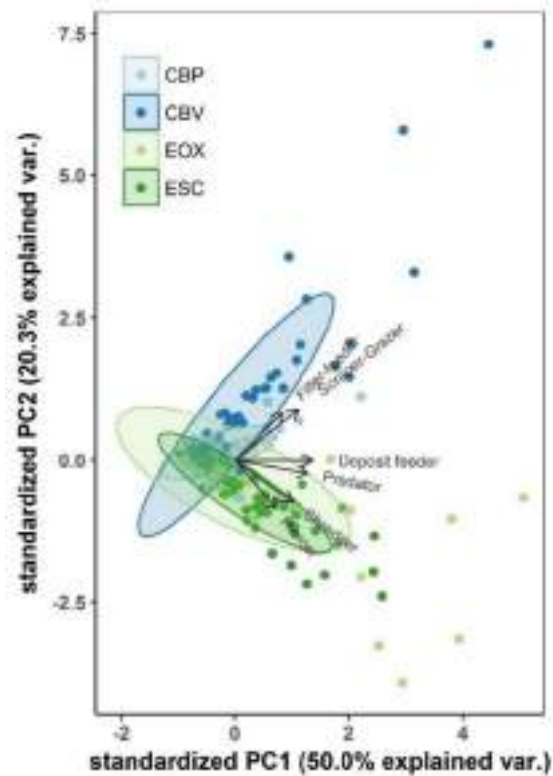


Figure 6.8. PCA of feeding groups of the macroinvertebrate communities.

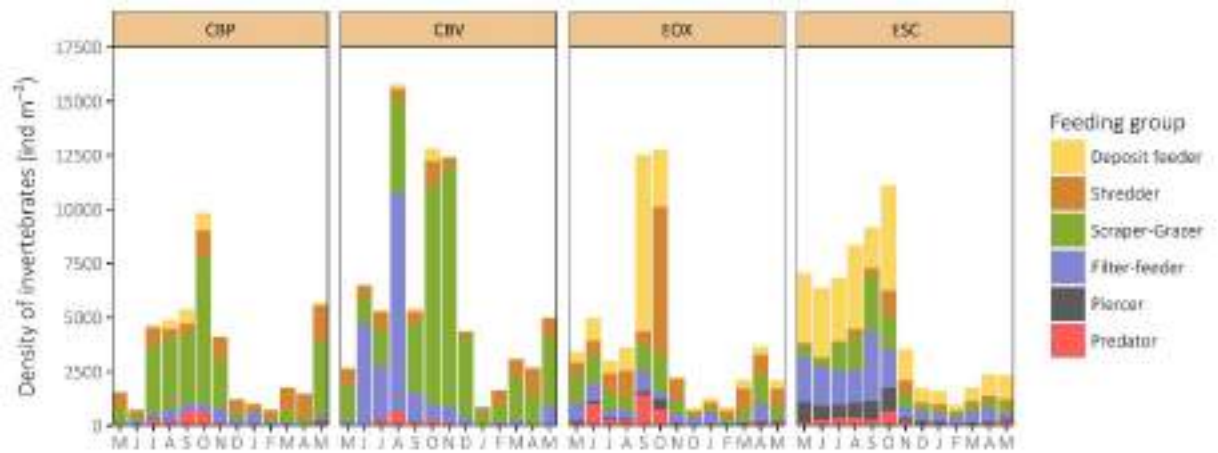


Figure 6.9. Histogram of the density of each feeding group at each site for each sampling occasion (i.e. month). Taxa were classified based on their dominant feeding group (Tachet et al. 2006).

6.4.2. Correlations between invertebrate abundance and feeding groups, and between invertebrates and algae

Chlorophyll-*a* was used as a metric of the total abundance of algae. Due to one or two extremely high values, *log* chlorophyll-*a* was used to test correlations between algae and

invertebrate abundance (Table 6.2). Although there was considerable scatter in the relationship (Figure 6.10), the total abundance of invertebrates and (log) chlorophyll-*a* showed a significant positive relationship (0.28); thus, samples with large numbers of invertebrates had high algal biomass, and vice versa. This correlation suggests that the factors influencing algal biomass also influence the total abundance of invertebrates. Strong positive correlations were also found between total invertebrate abundance and several of the metrics representing grazers; e.g. abundance of grazers (number of individuals that were grazers) was correlated total invertebrate abundance (0.89), as was the weighted abundance of grazers (0.92). Thus, samples with generally larger numbers of invertebrates tended to have more grazers. However, as these correlations are not strong, it appears that a somewhat different set of environmental controls may influence the abundance of grazers compared to the total number of invertebrates present.

Table 6.2. Correlation matrix between Chlorophyll-*a* abundance, log-transformed chlorophyll-*a* abundance and variables representing grazing pressure.

(log) chlorophyll	*				
0.28	Total Abundance	***	***	***	***
	0.79	Weight	***	***	***
	0.63	0.49	Nb taxa grazers	***	*
	0.89	0.92	0.60	Abundance grazers	***
	0.64	0.96	0.38	0.77	Grazer specialists

The scatter in the chlorophyll-invertebrate relationship (Figure 6.10) is greatest at low invertebrate abundances, and is driven by a systematic difference between the two rivers. Especially at this lower range, but in general across the whole range, chlorophyll-*a* values are higher in the Ehen than they are in Croasdale for equivalent abundance values. This suggests that some other factors permit higher algal abundance in the Ehen than they do in Croasdale for equivalent invertebrate densities. This interaction between environmental conditions, algae and invertebrates is explored in section 6.4.7.

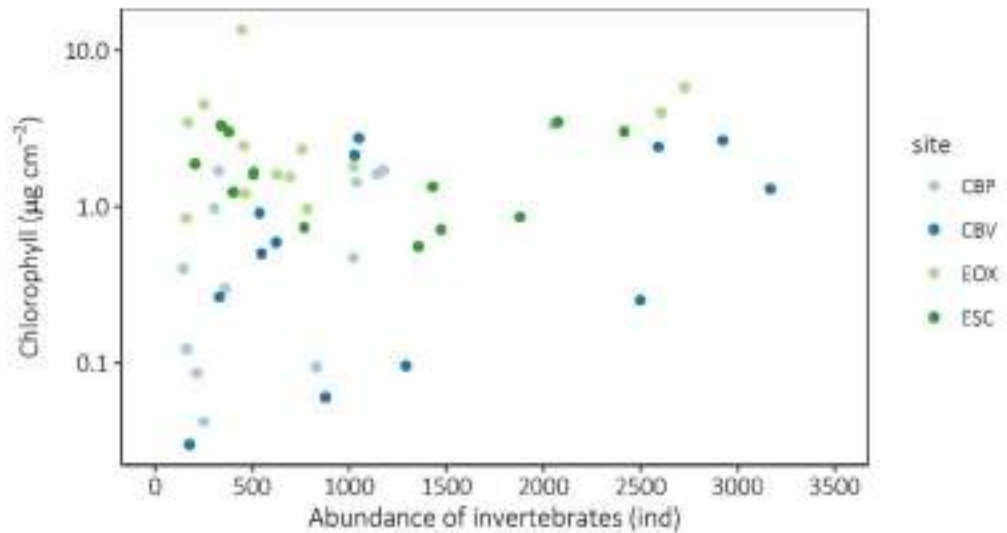


Figure 6.10. Scatterplot of the abundance of invertebrates and abundance of chlorophyll-*a*.

6.4.3. Environmental controls on algae

The GEEs suggested that grazing invertebrates exerted a significant influence on total abundance of algae (Table 6.3): values of chlorophyll-*a* were influenced by all three of the metrics used to represent potential grazing pressure. The total abundance of grazers was the most useful predictor of chlorophyll-*a* (highest Wald value (6.72)). Only the intercept was not significant, presumably due to the high between-river scatter at low invertebrate abundance (Figure 6.10) which limits the ability GEEs to confidently plot a single/common line at this part of the data range.

Table 6.3. Results of the Generalised Estimating Equations used to test the effect of different grazing metrics on chlorophyll-*a* abundance.

	Estimate	Std.err	Wald	Pr(> W)	Significant
Intercept	-0.344	0.286	1.45	0.229	NS
Weight of grazers	-0.010	0.004	5.09	0.024	*
Abundance of grazers	0.003	0.001	6.72	0.010	**
Grazing specialists	0.004	0.002	3.93	0.048	*

RDA was used to assess the environmental controls on the composition of the algal assemblage (i.e. the relative abundance of the three groups). An initial RDA was performed in order to identify the most useful explanatory variables to use in the final model; these variables were identified using forward selection. Variables included in the model were maximum discharge (Q_{max}), maximum stream power (SP $_{max}$), excess stream power (SP $_{e}$), conductivity (cond), pH (H $_{3}O$), temperature, total abundance of invertebrates (abundance), and abundance of grazers

6.5. DISCUSSION

6.5.1. Environmental differences between the two rivers: effects of the regulation

The River Ehen is regulated by Ennerdale Water and its associated weir, which have a strong influence on the hydrology and sediment dynamics of the river (see previous chapters). Croasdale Beck is unregulated, with the data on stream power and bed stability suggesting that it is a much more dynamic system. Discharges in Croasdale Beck show greater variability and faster response to rainfall events. Similarly, flows decrease more rapidly in Croasdale due to the absence of a lake. Local topography (i.e. bankfull width and mean slope) are also different; slope is higher but width is smaller in Croasdale Beck. Although discharge is also lower in this stream, these factors produced higher levels of ω as well as higher effective flow competence (ω_e). This is reflected in the difference in bed mobility between the two.

The calculation of CTM is constrained to some degree by the absence of information about particle displacement. Nonetheless, it successfully captured bed disturbance conditions and illustrated well the differences between the systems. All tracers were displaced and lost on several occasions at both sites in Croasdale Beck, especially during the winter storms of December 2015; the geometry of the channel visibly changed as a result of these very high flows. In contrast, bed disturbance was limited in the Ehen. The upstream site (ESC), located only *c.* 300 m downstream from the lake and weir, displayed the greatest stability, with even the 30-year return period floods that occurred during the study period was not competent to move all tracers.

The difference between the two systems is also reflected in the strength of the correlation between CTM (bed stability) and ω (flow competence). Studies looking at the effects of disturbance on freshwater organisms have found that discharge variables and bed disturbances are not necessarily correlated (e.g. Townsend et al. 1997a). The relationships between bed stability and metrics of flow competence (i.e. ω_e and ω_{max}) were significant, but showed higher coefficients of determination (r^2) in Croasdale compared to the Ehen, with ESC displaying the weakest correlation. Differences in the relationships can be related to differences in riverbed characteristics (e.g. particle size distribution, degree of armouring, sediment supply). Similar observations were reported in Chapter 5 and can be linked to the presence of a pavement, with the Ehen highly compacted and very resistant to movement. At the Oxbow (EOX), however, the

river showed slightly higher mobility but also higher ω . As this site hosts higher densities of mussels than ESC, it appears that they are tolerant to the degree of bed instability they experience here. It is also possible that these hydraulic conditions are beneficial, if they help avoid potentially damaging fine sediment deposition.

The analysis of water chemistry at the monthly scale is unlikely to detect ecologically important patterns, especially in relation to nutrients which can vary greatly during the course of a single flow event; as mentioned in Section 6.2, this is the subject of ongoing work by Martin Kelly and colleagues. However, the monthly data presented here are still a useful basis for ordinations, to generally compare sites and streams. Water chemistry was different between the two systems, especially for alkalinity and conductivity. This can be related to differences in the geological composition of the catchments: the upper Ehen is composed of igneous and granitic rocks, while Croasdale Beck drains through sedimentary (mostly argillaceous) formations.

Values of nitrogen (N) and phosphate (P) in the Ehen were rather high compared to 'normal' values recorded here (M. Kelly. pers comm) although there is no benchmark data for Croasdale to compare. The high values could be due to the methods used: freezing-thawing may help the release of N & P compounds that are normally bound and not easily available. However, this is not an issue for this study as the same method was used for all sites and statistical comparisons were made only between these rather than with other studies. Croasdale was generally cooler in summer and autumn, but slightly warmer in spring; winter temperatures overlapped between all sites. These differences most likely reflect the effect of lake thermal dynamics in the Ehen, although more data on lake water temperatures and finer temporal resolution data for both rivers are needed to fully assess this. Differences could also reflect groundwater inputs, although, again, no data are available to properly assess this for the four sites. Marked differences were also observed between the two rivers for conductivity and alkalinity. This can be explained by the geological nature of the catchments; the upper Ehen consists mostly of granitic bedrock characterised by slow weathering processes and low release of ions (Allan and Castillo 2007). Conversely, Croasdale Beck runs through sandstones and argillaceous rocks that tend to release higher levels of ions, hence the higher conductivity and alkalinity levels and their increase downstream from the headwaters (Allan and Castillo 2007). Levels of nitrate and nitrite were also generally higher in Croasdale Beck, which can potentially be explained by the higher (although still limited) agricultural activity within the catchment.

6.5.2. Ecological difference between the two rivers: also the effect of regulation?

Limitations exist to the interpretation of BenthosTorch readings as a measure of algal community composition. However, since the aim of this study was mainly to compare controls on total algal abundance (i.e. chlorophyll-*a*) in the two rivers, and given that the sampling was consistently undertaken by the same team with the same calibrated equipment, we are confident that some general comparison can be made.

Abundance of chlorophyll-*a* in Croasdale Beck showed regular seasonal patterns, with higher values in the summer (July-September) and lower in the winter (November-March). Trends in the Ehen differed between sites, with a peak in abundance observed in the winter at EOX, and high densities in ESC in both parts of the year (July-September, then December-February). This is consistent with the trends reported by Kelly (2013) who recorded higher algal biomass in the winter in the Ehen.

Composition of the algal community showed that green algae have the potential to be present in high abundance in Croasdale, but decrease quickly in the winter. In the Ehen levels of green algae were not as high, with more diatoms but also higher abundance of blue-green algae (cyanobacteria). Green algae form a source of food which is more nutritious and more attractive to invertebrate grazers than cyanobacteria (Feminella and Resh 1991). Diatoms are also frequently found in the diet of invertebrate grazers (e.g. Lange et al. 2011). Perhaps the higher proportion of cyanobacteria in the Ehen reflects the fact that the grazers present in this river are more selective and feed on the best food available (i.e. green algae and diatoms), since there is no shortage of algae (always present even in winter). It could also be related to the fact that fewer 'grazer specialists' were found in the Ehen compared to Croasdale; taxa classified as grazers may actually be more omnivorous than thought (see Wallace and Webster 1996) and the classification into separate groups may be unrepresentative of the true situation (Chevenet et al. 1994).

The stress values in the NMDS used to assess difference in macroinvertebrate assemblages were low, so conclusions about the similarities or dissimilarities between sites and rivers can be considered robust. Assemblages showed important dissimilarity between the two rivers, but also between the two Ehen sites. The large overlap between the 95% confidence ellipses show that the two sites in Croasdale share a common assemblage structure, despite some

differences observed in water chemistry. The two sites in the Ehen show little similarity, with ESC macroinvertebrate assemblages very different from those of Croasdale Beck (ellipse furthest away). ESC is located directly downstream from the lake, with a very stable riverbed and simple channel morphology (homogeneous habitat). EOX is c. 4 km further downstream, where bed stability is not as marked and flow competence is higher (i.e. higher ω). The NMDS axis 1 might be reflecting the influence of flow regulation; the furthest on the left the more natural, while the ESC site sits on the extreme right of the NMDS plot. EOX is situated between the two extremes, showing some potential 'recovery' of the invertebrate assemblage with distance downstream from the weir and lake.

The density of macroinvertebrates decreased sharply following the large floods of December 2015. The removal of animals is especially visible in CBV and EOX, where densities prior to the floods were highest. In relative terms, decreases in density were lower in CBP and ESC. While the recolonisation of patches after the events may have contributed to the population recovery in CBP, bed stability is likely to have played a role in protecting invertebrates from mass drift in ESC. The assemblage appears more constant over time and more resilient to the large floods. Several studies have reported the role of bed stability (Matthaei et al. 2000; Effenberger et al. 2006; Gibbins et al. 2007b) and the presence of a static armour layer (Gibbins et al. 2007a) in limiting loss of invertebrates during floods. Moreover, the recolonisation of patches is affected by both direct and indirect consequences of local disturbance history (Effenberger et al. 2008), with different patterns observed depending on micro-habitat conditions. Thus, some filter-feeders (e.g. *Simulium sp.*) and grazers (e.g. *Baetis sp.*) are known to be fast colonisers of disturbed patches (e.g. Matthaei et al. 1996) (i.e. dominant in CBP in January and February) while protected patches (i.e. showing little disturbance) conserve higher diversity (Effenberger et al. 2008) (i.e. reflected in the constant relative density of all feeding groups in ESC).

In addition to this difference in assemblage stability between ESC and the other sites, there is a clear difference in the dominant feeding group of the macroinvertebrate assemblages between the two rivers. Most importantly, scraper-grazers, which are the core hypothesis of Kelly et al. (2015), are not dominant in the River Ehen; instead, the river is dominated by shredders, piercers and deposit-feeders. It is well recognised that flow regulation can adversely impact macroinvertebrate communities (Boon 1998) and that certain feeding groups are more frequent downstream of impoundments, such as deposit-feeders and, to some extent, filter-feeders (Wallace and Webster 1996; Fleituch 2003; Vallania and Corigliano 2007). ESC is also

the only site where piercers are abundant. Piercers found in the river were mostly Trichopterans of the family *Hydroptilidae* which feed on the fluids contained in filamentous algae (Tachet et al. 2006). Their presence reflects the higher abundance of filamentous algae in ESC compared to other sites and confirms the higher bed stability at this particular site.

6.5.3. What controls algal biomass and community composition in the River Ehen?

The multivariate ordination revealed that season (represented by temperature) was the main environmental factor controlling algal composition and abundance. The partial-RDA was performed with the intention of removing this strong seasonal control and assessing which other environmental variable may be controlling differences in algal abundance and composition. ω_{max} was the only significant variable resulting from the forward selection procedure of the partial-RDA. Both ω_{max} and ω_e (representing flow competence) were highly correlated with the bed disturbance metric, highlighting the role of bed disturbance in controlling algal abundance (once the overriding influence of season is accounted for). Hence, the role of invertebrate grazing in controlling algal assemblage composition appears to be limited. However, it is possible that differences exist between the four sites. Wallace and Webster (1996) argue that the effect of grazing on algae is frequently unnoticed when the abundance of grazers is low, although it may still be influential. It is also possible that the occurrence of very high discharges during the winter period (30-year return flood) has affected the balance of the algae-grazers relationship. Kelly et al. (2015) have reported a peak in algal abundance in the winter for the last 4 years, usually occurring around December. During the period of the current study, the trend normally observed may have been overridden by the occurrence of the winter storms in December 2015. Based on the results indicating the role of bed disturbance, it seems likely that algal abundance would have continued to increase through the winter in the Ehen, had these floods not happened. In other words, unusually high flows and associated bed disturbance may have played a prevailing role this year compared to the 4 previous years reported by Kelly et al. (2015). Similarly, these floods may have changed the macroinvertebrate assemblages (e.g. Gibbins et al. 2010), potentially influencing the degree of grazing pressure.

GEEs suggested that total chlorophyll-*a* can be partly estimated from invertebrate grazing pressure. Chlorophyll-*a* was used as a simple metric of the total coverage of algae on the stream

bed. The GEES results differ from the ordination simply because the two are focusing on different things – the GEES on total biomass, the ordination on the taxonomic composition of this biomass. From the perspective of pearl mussel habitat quality, the former is perhaps most important, as it provides an indication of the potential smothering effects as well as the potential problems related to decay and oxygen demand. However, the results from the GEEs need to be interpreted with care. Both ‘abundance of grazers’ and ‘grazer specialists’ showed a positive relationship with chlorophyll-*a*, although the slope is almost horizontal (estimates = 0.003 and 0.004 respectively). ‘Weight of the trait grazing’ had a higher and negative slope (-0.010) although still very subtle. It is possible that the abundance of grazers simply reflects the total abundance of invertebrates, since both were highly correlated. Abundance of grazer specialists is also dependant on total abundance of invertebrates. In contrast, ‘weight’ represents an estimate of grazing pressure that integrates both the abundance of grazers (non-grazers are not included because category = 0) and gives more weight to grazer specialists. Thus, this metric might be the most useful to described grazing pressure on algal biomass. Nevertheless, it would be unwise to draw any conclusion from these results.

Additionally, it is possible that benthic algae communities showed only limited response to other environmental stressors (i.e. other than seasonality and flows) because the study only looked at abundance and relative composition from BenthosTorch readings. Changes in the relative abundance of species and/or traits of algae may form an adaptation to stressors that was not captured in this study (Passy 2007; Lange et al. 2011). Finally, other keys factors such as the punctual ‘flush’ of nutrients or light availability were not considered here although they are known to be key factors controlling algal communities (Hillebrand 2002; Lange et al. 2011).

6.6. FINAL REMARKS

This study aimed to test the roles of flow competence, bed disturbance, water chemistry and invertebrate grazing in controlling algal biomass in the River Ehen. The main hypothesis that grazing pressure might be a dominant factor could not be fully accepted. Seasonality, represented by water temperature, was the main factor driving algal composition, although GEES suggested that grazers may influence total biomass. When seasonal variations were accounted for in the ordination analysis, flow competence (which was strongly correlated with bed disturbance) proved to be the only significant environmental control on community structure. However, we suggest that the relative role played by grazers should not be dismissed

totally. The importance of flow competence revealed in this study may be related to the rare floods that occurred in winter 2015 which disrupted the 'typical' patterns of algal biomass growth cycle observed over the last 4 years by Kelly et al. (2015). The relationship between invertebrate grazers and algal biomass, although not picked-up as significant by the ordination, may have been different in the absence of very high flows. Further analysis is needed to better account for the high algal biomass in the winter in the River Ehen. Finally, the differences in macroinvertebrate assemblages and bed stability observed in ESC can be related to the conclusions of the previous chapters on the effects of flow regulation and the diversion of Ben Gill on the eco-geomorphic status of the Ehen. Effects are not limited to sediment dynamics (and the loss of suitable habitat for pearl mussels) but are also reflected in the macroinvertebrate communities (as per Quinlan 2014) and, to some extent, in the algal community.

6.7. REFERENCE LIST

- Aberle N, Beutler M, Moldaenke C, Wiltshire KH (2006). "Spectral fingerprinting" for specific algal groups on sediments in situ: a new sensor. *Archiv für Hydrobiologie* 167:575–592
- Abril M, Muñoz I, Casas-Ruiz JP, Gómez-Gener L, Barceló M, Oliva F, Menéndez M (2015). Effects of water flow regulation on ecosystem functioning in a Mediterranean river network assessed by wood decomposition. *Science of The Total Environment* 517:57–65
- Allan JD, Castillo MM (2007). *Stream Ecology: Structure and Function of Running Waters*, 2nd Ed. Springer, Dordrecht, The Netherlands
- Bagnold RA (1966). An Approach to the Sediment Transport Problem from General Physics. USGS Professional Paper 422-I
- Bagnold RA (1980). An Empirical Correlation of Bedload Transport Rates in Flumes and Natural Rivers. *Proceedings of the Royal Society of London A Mathematical and Physical Sciences* 372:453–473
- Baron JS, Poff L, Angermeier PL, Dahm CN, Gleick PH, Hairston NGJ, Jackson RB, Johnston CA, Richter BD, Steinman AD (2002). Meeting ecological and societal needs for freshwater. *Ecological Applications* 12:1247–1260
- Biggs BJF, Goring DG, Nikora VI (1998). Subsidy and stress responses of stream periphyton to gradients in water velocity as a function of community growth form. *Journal of Phycology* 34:598–607
- Boon PJ (1988). The impact of river regulation on invertebrate communities in the U.K. *Regulated Rivers: Research & Management* 2:389–409
- Boon PJ (1998). River restoration in five dimensions. *Aquatic Conservation: Marine and Freshwater Ecosystems* 8:257–264
- Brown D, Butterill G, Bayliss B (2008). Ben Ghyll Geomorphology report. Environment Agency, Version 2.0, Penrith, Cumbria
- Buendía C, Gibbins CN, Vericat D, Batalla RJ (2014). Effects of flow and fine sediment dynamics on the turnover of stream invertebrate assemblages. *Ecohydrology* 7:1105–1123
- Buendía C, Gibbins CN, Vericat D, Batalla RJ, Douglas A (2013). Detecting the structural and functional impacts of fine sediment on stream invertebrates. *Ecological Indicators* 25:184–196
- Buffington JM, Montgomery DR (1997). A systematic analysis of eight decades of incipient motion studies, with special reference to gravel-bedded rivers. *Water Resources Research* 33:1993–2029
- Carpentier C, Dahlhaus A, van de Giesen N, Maršálek B (2013). The influence of hard substratum reflection and calibration profiles on in situ fluorescence measurements of benthic microalgal biomass. *Environmental Science: Processes & Impacts* 15:783–793
- Chevenet F, Dolédec S, Chessel D (1994). A fuzzy coding approach for the analysis of long-term ecological data. *Freshwater Biology* 31:295–309
- Clausen B, Biggs BJF (1997). Relationships between benthic biota and hydrological indices in New Zealand streams. *Freshwater Biology* 38:327–342

- De Nicola DM, McIntire CD, Lamberti GA, Gregory S V., Ashkenas LR (1990). Temporal patterns of grazer-periphyton interactions in laboratory streams. *Freshwater Biology* 23:475–489
- Death RG, Winterbourn MJ (1994). Environmental Stability and Community Persistence: A Multivariate Perspective. *Journal of the North American Benthological Society* 13:125–139
- Death RG, Zimmermann EM (2005). Interaction between disturbance and primary productivity in determining stream invertebrate diversity. *Oikos* 111:392–402
- Dolédec S, Statzner B (2008). Invertebrate traits for the biomonitoring of large European rivers: an assessment of specific types of human impact. *Freshwater Biology* 53:617–634
- Edington JM, Hildrew AG (2005). A revised key to the caseless Caddisfly larvae of the British Isles, with notes on their ecology. Scientific Publication of the Freshwater Biological Association No. 53, Ambleside, UK
- Effenberger M, Engel J, Diehl S, Matthaei CD (2008). Disturbance history influences the distribution of stream invertebrates by altering microhabitat parameters: A field experiment. *Freshwater Biology* 53:996–1011
- Effenberger M, Sailer G, Townsend CR, Matthaei CD (2006). Local disturbance history and habitat parameters influence the microdistribution of stream invertebrates. *Freshwater Biology* 51:312–332
- Elliott JM, Humpesch UH (2010). Mayfly Larvae (Ephemeroptera) of Britain and Ireland: Keys and a Review of their Ecology. Scientific Publication of the Freshwater Biological Association No. 66, Ambleside, UK
- Environment Agency (2014). Restoring Sustainable Abstraction / Heavily Modified Water Body Monitoring Programme - 2010 to 2015. *Environment Agency*, Bristol
- European Union (2000). Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. *Official Journal of the European Communities* L237:1–73
- Feio MJ, Dolédec S (2012). Integration of invertebrate traits into predictive models for indirect assessment of stream functional integrity: A case study in Portugal. *Ecological Indicators* 15:236–247
- Feminella JW, Hawkins CP (1995). Interactions between Stream Herbivores and Periphyton: A Quantitative Analysis of past Experiments. *Journal of the North American Benthological Society* 14: 465–509p.
- Feminella JW, Resh VH (1991). Herbivorous caddisflies, macroalgae, and epilithic microalgae: dynamic interactions in a stream grazing system. *Oecologia* 87:247–256
- Ferguson RI (2005). Estimating critical stream power for bedload transport calculations in gravel-bed rivers. *Geomorphology* 70:33–41
- Fleituch T (2003). Structure and functional organization of benthic invertebrates in a regulated stream. *International Review of Hydrobiology* 88:332–344
- Gibbins C, Vericat D, Batalla RJ (2007a). When is stream invertebrate drift catastrophic? The role of hydraulics and sediment transport in initiating drift during flood events. *Freshwater Biology* 52:2369–2384
- Gibbins C, Vericat D, Batalla RJ, Gomez CM (2007b). Shaking and moving: low rates of sediment

- transport trigger mass drift of stream invertebrates. *Canadian Journal of Fisheries and Aquatic Sciences* 64:1–5
- Gibbins CN, Vericat D, Batalla RJ (2010). Relations between invertebrate drift and flow velocity in sand-bed and riffle habitats and the limits imposed by substrate stability and benthic density. *Journal of the North American Benthological Society* 29:945–958
- Greig SM, Sear DA, Carling PA (2007). A review of factors influencing the availability of dissolved oxygen to incubating salmonid embryos. *Hydrological Processes* 21:323–334
- Hassan MA, Zimmermann AE (2012). Channel response and recovery to changes in sediment supply. In: Church M, Biron PM, Roy AG (eds) *Gravel-bed Rivers: Processes, Tools, Environments*. John Wiley & Sons, Ltd., Chichester, UK, pp 464–473
- Heino J, Muotka T, Mykrä H, Paavola R, Hämäläinen H, Koskeniemi E (2003). Defining macroinvertebrate assemblage types of headwater streams: implications for bioassessment and conservation. *Ecological Applications* 13:842–852
- Hillebrand H (2002). Top-down versus bottom-up control of autotrophic biomass — a meta-analysis on experiments with periphyton. *Journal of the North American Benthological Society* 21:349–369
- Højsgaard S, Halekoh U, Yan J (2006). The R package geepack for Generalized Estimating Equations. *Journal of Statistical Software* 15:1–11
- Hynes HBN (1993). A Key to the Adults and Nymphs of the British Stoneflies (Plecoptera), with Notes on their Ecology and Distribution, 3rd Editio. Scientific Publication of the Freshwater Biological Association No. 17, Ambleside, UK
- Johnson MF, Reid I, Rice SP, Wood PJ (2009). Stabilization of fine gravels by net-spinning caddisfly larvae. *Earth Surface Processes and Landforms* 34:413–423
- Kasprzak P, Padisák J, Koschel R, Krienitz L, Gervais F (2008). Chlorophyll a concentration across a trophic gradient of lakes: An estimator of phytoplankton biomass? *Limnologica* 38:327–338
- Kelly M (2013). Nutrients and algae in the upper River Ehen and their implications for freshwater pearl mussels. Report to United Utilities Water Ltd.
- Kelly M, Snell M, SurrIDGE B, Barker P (2015). Algal interactions with freshwater pearl mussels in the River Ehen, Cumbria: characterisation and quantification of phytobenthos. Report to United Utilities Water Ltd.
- Killeen I (2006). The Freshwater Pearl Mussel, in the River Ehen Cumbria. Report on the 2006 Survey. Malacological Services, Dublin
- Killeen I, Moorkens E (2013). Environmental Monitoring of the River Ehen freshwater pearl mussel population 2012: A report to United Utilities. Malacological Services, Dublin
- Kondolf GM (1997). Hungry Water: Effects of Dams and Gravel Mining on River Channels. *Environmental Management* 21:533–551
- Kruskal JB (1964). Nonmetric multidimensional scaling: a numerical method. *Psychometrika* 29:115–129
- Lamberti GA, Feminella JW, Pringle CM (2007). Primary Producer-Consumer Interactions. In: Hauer FR, Lamberti GA (eds) *Methods in Stream Ecology*, Second Edition, Elsevier Inc.,

Oxford, UK, pp 537–559

- Lange K, Liess A, Piggott JJ, Townsend CR, Matthaei CD (2011). Light, nutrients and grazing interact to determine stream diatom community composition and functional group structure. *Freshwater Biology* 56:264–278
- Larsen S, Ormerod SJ (2010). Combined effects of habitat modification on trait composition and species nestedness in river invertebrates. *Biological Conservation* 143:2638–2646
- Lawrence JR, Scharf B, Packroff G, Neu TR (2002). Microscale evaluation of the effects of grazing by invertebrates with contrasting feeding modes on river biofilm architecture and composition. *Microbial Ecology* 44:199–207
- Liess A, Hillebrand H (2004). Invited review: Direct and indirect effects in herbivore – periphyton interactions. *Archiv für Hydrobiologie* 159:433–453
- Lobera G, Muñoz I, López-Tarazón JA, Vericat D, Batalla RJ (2016). Effects of flow regulation on river bed dynamics and invertebrate communities in a Mediterranean river. *Hydrobiologia* 1–22
- Marks JC, Power ME, Parker MS (2000). Flood disturbance, algal productivity, and interannual variation in food chain length. *Oikos* 90:20–27
- Marteau B, Batalla RJ, Vericat D, Gibbins C (2017). Asynchronicity of fine sediment supply and its effects on transport and storage in a regulated river. *Journal of Soils and Sediments*. doi: [in press]
- Matthaei C, Uehlinger U, Meyer E, Frutiger A (1996). Recolonization by benthic invertebrates after experimental disturbance in a Swiss prealpine river. *Freshwater Biology* 35:233–248
- Matthaei CD, Arbuckle CJ, Townsend CR (2000). Stable surface stones as refugia for invertebrates during disturbance in a New Zealand stream. *Journal of the North American Benthological Society* 19:82–93
- McCune B, Mefford MJ (2016). PC-ORD: Multivariate Analysis of Ecological Data. Version 7.0 for Windows. MjM Software Design, Gleneden Beach, Oregon, U.S.A.: 34p.
- Moir HJ, Gibbins CN, Soulsby C (2003). River Ehen Pearl Mussel Project: Fluvial Audit. University of Aberdeen: 26p.
- Nilsson A (1996). Aquatic Insects of North Europe, Volume 1: Ephemeroptera, Plecoptera, Heteroptera, Neuroptera, Megaloptera, Coleoptera, Trichoptera, Lepidoptera. Apollo Books
- O’Leary D (2013). Pearls in Peril LIFE+ GB - Action A3: Conservation Actions for the Freshwater Pearl Mussel in the River Ehen, Cumbria. Report LIFE 11 NAT/UK/383. West Cumbria River Trust, UK: 45p.
- Oksanen J, Blanchet FG, Friendly M, Kindt R, Legendre P, McGlenn D, Minchin PR, O’Hara RB, Simpson GL, Solymos P, Stevens MHH, Szoecs E, Wagner H (2017). vegan: Community Ecology Package. R package version 2.4-3. <https://cran.r-project.org/package=vegan>.
- Opsahl RW, Wellnitz T, Poff NL (2003). Current velocity and invertebrate grazing regulate stream algae: Results of an in situ electrical exclusion. *Hydrobiologia* 499:135–145
- Palmer TM (1995). The influence of spatial heterogeneity on the behavior and growth of two herbivorous stream insects. *Oecologia* 104:476–486

- Parker C, Clifford NJ, Thorne CR (2011). Understanding the influence of slope on the threshold of coarse grain motion: Revisiting critical stream power. *Geomorphology* 126:51–65
- Parker MS, Power ME (1997). Effect of stream flow regulation and absence of scouring floods on trophic transfer of biomass to fish in Northern California rivers - Technical Report UCAL-WRC-W-825. Berkeley, CA
- Passy SI (2007). Diatom ecological guilds display distinct and predictable behavior along nutrient and disturbance gradients in running waters. *Aquatic Botany* 86:171–178
- Peckarsky BL (1996). Alternative Predator Avoidance Syndromes of Stream-Dwelling Mayfly Larvae. *Ecology* 77:1888–1905
- Peterson CG (1996). Response of Benthic Algal Communities to Natural Physical Disturbance. In: Bothwell ML, Lowe RL (eds) *Algal Ecology - Freshwater Benthic Ecosystems*. Academic Press, San Diego, U.S.A., pp 375–403
- Piqué G, Vericat D, Sabater S, Batalla RJ (2016). Effects of biofilm on river-bed scour. *Science of the Total Environment* 572:1033–1046
- Poff NL, Ward J V (1992). Heterogenous currents and algal resources mediate in situ foraging activity of a mobile stream grazer. *Oikos* 65:465–478
- Ponsatí L, Acuña V, Aristi I, Arroita M, García-Berthou E, von Schiller D, Elosegi A, Sabater S (2015). Biofilm Responses to Flow Regulation by Dams in Mediterranean Rivers. *River Research and Applications* 31:1003–1016
- Quinlan E (2014). Ecogeomorphological dynamics of the River Ehen prior to its restoration. PhD thesis, University of Aberdeen, Scotland
- Quinlan E, Gibbins CN, Batalla RJ, Vericat D (2015). Impacts of Small Scale Flow Regulation on Sediment Dynamics in an Ecologically Important Upland River. *Environmental Management* 55:671–686
- R Core Team (2017). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria
- Schwendel AC, Death RG, Fuller IC, Joy MK (2011). Linking disturbance and stream invertebrate communities: how best to measure bed stability. *Journal of the North American Benthological Society* 30:11–24
- Schwendel AC, Death RG, Fuller IC, Tonkin TN (2012). A new approach to assess bed stability relevant for invertebrate communities in upland streams. *River Research and Applications* 28:1726–17939
- Sear DA, Jones JI, Collins AL, Hulin A, Burke N, Bateman S, Pattison I, Naden PS (2016). Does fine sediment source as well as quantity affect salmonid embryo mortality and development? *Science of the Total Environment* 541:957–968
- Steinman AD (1996). Effects of Grazers on Fresh water Benthic Algae. In: Bothwell ML, Lowe RL (eds) *Algal Ecology - Freshwater Benthic Ecosystems*. Academic Press, San Diego, U.S.A., pp 341–373
- Tachet H, Richoux P, Bournaud M, Usseglio-Polatera P (2006). Invertébrés d'eau douce - systématique, biologie, écologie. CNRS Edition, Paris
- Townsend CR, Scarsbrook MR, Dolédec S (1997a). Quantifying disturbance in streams:

- Alternative measures of disturbance in relation to macroinvertebrate species traits and species richness. *Journal of the North American Benthological Society* 16:531–544
- Townsend CR, Scarsbrook MR, Dolédec S (1997b). The intermediate disturbance hypothesis, refugia, and biodiversity in streams. *Limnology and Oceanography* 42:938–949
- Underwood GJC, Kromkamp J (1999). Primary production by phytoplankton and microphytobenthos in estuaries. *Advances in Ecological Research* 29:93–153
- Vallania A, Corigliano MDC (2007). The effect of regulation caused by a Dam on the distribution of the functional feeding groups of the benthos in the sub Basin of the Grande River (San Luis, Argentina). *Environmental Monitoring and Assessment* 124:201–209
- Vaughan IP, Noble DG, Ormerod SJ (2007). Combining surveys of river habitats and river birds to appraise riverine hydromorphology. *Freshwater Biology* 52:2270–2284
- Wallace ID, Wallace B, Philipson GN (2003). Keys to the Case-bearing Caddis Larvae of Britain and Ireland. Scientific Publication of the Freshwater Biological Association No. 61, Ambleside, UK
- Wallace JB, Webster JR (1996). The role of macroinvertebrates in stream ecosystem function. *Annual Review of Entomology* 41:115–39
- Wolman MG (1954). A method of sampling coarse river-bed material. *Transactions, American Geophysical Union* 35:951–956
- Wootton JT, Parker MS, Power ME (1996). Effects of Disturbance on River Food Webs. *Science* 273:1558–1561
- Young MR (2005). A literature review of the water quality requirements of the freshwater pearl mussel (*Margaritifera margaritifera*). Scottish Natural Heritage Commissioned Report No. 084 (ROAME No. F01AC609d): 18p.

CHAPTER 7.

SYNTHESIS AND CONCLUSIONS



*Confluence of Ben Gill with the Ehen at Ennerdale Water outlet, after the reconnection of Ben Gill.
Photos: Baptiste Marteau, July 2015.*

CHAPTER 7. SYNTHESIS AND CONCLUSIONS

7.1. CONTEXT

This thesis aimed to assess the geomorphological evolution of the River Ehen following the reconnection of its headwater tributary, Ben Gill; it provides information that is critical for the Environment Agency to help assess the Ehen's ecological response in the future. The core of this work sits on the back of the thesis of Emma Quinlan (2014) who studied the sedimentary, geomorphic and ecological conditions of the river prior to the reconnection.

Post-project monitoring has been long argued to be crucial to the proper evaluation of the success or failure of restoration projects (Bradshaw 1996; Boon 1998; England et al. 2008) and to the learning experience required for the future of ecological restoration (Hobbs and Harris 2001; Palmer et al. 2005). However, few restoration or rehabilitation programmes include both a pre- and post-project evaluation (Bernhardt et al. 2005; Alexander and Allan 2007; Jähnig et al. 2011; Pander and Geist 2013). In this context, and beyond the actual results of the restoration project itself, both the thesis of Emma Quinlan (2014) and this work hopefully represent an example of good practice (Jungwirth et al. 2002; Wohl et al. 2005; Alexander and Allan 2007; Friberg et al. 2011).

This project is also a unique example of system-scale and 'non-invasive' restoration/rehabilitation. It involved the reconnection of a tributary and its catchment, something different to the frequently reported gravel augmentation that involves material being 'dumped' in the channel or delivered artificially. In the case of the Ehen, the characteristics of the sediment delivered, as well as the volume and frequency of these deliveries, are controlled by the tributary and its ephemeral properties. Although the excavation of the new channel involved bringing diggers and engineering machines on site, none of the work required direct access to the Ehen. The direct or immediate effects of the work on the Ehen threatened pearl mussel population were virtually non-existent. In particular, great care was taken to prevent fine sediments from reaching the river during the time of the excavation, with mussel biologist having an input to the design of the engineering activities. Beyond the fact that these efforts were carried out for the purpose of protecting the population, the work on the Ehen adheres to Leopold's (1948) first 'rule' of restoration, as reported by Palmer et al. (2005) - 'the aim of restoration should be to do no harm'.

Finally, it is hoped that the reach of this work goes beyond the case of the River Ehen. Some of the information and data acquired as part of the post-project monitoring, which provided a better understanding of the focal system, may also provide valuable knowledge to the wider scientific community, whether they are involved in similar initiatives elsewhere, interested in fluvial dynamics or in the interactions between these dynamics and aquatic biota.

7.2. GENERAL RESEARCH APPROACH

The research presented in this thesis was divided in three main parts. First, in order to characterise the sediment input to the Ehen, it was crucial to monitor the geomorphic evolution of the newly reconnected tributary. To do so, an approach based on Structure-from-Motion photogrammetry (SfM) from aerial images was tested (Chapter 2). SfM allows the computation of 3D point-clouds from photographs. When combined with a network of GPS-referenced ground control points (GCPs), it is possible to geo-reference the models. 3D point-clouds were decimated using GIS software and specific geostatistical algorithms to create Digital Elevation Models (DEMs) for a total of eight flights undertaken over the study period. The comparison of successive DEMs (by means of DEMs of Difference (DoDs)) was used to determine the magnitude and nature of geomorphic changes in the channel (erosion and sedimentation) and, ultimately, to quantify the minimum volume of material supplied to the River Ehen. The methodology was illustrated with data from the first 3 surveys. The entirety of the data collected (8 surveys) were presented in more details in Chapter 5. Although SfM is now widely used in fluvial geomorphology, the novelty of the application to the Ehen resides in the type of camera used (fish-eye lens), the great attention to calibration and assessment of model errors, the high model resolution achieved, the relatively high temporal resolution of the survey design, and in its application to a river restoration project. The high model resolution and the high frequency of surveys provided valuable information for the assessment of changes in the Ehen in response to the renewed delivery of sediment.

The second main part of the project was the assessment of both sedimentary and geomorphic changes in the main-stem Ehen. By comparing suspended sediment loads two years prior and two years after the reconnection, it was possible to quantify the increase in fine suspended sediment loads (SSLs) related to this new delivery sediment (Chapter 3). To do so, data from a turbidity meter located c. 550 m downstream from the confluence of Ben Gill with the Ehen (Bleach Green gauging station) were used to compute suspended sediment concentrations

(SSCs). The relationship between turbidity and SSC was determined empirically for the post-reconnection period, with data of Quinlan et al. (2015a) used for the pre-reconnection period. Changes in SSL were related to the hydrological context of the four years used in the analysis. These changes should also be considered within the context of the ongoing erosion in the tributary, which is still adjusting to its new conditions. The work allowed appraisal of the role played by small ephemeral streams, a role often overlooked, especially in temperate regions. The scale of changes in SSL was important in the context of the relatively small size of Ben Gill catchment and the regulated nature of the main-stem Ehen. Its ecological significance is accentuated by the sensitivity of the freshwater pearl mussel to fine sediment deposition.

The fate of this increased SSL was assessed by looking at changes in in-channel fine sediment storage (Chapter 4). Using the method described by Lambert and Walling (1988), three morphological units (‘plane bed’, ‘riffle’ and ‘pool’ units) were sampled on thirteen occasions over the course of two years, with five samples per unit to cover spatial variations in storage. Samples were analysed for the amount of fine sediment stored, but also for the organic content and the particle size distribution of the stored sediment. Two key events were found to be significant in driving patterns of storage: the exceptional and localised rainfall event observed the day after the reconnection, which triggered a large release of fine sediment from Ben Gill, and the 30-year return floods of winter 2015 associated with the storms that hit the west of the UK. More generally, the use of a time-lapse camera facing the confluence of Ben Gill allowed for the characterisation of different flow scenarios that proved key to understanding variations in sediment storage. A particularly significant finding was that flows in Ben Gill are not always associated with high flows in the Ehen. This means that deliveries of fine sediments from the tributary are not necessarily met with competent flows in the Ehen, which can lead to the deposition of fines on the riverbed. Values of storage and computation of SSC were used to determine the reach-scale fine sediment budget. Additionally, data from a turbidity meter located c. 3.5 km downstream from the gauging station were used to compute fine sediment budget for this downstream reach. Comparison of the budget of these two reaches provided an insight into the role of lateral and intermittent sources of sediments in the upper Ehen.

The methodology presented in Chapter 2 is used for the entire data collected to capture geomorphic changes in Ben Gill. A similar approach was used to compute DoDs of the confluence bar, where most of the coarse sediment exported from Bill Gates is stored. These had to account for the fact that part of the bar was underwater, where capturing topography

from SfM photogrammetry remains challenging. Indeed, one of the aerial surveys could not be used over the confluence bar due to high water levels in the Ehen and high turbulences at the lake outlet. The fate of the coarse material supplied to the Ehen was assessed by monitoring (i) bed surface grain size distribution (GSD), using Wolman pebble count method (Wolman 1954); (ii) surface particle mobility, using painted tracers; and (iii) cross-sectional topography, surveyed with an acoustic Doppler current profiler (aDcp). These surveys were repeated regularly over a two-year period. A tool used to compare particle size distributions (Scheibelhofer et al. 2016) was introduced and successfully identified changes in GSD. Particle mobility was compared to the dataset collected by Quinlan et al. (2015a) to assess changes in mobility patterns following the reconnection. The topographic data provided a first order approximation of patterns of erosion and deposition in the channel. Together, these survey data were used to generate hypotheses about the processes occurring in the Ehen in response to the renewed delivery of coarser material from Ben Gill. These were complemented by visual observations of changes that were not necessarily captured by the quantitative surveys.

The third main part of the research, described in Chapter 6, stemmed from observations of unusual trends in algal biomass in the River Ehen, and concerns about what high biomass could mean for pearl mussels. While most rivers exhibit patterns of algal growth in the summer and lower biomass in the winter, routine monitoring by Kelly et al. (2015) revealed opposite trends in the Ehen. A hypothesis put forward by these authors, related to grazing pressure by invertebrates was tested in Chapter 6 by comparing conditions at two sites in the Ehen with two sites in a neighbouring stream, Croasdale Beck. For thirteen months, algal biomass and composition (diatom, green-algae and cyanobacteria) were sampled by Kelly et al., in parallel with invertebrate sampling, water chemistry analysis and measurement of bed disturbance using painted tracers carried out by the author. Analyses focussed on trying to disentangle the relative influence of flow competence, bed disturbance, water chemistry and invertebrate grazing on algal biomass, and how these may differ in the regulated River Ehen compared to the more dynamic and free flowing Croasdale Beck. Results provided insights into the complexity of environmental controls mediating biological interactions, and how flow alteration may influence these. The study also shed some light on the ecological consequences of the regulation of the Ehen and the diversion of its headwater tributary.

The main scientific findings of the thesis are summarised and discussed below. The discussion is framed by the need to assess the 'success[es]' (and 'failure[s]') of the restoration project, and

the requirement to consider the future of the freshwater pearl mussel population in the River Ehen.

7.3. MAIN SCIENTIFIC FINDINGS

The use and application of Structure-from-Motion photogrammetry for river restoration.

Structure-from-Motion photogrammetry (SfM) is widely used in physical geography (see reviews by Tarolli 2014; Micheletti et al. 2015; Smith et al. 2015) and particularly in fluvial geomorphology (Marcus and Fonstad 2010; Bangen et al. 2014). Along with other remote sensing techniques, SfM fostered the so-called ‘high resolution topography revolution’ (Vericat et al. 2017) and marked a turning point in the development of the ‘riverscape’ concept (Carbonneau et al. 2012). However, there is a field where few examples of the use of SfM exist - that of river restoration. Chapter 2 described the application of SfM to the reconnection of Ben Gill.

The SfM photogrammetry workflow, although similar to others found in the literature (e.g. Westoby et al. 2012), included some innovation in the assessment of model accuracy. Due to the limitation imposed by the use of a fish-eye lens, preliminary tests were performed using large ‘chessboards’ and painted semi-spheres to assess the quality of the SfM outputs. In addition to helping defining the best range of flight altitude, this step provided confidence that the SfM outputs would yield results with a precision and accuracy that would allow the capture of fine-scale geomorphic changes. The second innovation was the use of a bootstrapping procedure, run 1000 times, to randomly select part of the GCPs as Check-points (ChPs) (the rest being used as markers) and determine the registration error, model precision and model accuracy for each GCP. This was found to be more representative of the errors associated with the model created than a static selection of a set of ChPs. The tests and study results emphasised the need for an appropriate match between the equipment used and the design and objectives of the research. Results presented in Chapter 5 indicate that even regularly-criticised fish-eye lenses (Thoenen et al. 2014) can yield robust assessments of geomorphic change, give a suitable GCP network.

The high resolution of the DEMs was valuable in the detection of small-scale changes and the interpretation of processes. As regularly reported in the literature (e.g. Brasington et al. 2003; Wheaton et al. 2010b), positive changes were more affected by the application of minimum

levels of detection than negative ones. Thus, high-quality results, yielding better model accuracy and lower limits of thresholding, are more likely to provide not only better estimates, but also a more accurate assessment of the balance in the relative changes.

Some authors argue that, given the low cost and ease of use (Micheletti et al. 2014), SfM might become standard for the production of topographic data (Carbonneau and Dietrich 2016). The interesting 'deployment costs' vs. 'quality of results' ratio resulting from this study stresses the potential benefits of using such techniques and platforms more extensively in river restoration/rehabilitation contexts, where the multi-temporal characterisation of physical habitat is argued to be critical but too-often missing (Lamouroux et al. 2015).

Reconnecting a 'long-lost' ephemeral sub-catchment to the regulated River Ehen yielded a shift in main driver of suspended sediment dynamics during the first two years post-reconnection.

Part of the flux of material measured from the DoDs is made of fine sediment. For example, the heavy rainfall event that triggered important erosion in Ben Gill on the first day it was opened generated a peak in SSC that was out of the range of the turbidity sensor (i.e. 1000 NTU). It is estimated that over 35.7 t of fines entered the Ehen from Ben Gill over this 48-h period, representing c. 23% of the average sediment yield pre-reconnection. These extreme conditions were not met again during the course of this study, although annual SSL increased by 65% on average following the reconnection. This is significant given the relative size of the two systems; Ben Gill drains only 0.55 km² and its reconnection represented a 1.2% increase in catchment size. Maximum SSCs increased, although the annual mean and median SSCs remained unchanged. Thus, baseline SSCs are not affected by the reconnection; instead, the effects of sediment delivery by Ben Gill are limited to frequent and high SSCs events, but which are short in duration. The transport-frequency curves provided insight into the timing and magnitude of the events.

It is important to note that flows in Ben Gill had a negligible effect on the hydrology of the Ehen. The two years pre- and two years post-reconnection both exhibited a wetter and a dryer year, but neither differences in water yield nor in discharge statistics was found in relation to the reconnection. The reconnection only appeared to affect SSCs, with a higher proportion of the annual sediment yield transported over a shorter period of time in the post-reconnection period. Overall, these results confirm that plumes of fine sediments are delivered into the Ehen

by Ben Gill intermittently (i.e. when Ben Gill is flowing) and that most of the SSL is transported through intense but short-lived SSC events. These changes were observed during the two years post-reconnection, with the newly created section of Ben Gill channel still undergoing a relatively intense activity as it adjusts to its new conditions.

Despite a 65% increase in SSL, the relationship between SSC and discharge revealed that the upper River Ehen remained sediment-supply limited. In their earlier study, Quinlan et al. (2015a) argued that the river showed limited sedimentary activity. This was confirmed during period of the current study which sat immediately prior to the opening of Ben Gill, and then following the reconnection. In other words, the upper Ehen could theoretically carry more sediment than it currently receives. Rivers hosting freshwater pearl mussel are typically oligotrophic supply-limited systems (Skinner et al. 2003). Their presence in the Ehen, with some individuals being older than the diversion of Ben Gill, indicates that mussels were present long before human intervention, and that they benefited from the limited sedimentary activity. Thus, while the river could transport more sediment, this would mean a deviation from its natural state and increased risks of deposition and accumulation of fine material on the riverbed.

The scatter-plot of the relationship between discharge and SSC pre- and post-reconnection showed that this relationship has been altered since Ben Gill was reconnected. The difference is most obvious at low and medium discharges. While patterns remained unchanged at low flows, the scatter in the relationship is greater below $c. 20 \text{ m}^3 \text{ s}^{-1}$. Fluvial dynamics at low flows are largely controlled by the supply from Ben Gill, so are not intrinsically related to internal processes of the Ehen. The best illustration of changes in the basic hydraulic-sediment transport relation concerns medium flows; material deposited during previous events is temporarily stored in the riverbed and becomes available on the rising limb of the following event. However, the amount of sediment available is quickly exhausted and the scatter shows no further increase in SSC over $c. 20 \text{ m}^3 \text{ s}^{-1}$.

Other evidence of changes following the reconnection lies in the difference in the turbidity-SSC relationships. Data from Quinlan et al. (2015a) were compared to the empirical calibration (field-based) of the turbidity meters performed in the current study. The two linear regressions were found to be significantly different. This can be interpreted as a change in the quality or character of the suspended sediments and can be related to the new source of sediment -Ben Gill. Although the exact nature of these changes is unknown (e.g. change in colour, particle

size, shape, mineralogy, organic content), it is an additional evidence (along with the changed Q-SSC relationship) that Ben Gill has become the main driver of fine sediment dynamics in the upper Ehen, both in quantitative and qualitative terms. Wider repercussions and potential implications of the pearl mussels are discussed in some of the following sections.

The fate of increases in suspended sediment delivery is controlled by the degree of (a)synchronicity in flows between the tributary and those in the main-stem.

Excessive deposition of fine sediment is known for having marked ecological effects (Wood and Armitage 1997; Bilotta and Brazier 2008; Buendía et al. 2014). This becomes most problematic for species that spend part or the entirety of their life cycle buried within the subsurface zone (e.g. salmonids, Greig et al. 2005) as is the case of the freshwater pearl mussel (Bauer 1988; Buddensiek et al. 1993; Young et al. 2001; Geist and Auerswald 2007). Moreover, these effects can be exacerbated by the presence of organic matter (Tarr 2008). Thus, assessing the risks associated with the increase in SSL requires a careful monitoring of in-channel fine sediment storage, including volumes, particle sizes and the organic content of the stored sediment. A better understanding of the relationship between flows in Ben Gill and those in the Ehen was necessary to characterise controls on fine sediment storage.

Of the three morphological units present within the main study reach, the pool always showed higher in-channel storage. The two other units (riffle and plane bed) showed no significant differences between each other. Temporal variations in in-channel storage over the study period were dominated by two main events; the heavy rainfall on the first day of the opening of Ben Gill and the associated release of fine sediment (significant increase in storage), and the series of large floods in December 2015 (significant decrease in storage). These changes were particularly noticeable in the pool. Overall, the average amount of sediment stored in the section doubled between the start and the end of this study (from 1.8 to 3.6 t), with a peak at > 7.4 t after a dry spell associated with frequent release of fines from Ben Gill.

Compared to pre-reconnection conditions, the peak in storage represented a 350% increase. By the end of the study, storage had stabilised around c. 200% of pre-reconnection values. Abrupt changes in fine sediment load and deposition may have ecological consequences (e.g. Buendía et al. 2013b, 2014; Béjar et al. 2017). Levels of fine sediment in the riverbed of the Ehen are not excessive when compared to the literature for the UK and remain typical of rivers

with limited sedimentary activity. The maximum of $1,800 \text{ g m}^{-3}$ recorded in the pool is far from values found in small agricultural catchments (e.g. Walling et al. 2002; $23,400 \text{ g m}^{-2}$) or lowland rivers (e.g. Heppell et al. 2009; $66,800 \text{ g m}^{-2}$) and reach-scale averages of 224 to 907 g m^{-2} are in line with what most authors have reported in the UK (i.e. 200 to 2000 g m^{-2} ; e.g. Walling et al. 1998; Owens et al. 1999; Wilson et al. 2004; Collins and Walling 2007b). Nonetheless, these fines could potentially have implications for the pearl mussels (see further discussion below).

Characteristics of stored sediment (i.e. particle size distribution, organic content) differed in the pool compared to the riffle and the plane bed. The reconnection had no influence on the size distribution of stored sediment, most likely reflecting the absence of change in channel hydraulics; i.e. the processes and conditions involved in the deposition of fines remained unchanged. Some differences were observed in the composition of stored sediment, with lower percentages of organic matter (from c. 10 to 6%). However, this relative decrease is probably related to the fact that average in-channel storage increased by a factor of 2 following the reconnection. The floods of December 2015, however, resulted in a change in particle size distribution. The proportions of sand increased and silt decreased, while clay remained similar. These observations can be related to the size-selective retention by the pavement which retained the coarsest (i.e. sand) and the most cohesive fractions (i.e. clay), and resulted in an overall coarsening of the surface layer (e.g. Whiting and King 2003).

Variations in the amount of fine sediment supplied and stored in the riverbed were assessed through the lens of the relationship between flows in the Ehen and those in Ben Gill. Three main scenarios of flow (a)synchronicity were identified and linked to different patterns of in-channel storage. When Ben Gill flows, it delivers large volumes of fine sediments. If this happens when flows in the Ehen are low (e.g. compensation flow, no weir overflow), this generates high SSCs with virtually no dilution effect (referred to as 'Scenario 1'). Such conditions (total asynchronicity) are responsible for extensive deposition of fines on the riverbed. When Ben Gill flows but flows in the Ehen are high (total synchronicity, Scenario 3), the dilution of the sediments brought by Ben Gill means that no or very little (i.e. below detection limits imposed by sampling error) deposition occurs. Additionally, when flows are very high, the energy available is also capable of cleansing the bed of material deposited previously. There are numerous intermediate scenarios which were grouped together as Scenario 2. These were found to have mixed effects depending on the degree of (a)synchronicity. Clearly, the deposition of fines is conditioned by the presence or absence of high flows in the Ehen, with

type 1 Scenarios most problematic ecologically. Although it is not possible to anticipate heavy localised rainfall events, such as the one observed on the day following the reconnection, from a management perspective it is evident that limiting the number of days when lake levels are too low for the weir to overspill would decrease the chances of observing type 1 scenarios.

Intermittent sources of fine sediment may be the main source of suspended sediment in supply-limited systems.

The importance of tributaries for main-stem fluvial processes is often highlighted in terms of coarse material delivery (Rice 1998, 2016; Lisenby and Fryirs 2017). They can, however, have a major influence on the delivery of finer material (Webb et al. 2000; Collins and Walling 2006). Ephemeral or intermittent tributaries can show high variability in their sediment delivery (e.g. López-Tarazón et al. 2011; Tena and Batalla 2013). As these streams are mostly studied in arid and Mediterranean regions, little is known about their role in temperate climate regions.

The computation of reach-scale sediment budgets revealed the dominance of intermittent lateral sources of fine sediments in two reaches studied within the upper Ehen. These sources differed in their nature -a single ephemeral tributary (Ben Gill) in the upper reach and a combination of ditches and surface run-off in the lower reach. Nevertheless, the results are similar with an estimated minimum of 40% of the annual sediment budget coming from these intermittent lateral sources.

While the importance of ephemeral streams for suspended sediments in wet climates is understudied, the release of fine sediments from agricultural fields and surface run-off is well documented (e.g. Collins et al. 2012). It is especially exacerbated in regulated systems where input from upstream is negligible as a result of sediment trapping by dams. Additionally, failure of pearl mussel recruitment has been linked to high water turbidity and sedimentation (Österling et al. 2010), which can be attributed to such catchment processes and changes in land-use (Varandas et al. 2013). One implication of this is that it is possible to target such sources of fines and to put management schemes in place to limit the input of fine material. This has been advocated by the Environment Agency and actions in the Ehen have been taken to remedy this problem (e.g. APEM 2015). Finally, a continued monitoring of SSC will help define whether part of this large volume of fine sediments Gill is generated by adjustments in the

newly created section of Ben Gill in response to the reconnection, or whether the supply of sediment is likely to continue in the future at a similar rate.

Ben Gill supplies coarse sediment to the Ehen, although exports are not matched with periodic removal from the confluence bar.

Tributaries are widely recognised as playing important roles in fluvial systems. They can affect environmental conditions in main-stem river channels (Rice et al. 2001a) as well as the biology and ecology downstream of confluences (e.g. Rice et al. 2006, 2008). The influence of tributaries is particularly important downstream from impoundments, from a geomorphological (Lisenby and Fryirs 2017) as well as an ecological perspective (Stevens et al. 1997).

The delivery of coarse sediment by Ben Gill was at the core of the Ehen restoration project. However, no information existed in terms of the rate of delivery. Monitoring the geomorphic evolution of Ben Gill and the confluence bar proved critical in determining how much sediment is transferred and readily available for transport in the Ehen.

Due to the 'snapshot' nature of the methods used, estimates of fluxes are only limited to what was captured and so represents only minimum values (i.e. sediment supplied from upstream the engineered channel is not computed in the estimates). Additionally, local compensation of scour and fill processes (Lindsay and Ashmore 2002) that may occur between the survey periods could also interfere on the estimates. Ben Gill exported an estimated 412 m³ over the 2-year period of this study. However, only a fraction of this volume is mobilised by the river since c. 75% of the material remained stored in the confluence bar (307 m³). In fact, the bar has shown limited signs of erosion throughout the study; only 8% of the material that was previously deposited ended up being re-mobilised. Although there are limitations to these estimates (e.g. poor underwater topography around the bar), it can be supported by additional field observations not included in the thesis. Series of painted tracers were seeded in Ben Gill early in the study with the aim of computing estimates of bedload transport rates. However, tracer recovery rates were very poor; only particles that were not in the main channel (i.e. not directly subject to flows) were recovered. More interestingly, only a couple of all these lost tracers were later found in the upper Ehen; it is likely that the rest (c. 150) were trapped in the gravel bar and were not remobilised once deposited there.

Overall, the average rate of net export is estimated at just over $52 \text{ m}^3 \text{ y}^{-1}$. If we consider that a large fraction of this material is now deposited in the riffle, where a gravel bar has been developing and sedimentation was documented, only a small amount of material is actually available for dispersion elsewhere in the reach. These findings might explain why the (slow) rate of the geomorphic response in the Ehen differs from the (large) scale of changes in Ben Gill.

The renewed delivery of coarse sediment is improving bed mobility conditions.

A growing number of restoration or rehabilitation initiatives are initiated in recognition of the consequences of sediment starvation and consecutive fluvial adjustments from river regulation (e.g. Kondolf et al. 2014; Smith et al. 2014). For instance, gravel augmentation is common-place in restoration or rehabilitation projects where rivers are disconnected from their natural sediment supply (e.g. Habersack and Piégay 2008; Gaeuman 2012) and particularly with the aim to improve habitat for a target species (e.g. Wheaton et al. 2004a; Merz et al. 2006; Pasternack 2008). However, the artificial injection of sediment has several limitations (Harvey et al. 2005) and does not restore sediment connectivity. Perhaps more desirable as a long-term solution is to reconnect the affected river with its natural source(s) of sediment. The reconnection of Ben Gill to the River Ehen is an example of the restoration of catchment connectivity and offers the possibility to study geomorphological adjustments to the renewed delivery of coarse material in a sediment-starved system.

The riverbed of the Ehen showed signs of compaction and stability prior to its restoration (Quinlan et al. 2015a), with a low degree of channel complexity. Following the reconnection, the delivery of coarse material from the tributary has recommenced. Along with the increased sedimentary and geomorphic activity, tracer data suggest that surface particle mobility has improved following the reconnection. These results are in line with conclusions from flume experiments that investigated the behaviour of gravel addition to armoured bed (e.g. Sklar et al. 2009; Koll et al. 2010; Venditti et al. 2010a). The absence of large-scale geomorphic reworking suggest that the new sediment delivered has some but limited interaction with the existing surface layer. Although the exact degree of armouring is unknown, it is clear from Plate 7.1 that the subsurface layer is much finer than the compact and stable surface layer, which appears totally covered in algae (i.e. a sign of stability). Thus, the new material is likely to be

moving as a carpet-layer of sediment on top of the old bed, accumulating in preferential depositional areas (e.g. right bank in the riffle) and filling the very rare interstices where the pavement has been breached (Plate 7.1). Nevertheless, it is sufficient to increase surface particle mobility significantly in the two most active morphological units (i.e. plane bed and riffle).



Plate 7.1. Photographic evidence of partial break-up of the pavement downstream from a hydraulic jump. Arrow shows flow direction. (Photo: Baptiste Marteau).

Despite this relative increase, mobility patterns remain rather limited in the upper Ehen. The 30-year return period flood was barely able to mobilise particles of a distribution coarser than the surface layer. In addition, although no pre- and post-reconnection comparison was possible for the pool, it appears that particle mobility is very limited in this unit. Nevertheless, given the direction of change and the continued delivery of coarse material from Ben Gill, it can be hypothesised that surface particle mobility should increase with time. Interpretation of flume studies (e.g. Venditti et al. 2010b, a) suggest that this may improve once (i) the thickness of the carpet-layer increases (i.e. above 1 to 2 times the D_{50} of the surface layer); (ii) larger particles are being added to the carpet; and/or (iii) channel complexity increases, changing the distribution of velocities and creating conditions favourable (during high flows) for the break-up of the pavement.

The upper Ehen is showing early signs of a geomorphological response to the renewed delivery of coarse material.

As river channels show different phases in their response to dam closure (Petts and Gurnell 2005), they are likely to experience similar periods of relaxation following restoration or

rehabilitation actions. Added gravel can either be transported alongside the original load without much interactions (termed “passive dispersal”) or can result in a complete metamorphosis of the channel (“active transformation”) (Knighton 1991). The morphological response of the Ehen to the reconnection of Ben Gill is likely to involve a gradual shift along this spectrum, as the interaction of the new material with the existing riverbed increases with time. Early signs of changes were observed during the first two years post-reconnection.

The first and most obvious sign of change is the development of the large bar at the confluence of Ben Gill and the Ehen. The topography of the riverbed downstream from the weir was uniform and showed no evidence of the presence of an old depositional bar immediately prior to the reconnection. Aerial photo from 1970 (pre-diversion, Plate 7.2) demonstrates that the confluence bar at this time was extensive, covering a large part of the section directly downstream from the dam (arrow 1). By 2003, there was no evidence left of this confluence bar. Two years after the re-opening of the channel, the depositional feature has regained most of its initial size.



Plate 7.2. Aerial photos of the confluence of Ben Gill with the River Ehen, at the outlet of Ennerdale Water. Flow direction in the main-stem Ehen is from left to right. Arrows 1 & 2 refer to different morphological features detailed in the text.

(Credit: 1970, Environment Agency [Penrith]; 2003, Google Maps; 2016, Jason Hagon on the account of the University of Aberdeen).

Another depositional feature is visible from these images (Plate 7.2, arrow 2), a few hundred metres downstream from the confluence. This feature was lost following the disconnection

(2003) but has now started to redevelop (2016; arrow 2). While the size of the bar was clearly greater in 1970 than it is today, it indicates that the direction of changes in the upper Ehen is towards a recovery of the geomorphic features that existed prior to the diversion of Ben Gill.

The development of this lateral bar (in the riffle of the study reach) was confirmed by the repeat topography surveys. These surveys also revealed an overall lowering of the riverbed in the plane bed (directly downstream from the confluence) and some erosion in the transitional area (downstream from hydraulic jump, where Plate 7.1 was taken). Overall, net changes are rather limited but the spatial variations in the direction of change shows that the complexity of channel morphology is slowly increasing.

Adjustments were also observed in bed surface grain size distributions, and particularly in the riffle. There, grain sorting increased and the distribution became finer. Although these changes are small, they were -and remained- significant compared to pre-reconnection conditions. This illustrates that adjustments in bed texture in response to the restoration have the potential to last over time.

The flow regulation by Ennerdale Lake and initial diversion of Ben Gill, as well as its reconnection, have potential implications –not just for the freshwater pearl mussel but freshwater organisms more generally. These are discussed in the section which follows.

The consequences of flow regulation and the diversion of Ben Gill also affect macroinvertebrate communities and algal biomass.

Freshwater pearl mussels require high quality water, and particularly well-oxygenated interstitial water (Bauer 1988; Young 2005). The presence of algae may lead to a blocking of interstitial spaces and smothering of juvenile pearl mussels (Young et al. 2003). The decay of organic matter may also increase the biological oxygen demand and decrease interstitial oxygen levels (Greig et al. 2007). Anecdotal evidence of dense algal mat on the riverbed (Killeen 2006) has raised concerns about how this may affect the mussel population of the Ehen (Kelly 2013). Additionally, Kelly et al. (2015) have reported unusual patterns of algal growth in the winter, with lower biomass found in the summer. As presented in Chapter 6, understanding the controls on algal biomass, in the light of the comparison with a neighbouring dynamic and free-

flowing stream (Croasdale Beck), has revealed the importance of flow regulation and bed stability in the Ehen.

Notwithstanding differences in catchment size and flow magnitude, the hydrological regime of Croasdale Beck appeared markedly more dynamic and variable than that of the Ehen. Study of painted tracers, used to monitor bed disturbance, also indicated that the Ehen had a more stable riverbed. The floods of December 2015 had a significant effect on bed disturbance (all tracers lost) and channel geometry (personal observations) in Croasdale, while not all tracers were moved in the Ehen. Between-site differences were also observed, particularly in the Ehen. The relationship between metrics of flow competence (i.e. maximum unit stream power and excess unit stream power) and bed disturbance was significant for all sites, but the upper site in the Ehen (ESC, closest to the lake and weir) showed the weakest coefficient of determination. This means that particle displacement is controlled by other factors than just the energy available, which is likely related to the presence of a pavement combined with lower flow competence. High bed compaction and lack of particle movement was already noticed by Quinlan et al. (2015a) and is typical of rivers suffering from human alteration leading to limited (coarse) sediment supply (Williams and Wolman 1984; Church 1995; Kondolf 1997).

Similar conclusions about the nature of the River Ehen can be drawn from an ecological perspective. The ordination of macroinvertebrate assemblages indicated significant dissimilarities between the upper Ehen site (ESC) and the two Croasdale Beck sites, with the lower Ehen site (EOX) situated in-between along the principal axis. This was interpreted as reflecting the degree of alteration, with Croasdale Beck being free-flowing and highly dynamic, ESC suffering from the regulation and diversion of Ben Gill and EOX showing signs of potential 'recovery' with distance downstream from the lake. It was also hypothesised in Chapter 6 that the limited bed disturbance at ESC played a role in maintaining a constant balance in functional feeding groups by providing refugia during floods. Similar observations were made elsewhere about the role of bed stability (Matthaei et al. 2000; Gibbins et al. 2007b, a) which may have prevented the dominance of fast-colonisers once flows receded (Effenberger et al. 2008). ESC was the only site with numerous 'piercers', such as the Trichopteran *Hydroptilidae* larvae which feed on filamentous algae (Tachet et al. 2006). Their presence reflect the high stability of the riverbed, but also sub-optimal conditions for the pearl mussel (Young et al. 2003).

No clear or strong link could be found between invertebrate grazing pressure and algal community composition from the ordination. While seasonality, represented by water

temperature, was the strongest controlling factor, unit stream power (and the related bed disturbance) remained the only other environmental variable capable of explaining patterns in algal community changes. This likely reflects the large floods experienced in December 2015 which altered the cycle of winter algal growth observed by Kelly et al. (2015) during the previous years. Although not picked as significant in the ordination, the weight of the 'grazing-scraping' category in the macroinvertebrate assemblages (i.e. abundance of taxa multiplied by its affinity for the category 'scraper-grazer') was found to be negatively significantly correlated with abundance of chlorophyll-*a* when using Generalised Estimating Equations. While this cannot be used as strong proof of the influence of grazing on algal biomass (other metrics of grazing pressure showed mixed and to some extent confusing signals), it suggests that there may be an underlying link between the two, particularly in the Ehen where biological interactions between primary producers and grazers may have been blurred by the effects of the 30-year return flood which occurred.

7.4. APPRAISAL OF THE SUCCESS[ES] (AND FAILURE[S]) OF THE RESTORATION PROJECT

7.4.1. Implication of adjustments in channel morphology and processes for the freshwater pearl mussel.

The research has revealed that the upper Ehen is undergoing sedimentary and geomorphic adjustments in response to the reconnection of Ben Gill. Some of these changes may have implications for the freshwater pearl mussel population living in the river. Despite a few knowledge gaps in the interaction between the mussel and its habitat (Quinlan et al. 2015b), this section tries to determine how the observed changes in the Ehen may affect its population. To do so, it draws heavily on the review of their physical habitat requirements by Quinlan et al. (2015b).

Hydraulics

Hydraulic conditions in the Ehen are conditioned by the geomorphic adjustments of the channel and flow regulation. While an analysis of the latter is out of the scope of this thesis, it has been observed that channel complexity has started to increase in response to the reconnection of Ben Gill. This was particularly visible in the riffle, with the formation of a lateral bar on the true right bank and a slight deepening on the opposite side. Optimum mean water

column velocities for freshwater pearl mussel are described as ‘moderate-fast’ (between 0.25 and 0.75 m s⁻¹; Hastie et al. 2000), although at the reach-scale, mussels abundance is correlated with the presence of rapids (Hastie et al. 2003). They are usually found at depths between 0.3 and 0.4 m (at low flow; Hastie et al. 2000), although unnaturally higher abundance can be found at greater depths, or less accessible areas, where they are protected from illegal fishing (Cosgrove et al. 2007), sometimes as deep as 6 m (Degerman et al. 2009). Although fishing is impossible to predict, it is likely that the continued evolution of the channel morphology in response to the new sediment supply will result in a higher diversity of habitat. For instance, the lateral bar forces flow to the left, generating higher velocities and higher water depth which should better suit pearl mussels. Results from the 1D modelling exercise presented in Chapter 5 indicate that, at compensation flow (i.e. experienced c. 20% of the time during this study), water depth over the entire study reach varies between 0.35 and 0.44 m, and mean column velocity spans from 0.32 to 0.38 m s⁻¹. These conditions are not highly suitable for mussels, so adjustments resulting in faster and deeper areas should provide improved habitat.

Substrate size and stability

Pearl mussels are considered to thrive in the presence of boulders and cobbles, providing a relative stable bed. However, Quinlan et al. (2015b) stressed that although this is widely accepted among specialists, no detailed studies of the degree of relative stability required by mussels have been undertaken. In fact, they argue that a certain degree of disturbance is required to prevent sediment compaction and remove fine particles, particularly for juveniles habitat (Geist and Auerswald 2007). Additionally, mussels also require clean matrices of coarse sand to gravel size material where they can bury (Hastie et al. 2000). Thus, Quinlan et al. (2015b) supported the need to consider the entire GSD when monitoring mussel habitat, and not just focusing on one fraction of the distribution (Tarr 2008). GSDs have not changed in the pool section of the study reach, but have shown small and more consistent changes in the plane bed and riffle, respectively. The proportion of the largest clasts (> 128 mm) remained relatively unchanged, which means that (i) they were not moved during the study and (ii) that no particles of this size were added as new material from Ben Gill. This, in addition to the limited surface particle mobility observed during this study (despite a small but significant increase following the reconnection), shows that the stability of the riverbed is not compromised. This is of importance given the sensitivity of pearl mussels to being washed away during high flows (Skinner et al. 2003). Perhaps more important is the trend towards a fining of the GSD, in the

riffle especially, with an increase in density of particles < 22.6 mm, which represent fine to coarse gravel. A limitation to consider here is the absence of data on coarse sand and fine gravel. These fractions were too coarse to be captured as in-channel fine sediment storage (< 2 mm) but too small to be measured using the Wolman pebble count method. Photographic evidences show that some of this fraction is being transported to depositional areas (e.g. behind boulders, Plate 7.3) but further investigations are needed to determine the extent of these depositions.



Plate 7.3. Photographic evidence of sand deposition behind a boulder, located in the pool (River Ehen). (Photo: Baptiste Marteau, 08/2016).

Overall, by the end of the study period, there was no great evidence that riverbed stability had been compromised by the reconnection and some areas (e.g. riffle) display signs of particle fining that could correspond to the fraction suitable for pearl mussels.

Suspended fine sediments

Quinlan et al. (2015b) reported on the difficulty to draw conclusions from the literature on tolerance of pearl mussels for suspended sediments (SS). The main difficulty arose from the use of different units to define “suspended solids”. Some authors have reported values of turbidity, as low as 1 to 1.9 NTU, below which juveniles were absent from sites (Österling et al. 2010 and citations therein). Others have reported tolerance limits of 30 mg l⁻¹ for adults, and long-term lasting effects with concentrations above 10 mg l⁻¹ (Valovirta 1998). Additionally,

some studies of habitat requirement for the species make no mention of SSC other than the associated risks of deposition (e.g. Hastie et al. 2000; Tarr 2008).

Research is ongoing to better understand the causes and consequences of suspended materials on pearl mussels. One hypothesis is that each fraction of the suspended sediments may cause different issues; large particles (i.e. fine sand) may be transported by high velocities and causing physical harm (abrasion), while finer particles could impede the feeding process of juveniles and young adults (E. Moorkens, pers. comm.). Nevertheless, the results from chapters 3 and 4 suggest that SSCs may not be the biggest issue in the Ehen. The frequency and magnitude of high SSC events have increased following the reconnection, but these events are generally short-lived. Additionally, SSCs at baseflow remain unaffected and are very low (close to the limit of detection of the turbidity metres). The deposition of this fine material, however, may have more consequences for pearl mussels.

Deposited fine sediments

Excessive volumes of fine sediment are considered problematic for mussels (Bauer 1988; Beasley and Roberts 1999; Geist and Auerswald 2007). Fine sediment is particularly detrimental for juveniles, as soft substratum is unsuitable for borrowing and it may clog up their inhalant siphons (Buddensiek et al. 1993; Buddensiek 1995). This is why they are rarely found in areas with dominant silt substrate (Hastie et al. 2000; Morales et al. 2004). Two separate issues arise with fine sediments: (i) the presence of fine particles themselves, which can clog interstitial pores and limit the exchange of water and oxygen between the surface and the subsurface, and (ii) the presence of organic matter which increases the Biological Oxygen Demand (BOD, i.e. oxygen is consumed by micro-organisms when degrading the organic matter) and further reduces levels of oxygen (Greig et al. 2007; Malcolm et al. 2008). No formalised standards exist in the literature regarding the tolerance limits of mussels to fine sediments, so no direct conclusion can be drawn from the levels of in-channel storage reported in chapter 4. Nonetheless, the 2-fold increase in fine sediment storage following the reconnection signals a potentially problematic trajectory, if it continues.

It appears that they were already suffering from deposition prior to the reconnection (Killeen 2006; Killeen and Moorkens 2013) so changes in stored sediment indicate that conditions have not improved. In addition, the levels of organic content reported in this study are much higher than what was suggested as limiting thresholds by Tarr (2008). Despite some differences in

sampling methods, she found that pearl mussels were absent from sites with more than 0.5 to 1% of organic matter, while levels reported in the Ehen oscillated between 6 and 10%. Again, this would suggest that this aspect of has not improved since the reconnection.

Algae

Fine organic silt resulting from decaying algae may exacerbate the clogging of interstitial pores, further reducing the oxygen levels in the subsurface (Moorkens 1999). However, little is known about the direct impact of algal growth on pearl mussels. Skinner et al. (2003) link the presence of algae with the risks associated with eutrophication. This does not appear to be the case of the River Ehen, despite the abundance of algae at times (Kelly et al. 2015). Nevertheless, the findings from Chapter 6 indicate that ecologically, the River Ehen (and particularly the site ESC, situated near the lake and weir) has, at least historically, been affected by the flow regulation and the tributary diversion from an ecological perspective. Considering the observed increase in particle mobility (Chapter 5) and the continued supply of coarse material by Ben Gill, it is likely that bed mobility will further increase in the future. This will probably induce a shift of both the macroinvertebrates and algal communities towards greater similarities with site EOX (situated further downstream and showing higher similarities with the non-impounded free-flowing stream Croasdale Beck). Given the role of bed disturbance in controlling algal growth (as per the ordination results in Chapter 6), it can be suggested that conditions in the Ehen will improve as more coarse sediment is transported downstream, with the carpet-layer increasing in thickness and size distribution, and interacting further with the original riverbed, all contributing to a more dynamic bed.

7.4.2. The restoration project

7.4.2.1. Coping with uncertainty

Wheaton et al. (2008) ended their essay on *The Scope of Uncertainties in River Restoration* by stating that ‘an emerging challenge [in river restoration] is to “do the right thing right”’, separating technical from ethical concerns. In their typology of uncertainty, they differentiate uncertainty due to variability and uncertainty due to limited knowledge (Wheaton et al. 2008); both of these need to be integrated in the evaluation of the success or failure of a given project.

Arguably, the objective and philosophy of the Ehen restoration project were correct from a conservation perspective. The status of the focal species, in the river but also within its entire

range, supported the need for action. Given the ageing mussel population on the Ehen (i.e. no or limited recent recruitment), time can be considered as ticking for this important enclave. The risks associated with the 'no action' scenario were assessed and the decision was made to act. From a geomorphological perspective, the 'process-based' approach chosen by the agencies is arguably superior to any 'form-based' approach (e.g. Wheaton et al. 2004a). Instead of actively intervening in the channel to try, for instance, to disrupt the pavement or to recreate channel complexity, the decision was made to act 'passively' by reconnecting an entire sub-catchment to its main-stem and to 'let the tributary do the work'. One may argue that this type of restoration was the easiest scenario, since there was no need to determine the exact location, volume and frequency of actions (e.g. gravel augmentation, re-meandering). It was probably also one of the simplest options from a technical (engineering) perspective. However, it seriously increased the level of uncertainty, both those due to limited knowledge and due to variability.

Limited knowledge. Numerous examples exist of restoration or rehabilitation initiatives, in both the scientific and grey literatures; they consist of dam removal (e.g. Doyle et al. 2003, 2005; Orr and Stanley 2006; Major et al. 2012), gravel augmentation (e.g. Bunte 2004; Wheaton et al. 2004b; Merz and Chan 2005; Arnaud et al. 2017), channel re-meandering (e.g. Lorenz et al. 2009; Rogiers et al. 2011; Kristensen et al. 2014; Pedersen et al. 2014), etc. Because examples of tributary reconnection are scarce, there is limited knowledge of the uncertainty and the potential outcomes of what was implemented in the Ehen.

Variability. Uncertainty due to variability is increased in the case of the Ehen because of the ephemeral nature of the sub-catchment that has been reconnected. Predicting flows in intermittent streams is very difficult (Williams 2005); this was demonstrated in the complex relationship between flows in the main-stem and those in Ben Gill. This uncertainty is significant because this relationship drives the fate of fine sediments once they reach the Ehen.

The different actors involved in the project were aware of the general risks associated with the reconnection. However, while predictable uncertainties were considered, the possibility of some unpredictable uncertainties arising was not explicitly evaluated or considered in the decision-making process. Some of the data presented in this thesis provide evidence of some of the unpredicted changes – the unanticipated consequences of the reconnection - and hence help assess overall project success.

7.4.2.2. 'Ecological' success[es] and failure[s] of the Ehen project

The 'ecological success' is widely recognised as the most important outcome of a restoration project (e.g. Palmer et al. 2005; Wohl et al. 2005; Alexander and Allan 2007). Palmer et al. (2005) identified five key components to evaluate the 'ecological' success of a restoration initiative (relating to the ecology, hydrology and geomorphology), which are used here to provide a sketch evaluation for the restoration of the River Ehen.

Identification of dynamic ecological endpoints to guide restoration.

The guiding image used to conduct the Ehen project was that of a thriving and naturally recruiting pearl mussel population. Little quantitative evidence exists of how the river was prior to the diversion apart from a few photographs from neighbours or local newspapers. Nevertheless, an integrative review of the history and changes that occurred in the catchment (Alvarez-Codesal and Sweeting 2015) along with knowledgeable pearl mussel specialists have allowed for the development of a general image of what the river should look like to support a healthy population.

Measurable enhancement of 'ecological' conditions.

Given their broad definition of 'ecological', it is possible to provide part of the answer. As indicated in the Introduction (Chapter 1), measuring the success on the productivity and successful recruitment of pearl mussel in the Ehen was out of the scope of this thesis. Instead, the focus was on monitoring physical habitat and underlying habitat-forming processes. In this context, the findings of the work are helping to highlight successes and failures. Some natural sediment dynamics have been restored, although it is difficult to compare with pre-diversion conditions. Ben Gill is successfully delivering coarser sediment, part of which is carried downstream and is starting to re-create channel complexity. Some signs of particle fining are visible, which are in line with pearl mussel habitat requirements. However, the extent of these changes is limited and mostly observed in the riffle. Particle mobility has decreased, although this is hypothesised to be a temporary response, potentially hiding an actual longer-term improvement of bed mobility. Potentially overshadowing these successes is the fact that SSL have increased and in-channel storage has actually doubled in the first two years since the reconnection.

Ecosystem resilience has increased.

The fact that two decoupled systems -the main-stem and its tributary- have been reconnected is an argument for increased ecosystem resilience. The sub-catchment is now capable of producing and delivering sediments. In turn, the main-stem received higher volumes of coarse sediment and regained some geomorphological dynamism. All these signs are relatively small but indicate that the system is becoming more self-sustaining than it was before. A full evaluation of resilience will be possible once effects of the restoration on the pearl mussel population are evident to the mussel biologists undertaking this work.

No lasting harm was inflicted.

This concern was at the heart of the discussions between the different actors of the project; what if the reconnection actually does more harm than good to the pearl mussel? It is too early to say whether the counter-productive increase in fine sediment deposition will outstrip the potential gains in coarse sediment related geomorphic and hydraulic conditions. As things stand, the pearl mussels are monitored by I. Killeen and E. Moorkens who regularly report signs of stress within the population, and the Environment Agency awaits evidence of changes in the population's condition.

Some level of pre- and post-project assessment is conducted and communicated.

This is one of the strongest assets of the Ehen project. The Environment Agency and partners have been launching and commissioning investigations to understand the different components of the system, including river habitat survey (Moir et al. 2003), hydraulic modelling (Gibbins et al. 2005), investigation into near-bed velocity conditions and requirements (Atkins 2014), monitoring of algae (Kelly 2013; Kelly et al. 2015), assessment of fish stocks (CEFAS and EA 2013), monitoring of the pearl mussel population (Killeen and Oliver 1997; Oliver and Killeen 1997; Killeen 2006; Killeen and Moorkens 2013), and the detailed assessment of pre-reconnection conditions through Emma Quinlan's PhD (Quinlan 2014); all of this has been followed by the present work, assessing the sedimentary and geomorphic changes in response to the reconnection. The communication aspect, however, is more difficult to assess from the authors' point of view due to the direct involvement in the project. Information signs communicating to the public the nature and rationale for the reconnection were erected on site, and meetings were held. Nonetheless, it is evident that some misunderstandings remain amongst the public (based on comments made to us, the Environment Agency and other staff

on site), especially about that Ben Gill is 'always dry and unsightly'. Perhaps communication was not focussed enough on the ephemeral proprieties of the tributary. As a consequence, the restoration work has been criticised occasionally as '*money wasted for a stream that doesn't even run*'.

7.4.2.3. Other aspects of restoration appraisal

In the same paper, Palmer et al. (2005) also advocate the need to consider other forms of 'success': the satisfaction of stakeholder needs, and the learning success (i.e. advance in science and management).

Stakeholders success.

This measure of success includes aesthetics, costs, and meeting the perceived goals (Alexander and Allan 2007). Criticism about the aesthetic impact of the work did not arise from stakeholders but from the public (as above). Because Ben Gill crosses a very frequently used hiking trail, the reconnection of the tributary was constrained by the obligation to build a footbridge. To ensure public safety, the whole field surrounding the channel has been fenced off. Thus, many locals and hikers have criticised the non-natural look of the work.

Until the 'ecological' success of the restoration is fully assessed, and provided that it is a global 'ecological' success, all project stakeholders remain concerned by the risks posed by the increased suspended sediment supply for pearl mussels.

Because the costs of the project were already high, and given the 'process-based' philosophy of the project, there was no budget allocated for potential 'in-case-of-emergency' intervention. Because of the marked erosion generated by the exceptional rainfall event on the day after the reconnection, the need to intervene was quickly voiced amongst the stakeholders. Several options were put on the table, including manually removing visible lenses of clay, pumping the water out of Ben Gill during flow events, and adding hard points in the channel to prevent further degradation, etc. Eventually, it was decided to not intervene but to monitor closely the situation. This decision was made because of the desire to adhere to project philosophy (to recover natural processes) and the fact that small scale management carried its own risks and uncertainties.

Learning experience.

In a book published in 1859, Scottish author Samuel Smiles wrote '*We learn wisdom from failure much more than from success*'. Until the benefits (or otherwise) of the restoration for the pearl mussel population are apparent through improved (or reduced) recruitment, and although lots were learned from the project in general, part of the learning experience from this project come from the things that were unexpected and cause anxiety. These 'failures' may be related to the lack of anticipation, or to limited consideration of the 'predictable uncertainties'.

Some uncertainties were unpredictable, such as the occurrence of a heavy rainfall on the day following the reconnection. Little can be learned from this as it is unlikely to be repeated again under similar circumstances. However, a careful assessment of the old alluvial fan where Ben Gill channel was excavated would have revealed the importance in size of the underlying layer of clay which is partly responsible for the delivery of fine sediments. Similarly, the increase in compensation flow associated with a continued abstraction from the lake by the water company is responsible for higher and longer-lasting lake level drawdowns. As more water is release through compensation flow, the frequency of lake overspill is reduced to wet periods or higher hydrological events (the lake needs to refill before overspilling). As a consequence, the probability of experiencing type-1 flow scenarios (see Chapter 4 for details), where Ben Gill flows but discharge in the Ehen remain low, is increased. Consequently, since Scenario 1 is responsible for most of the observed increase in fine sediment deposition, the risks for the pearl mussels also increases.

Finally, the different component of this PhD also provided insights into the functioning of the River Ehen, as well as scientific knowledge of wider implications.

7.5. BEYOND THE RESTORATION: FUNCTIONING OF THE EHEN AND OTHER FLUVIAL SYSTEMS

The unexpected magnitude of fine sediment delivery from Ben Gill has provided the opportunity to study the role played by ephemeral streams in the suspended dynamics of main-stem rivers in temperate regions.

Although not the main focus of the restoration project, the study of Croasdale Beck has shown the dynamism and ability to deliver water and sediment of this stream. Before the

reconnection, it was the most upstream tributary of the River Ehen. This one, and other tributaries further downstream, may help 're-naturalise' and limit the downstream extent of flow regulation effects.

Tributaries are often earmarked for water abstraction and diversion (e.g. many in Scotland, including e.g. Glen Lyon, see Buddendorf et al. 2017). This work in Ehen lends general support to the idea that careful thought should be given to such development, especially when multiple tributaries in the same system have water diverted, because of their potentially significant role. Even small run-of-river HEP schemes, that do not reduce discharge, may have an impact if they alter delivery of sediment to mainstems.

7.6. THE FUTURE OF THE FRESHWATER PEARL MUSSEL IN THE EHEN

Conservation requires understanding the physiology, biology, behaviour and habitat requirements of the target species, and its interactions with other species. It also requires knowledge of the habitat forming processes in the area under study, and which potentially are subject to management. These habitat-forming processes have been the subject of this PhD. Unfortunately, in the case of the freshwater pearl mussel, understanding of the other elements is incomplete, and this imposes design constraints on river habitat and catchment management. For instance, a key constraint is the absence of a precise understanding of levels of fine sediment, as well as the composition of this sediment, that mussels can tolerate, and the degree of bed stability they need, or conversely, the degree of instability they can tolerate (see review by Quinlan et al. 2015b). Thus, setting precise targets for 'optimum' habitat in the Ehen has not been possible. The philosophy adopted has therefore been one of physical process-restoration (rather than 'micro-managing' habitat features, or biological interventions such as restocking), supported by wider measures focussed on better land and riparian management.

It is too early to say whether the observed changes in habitat will lead to better productivity of the pearl mussel. A continued monitoring of the population is required and is being undertaken by Ian Killeen and Evelyn Moorkens. Similarly, the fate of salmonid hosts also needs to be monitored closely. Their presence in the river is key to the recruitment of juveniles. The success of the restoration project is bound up not just in how it affects mussels but how it affects fish. The provision of loose, clean gravel sized material may improve conditions for spawning so the

changes so far observed are positive. However, salmonid egg survival may be threatened by the same factors related to fine sediment that impact buried juvenile mussels.

Further outputs are expected to come from this project. As part of this project, further work on the depositional bar to assess the potential size-selective entrainment of particles which could explain the limited erosion. In the continuation of the work started by Emma Quinlan (Quinlan et al. 2014), sub-surface dissolved oxygen was monitored in the riffle throughout the post-reconnection period to assess the potential changes in response to increased sedimentary activity. The data are being analysed and should provide further insights into the evolution of pearl mussel habitat quality in the Ehen.

This project has been going on against a backdrop of other mussel initiatives, such as captive breeding. The Freshwater Biological Association (FBA) is successfully breeding young mussels in their 'Ark' facilities in Windermere. They have been able to rear mussels from different rivers in the hope to maintain the genetic diversity of the species. With their work starting in 2008, the very first young adults descending from mussels living in the Ehen have been reintroduced this summer¹. Their adaptation to the wild is monitored closely, and more re-introductions are expected in the future.

7.7. CONCLUSIONS

Prospects for the River Ehen and its freshwater population are better than they looked 10 years ago. In addition to the ongoing initiatives, the agencies are working on further ambitious plans of removing the weir at the lake outlet within the next 5 to 10 years. The removal of another small weir located near the gauging station is also discussed. By then, the licence for water abstraction from the lake will have been revoked, and a proper assessment of the success of the restoration will be possible. The Environment Agency demonstrates a very forward-thinking approach. It is working closely with United Utilities to detect and target water-related issues. The work described in this thesis, funded by these two agencies, is testament to their commitment to sustainable catchment management. Monitoring of Ben Gill and the Ehen is now secured up until 2020, so how these systems will respond to the reconnection over longer timescales than reported here can hopefully be determined.

¹ *Freshwater Matters*, FBA monthly bulletin, June-July 2017.

The need for the restoration of rivers will continue to grow. Sharing from experiences like this will foster general learning, and benefits both the ecosystems and society.

7.8. REFERENCE LIST

- Alexander GG, Allan JD (2007). Ecological success in stream restoration: Case studies from the midwestern United States. *Environmental Management* 40:245–255
- Alvarez-Codesal S, Sweeting RA (2015). Historic changes in the Upper River Ehen Catchment. A Report for United Utilities. FBA unpublished report (S/0016/W)
- APEM (2015). Upper River Ehen and Ennerdale Water Catchment Walkover Survey. APEM Scientific Report 414068. Natural England, February 2016 v 0.1 Final: 21p.
- Arnaud F, Piégay H, Béal D, Collery P, Vaudor L, Rollet AJ (2017). Monitoring gravel augmentation in a large regulated river and implications for process-based restoration. *Earth Surface Processes and Landforms* 42:2147–2166
- Atkins (2014). An Investigation into relationships between velocity, bed shear stress and flow requirements in the River Ehen. Report to the Environment Agency No.5122646: 59p.
- Bangen SG, Wheaton JM, Bouwes N, Bouwes B, Jordan C (2014). A methodological intercomparison of topographic survey techniques for characterizing wadeable streams and rivers. *Geomorphology* 206:343–361
- Bauer G (1988). Threats to the freshwater pearl mussel *Margaritifera margaritifera* L. in Central Europe. *Biological Conservation* 45:239–253
- Beasley CR, Roberts D (1999). Towards a strategy for the conservation of the freshwater pearl mussel *Margaritifera margaritifera* in County Donegal, Ireland. *Biological Conservation* 89:275–284
- Béjar M, Gibbins CN, Vericat D, Batalla RJ (2017). Effects of suspended sediment transport on invertebrate drift. *River Research and Applications* 33:1655–1666
- Bernhardt ES, Likens GE, Hall RO, Buso DC, Fisher SG, Burton TM, Meyer JL, Mcdowell WH, Mayer MS, Bowden WB, Findlay SEG, Macneale KH, Stelzer RS, Lowe WH (2005). Can't See the Forest for the Stream? In-stream Processing and Terrestrial Nitrogen Exports. *BioScience* 55:219
- Bilotta GS, Brazier RE (2008). Understanding the influence of suspended solids on water quality and aquatic biota. *Water Research* 42:2849–2861
- Boon PJ (1998). River restoration in five dimensions. *Aquatic Conservation: Marine and Freshwater Ecosystems* 8:257–264
- Bradshaw AD (1996). Underlying principles of restoration. *Canadian Journal of Fisheries and Aquatic Sciences* 53:3–9
- Brasington J, Langham J, Rumsby B (2003). Methodological sensitivity of morphometric estimates of coarse fluvial sediment transport. *Geomorphology* 53:299–316
- Buddendorf WB, Malcolm IA, Geris J, Wilkinson ME, Soulsby C (2017). Metrics to assess how longitudinal channel network connectivity and in-stream Atlantic salmon habitats are impacted by hydropower regulation. *Hydrological Processes* 31:2132–2142
- Buddensiek V (1995). The culture of juvenile freshwater pearl mussels *Margaritifera margaritifera* L. in cages: A contribution to conservation programmes and the knowledge

- of habitat requirements. *Biological Conservation* 74:33–40
- Buddensiek V, Engel H, Fleishauer-Rössing S, Wachtler K (1993). Studies on the chemistry of interstitial water taken from defined horizons in the fine sediments of bivalve habitats in several northern German lowland waters. II: Microhabitat of *Margaritifera margaritifera* L., *Unio crassus* P. and *Unio tumidus* P. *Archiv für Hydrobiologie* 127:151–166
- Buendía C, Gibbins CN, Vericat D, Batalla RJ (2014). Effects of flow and fine sediment dynamics on the turnover of stream invertebrate assemblages. *Ecohydrology* 7:1105–1123
- Buendía C, Gibbins CN, Vericat D, Batalla RJ, Douglas A (2013). Detecting the structural and functional impacts of fine sediment on stream invertebrates. *Ecological Indicators* 25:184–196
- Bunte K (2004). Gravel Mitigation and Augmentation Below Hydroelectric Dams: A Geomorphological Perspective. *Report to the Stream Systems Technology Center*, Fort Collins, CO
- Carbonneau P, Fonstad MA, Marcus WA, Dugdale SJ (2012). Making riverscapes real. *Geomorphology* 137:74–86
- Carbonneau PE, Dietrich JT (2016). Cost-Effective Non-Metric Photogrammetry from Consumer-Grade sUAS: Implications for Direct Georeferencing of Structure from Motion Photogrammetry. *Earth Surface Processes and Landforms* 42:473–486
- CEFAS, EA (2013). Annual Assessment of Salmon Stocks and Fisheries in England and Wales 2012. Preliminary assessment prepared for ICES : 140p.
- Church M (1995). Geomorphic Response to River Flow Regulation - Case-Studies and Time-Scales. *Regulated Rivers-Research & Management* 11:3–22
- Collins AL, Walling DE (2006). Investigating the remobilization of fine sediment stored on the channel bed of lowland permeable catchments in the UK. *Sediment dynamics and the hydromorphology of the fluvial system (Proceedings of a symposium held in Dundee, UK)* 306:471–479
- Collins AL, Walling DE (2007). The storage and provenance of fine sediment on the channel bed of two contrasting lowland permeable catchments, UK. *River Research and Applications* 23:429–450
- Collins AL, Zhang Y, McChesney D, Walling DE, Haley SM, Smith P (2012). Sediment source tracing in a lowland agricultural catchment in southern England using a modified procedure combining statistical analysis and numerical modelling. *Science of the Total Environment* 414:301–317
- Cosgrove PJ, Hastie LC, Sime I (2007). Recorded natural predation of freshwater pearl mussels *Margaritifera margaritifera* (L.) in Scotland. *Journal of Conchology* 39:469–472
- Degerman E, Alexanderson S, Bergengren J, Henrikson L, Johansson B-E, Larsen BM, Söderberg H (2009). Restoration of freshwater pearl mussel streams. *WWF Sweden, Solna*
- Doyle MW, Stanley EH, Harbor JM (2003). Channel adjustments following two dam removals in Wisconsin. *Water Resources Research* 39:1–15
- Doyle MW, Stanley EH, Orr CH, Selle AR, Sethi S a., Harbor JM (2005). Stream ecosystem response to small dam removal: Lessons from the Heartland. *Geomorphology* 71:227–244

- Effenberger M, Engel J, Diehl S, Matthaei CD (2008). Disturbance history influences the distribution of stream invertebrates by altering microhabitat parameters: A field experiment. *Freshwater Biology* 53:996–1011
- England J, Skinner KS, Carter MG (2008). Monitoring, river restoration and the Water Framework Directive. *Water and Environment Journal* 22:227–234
- Friberg N, Bonada N, Bradley DC, Dunbar MJ, Edwards FK, Grey J, Hayes RB, Hildrew AG, Lamouroux N, Trimmer M, Woodward G (2011). Biomonitoring of Human Impacts in Freshwater Ecosystems: The Good, the Bad and the Ugly. *Advances in Ecological Research* 44:1–68
- Gaeuman D (2012). Mitigating downstream effects of dams. In: Church M, Roy AG, Biron PM (eds) *Gravel-bed Rivers: Processes, Tools, Environments*. John Wiley & Sons, Ltd., Chichester, UK,
- Geist J, Auerswald K (2007). Physicochemical stream bed characteristics and recruitment of the freshwater pearl mussel (*Margaritifera margaritifera*). *Freshwater Biology* 52:2299–2316
- Gibbins C, Vericat D, Batalla RJ (2007a). When is stream invertebrate drift catastrophic? The role of hydraulics and sediment transport in initiating drift during flood events. *Freshwater Biology* 52:2369–2384
- Gibbins C, Vericat D, Batalla RJ, Gomez CM (2007b). Shaking and moving: low rates of sediment transport trigger mass drift of stream invertebrates. *Canadian Journal of Fisheries and Aquatic Sciences* 64:1–5
- Gibbins CN, Pokrajac D, Campbell L (2005). Hydraulic modelling of River Ehen sites. Project report for English Nature - Contract JB 218. University of Aberdeen: 10p.
- Greig SM, Sear DA, Carling PA (2005). The impact of fine sediment accumulation on the survival of incubating salmon progeny: Implications for sediment management. *Science of the Total Environment* 344:241–258
- Greig SM, Sear DA, Carling PA (2007). A review of factors influencing the availability of dissolved oxygen to incubating salmonid embryos. *Hydrological Processes* 21:323–334
- Habersack H, Piégay H (2008). River restoration in the Alps and their surroundings: past experience and future challenges. In: Habersack H, Piégay H, Rinaldi M (eds) *Gravel-Bed Rivers VI: From Process Understanding to River Restoration*. Elsevier, pp 703–735
- Harvey B, McBain S, Reiser D, Rempel L, Sklar L (2005). Key Uncertainties in Gravel Augmentation: Geomorphological and Biological Research Needs for Effective River Restoration.
- Hastie LC, Boon PJ, Young MR (2000). Physical microhabitat requirements of freshwater pearl mussels, *Margaritifera margaritifera* (L.). *Hydrobiologia* 429:59–71
- Hastie LC, Cooksley SL, Scougall F, Young MR, Boon PJ, Gaywood MJ (2003). Characterization of freshwater pearl mussel (*Margaritifera margaritifera*) riverine habitat using River Habitat Survey data. *Aquatic Conservation: Marine and Freshwater Ecosystems* 13:213–224
- Heppell CM, Wharton G, Cotton JA, Bass JAB, Roberts SE (2009). Sediment storage in the shallow hyporheic of lowland vegetated river reaches. *Hydrological Processes* 23:2239–2251

- Hobbs RJ, Harris JA (2001). Restoration Ecology : Repairing the Earth's Ecosystems in the New Millennium. *Restoration Ecology* 9:239–246
- Jähnig SC, Lorenz AW, Hering D, Antons C, Sundermann A, Jedicke E, Haase P (2011). River restoration success: A question of perception. *Ecological Applications* 21:2007–2015
- Jungwirth M, Muhar S, Schmutz S (2002). Re-establishing and assessing ecological integrity in riverine landscapes. *Freshwater Biology* 47:867–887
- Kelly M (2013). Nutrients and algae in the upper River Ehen and their implications for freshwater pearl mussels. Report to United Utilities Water Ltd.
- Kelly M, Snell M, SurrIDGE B, Barker P (2015). Algal interactions with freshwater pearl mussels in the River Ehen, Cumbria: characterisation and quantification of phytobenthos. Report to United Utilities Water Ltd.
- Killeen I (2006). The Freshwater Pearl Mussel, in the River Ehen Cumbria. Report on the 2006 Survey. Malacological Services, Dublin
- Killeen I, Moorkens E (2013). Environmental Monitoring of the River Ehen freshwater pearl mussel population 2012: A report to United Utilities. Malacological Services, Dublin
- Killeen I, Oliver G (1997). The Freshwater Pearl Mussel (*Margaritifera margaritifera* [L. 1758]) in the River Ehen. Part 1. Report on 1996 Survey. Department of Zoology, National Museum of Wales, Cardiff: 24p.
- Knighton AD (1991). Channel bed adjustment along mine-affected rivers of northeast Tasmania. *Geomorphology* 4:205–219
- Koll K, Koll K, Dittrich A (2010). Sediment transport over static armour layers and its impact on bed stability. *International River Flow Conference - Braunschweig* 929–936
- Kondolf GM (1997). Hungry Water: Effects of Dams and Gravel Mining on River Channels. *Environmental Management* 21:533–551
- Kondolf GM, Gao Y, Annandale GW, Morris Gregory L, Jiang E, Zhang J, Yongtao C, Carling P, Fu K, Guo Q, Hotchkiss R, Peteuil C, Sumi T, Wang H-W, Wang Z, Wei Z, Wu B, Wu C, Yang CT (2014). Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents. *Earth's Future* 2:256–280
- Kristensen EA, Kronvang B, Wiberg-Larsen P, Thodsen H, Nielsen C, Amor E, Friberg N, Pedersen ML, Baattrup-Pedersen A (2014). 10 years after the largest river restoration project in Northern Europe: Hydromorphological changes on multiple scales in River Skjern. *Ecological Engineering* 66:141–149
- Lambert CP, Walling DE (1988). Measurement of channel storage of suspended sediment in a gravel-bed river. *Catena* 15:65–80
- Lamouroux N, Gore JA, Lepori F, Statzner B (2015). The ecological restoration of large rivers needs science-based, predictive tools meeting public expectations: An overview of the Rhône project. *Freshwater Biology* 60:1069–1084
- Leopold A (1948). A Sand County Almanac. Oxford University Press
- Lindsay JB, Ashmore PE (2002). The effects of survey frequency on estimates of scour and fill in braided river model. *Earth Surface Processes and Landforms* 27:27–43

- Lisenby PE, Fryirs KA (2017). Sedimentologically significant tributaries: Catchment-scale controls on sediment (dis)connectivity in the Lockyer Valley, SEQ, Australia. *Earth Surface Processes and Landforms* 1504:1493–1504
- López-Tarazón JA, Batalla RJ, Vericat D (2011). In-channel sediment storage in a highly erodible catchment: the River Isábena (Ebro Basin, Southern Pyrenees). *Zeitschrift für Geomorphologie* 55:365–382
- Lorenz AW, Jähnig SC, Hering D (2009). Re-meandering German lowland streams: qualitative and quantitative effects of restoration measures on hydromorphology and macroinvertebrates. *Environmental management* 44:745–54
- Major JJ, Podolak CJ, Keith MK, Grant GE, Spicer KR, Pittman S, Bragg HM, Wallick JR, Tanner DQ, Rhode A, Wilcock PR (2012). Geomorphic response of the Sandy River, Oregon, to removal of Marmot Dam. *Professional Paper* 64
- Malcolm IA, Greig SM, Youngson AF, Soulsby C (2008). Hyporheic influences on salmon embryo survival and performance. *American Fisheries Society Symposium* 1–24
- Marcus WA, Fonstad MA (2010). Remote sensing of rivers: the emergence of a subdiscipline in the river sciences. *Earth Surface Processes and Landforms* 35:1867–1872
- Matthaei CD, Arbuckle CJ, Townsend CR (2000). Stable surface stones as refugia for invertebrates during disturbance in a New Zealand stream. *Journal of the North American Benthological Society* 19:82–93
- Merz JE, Chan LKO (2005). Effects of gravel augmentation on macroinvertebrate assemblages in a regulated California river. *River Research and Applications* 21:61–74
- Merz JE, Pasternack GB, Wheaton JM (2006). Sediment budget for salmonid spawning habitat rehabilitation in a regulated river. *Geomorphology* 76:207–228
- Micheletti N, Chandler JH, Lane SN (2015). Structure from Motion (SfM) Photogrammetry. In: Cook SJ, Clarke JH, N. LS (eds) *Geomorphological Techniques*. British Society for Geomorphology, London, UK, pp 1–12
- Micheletti N, Chandler JH, Lane SN (2014). Investigating the geomorphological potential of freely available and accessible structure-from-motion photogrammetry using a smartphone. *Earth Surface Processes and Landforms* 40:473–486
- Moir HJ, Gibbins CN, Soulsby C (2003). River Ehen Pearl Mussel Project: Fluvial Audit. University of Aberdeen: 26p.
- Moorkens EA (1999). Conservation management of the freshwater pearl mussel *Margaritifera margaritifera*. Part 1: Biology of the species and its present situation in Ireland. *Irish Wildlife Manuals* 8:2–35
- Morales JJ, Negro AI, Lizana M, Martínez A, Palacios J (2004). Preliminary study of the endangered populations of pearl mussel *Margaritifera margaritifera* (L.) in the River Tera (north-west Spain): Habitat analysis and management considerations. *Aquatic Conservation: Marine and Freshwater Ecosystems* 14:587–596
- Oliver PG, Killeen IJ (1997). The Freshwater Pearl Mussel (*Margaritifera margaritifera* [L. 1758]) in the River Ehen. Part 3. A management Plan. English Nature Research Reports Series No. 226

- Orr CH, Stanley EH (2006). Vegetation development and restoration potential of drained reservoirs following dam removal in Wisconsin. *River Research and Applications* 22:281–295
- Österling ME, Arvidsson BL, Greenberg LA (2010). Habitat degradation and the decline of the threatened mussel *Margaritifera margaritifera*: influence of turbidity and sedimentation on the mussel and its host. *Journal of Applied Ecology* 47:759–768
- Owens PN, Walling DE, Leeks GJL (1999). Deposition and storage of fine-grained sediment within the main channel system of the River Tweed, Scotland. *Earth Surface Processes and Landforms* 24:1061–1076
- Palmer MA, Bernhardt ES, Allan JD, Lake PS, Alexander G, Brooks S, Carr J, Clayton S, Dahm CN, Follstad Shah J, Galat DL, Loss SG, Goodwin P, Hart DD, Hassett B, Jenkinson R, Kondolf GM, Lave R, Meyer JL, O'Donnell TK, Pagano L, Sudduth E (2005). Standards for ecologically successful river restoration. *Journal of Applied Ecology* 42:208–217
- Pander J, Geist J (2013). Ecological indicators for stream restoration success. *Ecological Indicators* 30:106–118
- Pasternack GB (2008). Spawning habitat rehabilitation: Advances in analysis tools. In: Sear DA, DeVries P, Greig S (eds) *Salmonid spawning habitat in rivers: physical controls, biological responses, and approaches to remediation. Symposium 65, American Fisheries Society*. Bethesda, MD, pp 321–348
- Pedersen ML, Kristensen KK, Friberg N (2014). Re-meandering of lowland streams: will disobeying the laws of geomorphology have ecological consequences? *PLoS one* 9:1–20
- Petts GE, Gurnell AM (2005). Dams and geomorphology: Research progress and future directions. *Geomorphology* 71:27–47
- Quinlan E (2014). Ecogeomorphological dynamics of the River Ehen prior to its restoration. PhD thesis, University of Aberdeen, Scotland
- Quinlan E, Gibbins CN, Batalla RJ, Vericat D (2015a). Impacts of Small Scale Flow Regulation on Sediment Dynamics in an Ecologically Important Upland River. *Environmental Management* 55:671–686
- Quinlan E, Gibbins CN, Malcolm I, Batalla RJ, Vericat D, Hastie L (2015b). A review of the physical habitat requirements and research priorities needed to underpin conservation of the endangered freshwater pearl mussel *Margaritifera margaritifera*. *Aquatic Conservation: Marine and Freshwater Ecosystems* 124:107–124
- Quinlan E, Malcolm IA, Gibbins CN (2014). Spatio-temporal variability of dissolved oxygen within the shallow subsurface zone of a freshwater pearl mussel bed. *Fundamental and Applied Limnology / Archiv für Hydrobiologie* 185:281–294
- Rice S (1998). Which tributaries disrupt downstream fining along gravel-bed rivers? *Geomorphology* 22:39–56
- Rice SP (2016). Tributary connectivity, confluence aggradation and network biodiversity. *Geomorphology*. doi: 10.1016/j.geomorph.2016.03.027
- Rice SP, Ferguson RI, Hoey TB (2006). Tributary control of physical heterogeneity and biological diversity at river confluences. *Canadian Journal of Fisheries and Aquatic Sciences* 63:2553–

2566

- Rice SP, Greenwood MT, Joyce CB (2001). Tributaries, sediment sources, and the longitudinal organisation of macroinvertebrate fauna along river systems. *Canadian Journal of Fisheries and Aquatic Sciences* 58:824–840
- Rice SP, Kiffney P, Greene C, Pess GR (2008). The Ecological Importance of Tributaries and Confluences. In: Rice SP, Roy AG, Rhoads BL (eds) *River Confluences, Tributaries and the Fluvial Network*. John Wiley & Sons, Ltd, Chichester, UK, pp 209–242
- Rogiers B, Lermytte J, de Bie E, Batelaan O (2011). Evaluating the impact of river restoration on the local groundwater and ecological system: A case study in NE Flanders. *Geologica Belgica* 14:265–276
- Scheibelhofer O, Besenhard MO, Piller M, Khinast JG (2016). Comparing particle size distributions of an arbitrary shape. *Powder Technology* 294:134–145
- Skinner A, Young M, Hastie L (2003). Ecology of the Freshwater Pearl Mussel. *Conserving Natura 2000 Rivers Ecology Series No 2*, English Nature, Peterborough
- Sklar LS, Fadde J, Venditti JG, Nelson P, Aleksandra Wydzga M, Cui Y, Dietrich WE (2009). Translation and dispersion of sediment pulses in flume experiments simulating gravel augmentation below dams. *Water Resources Research* 45:1–14
- Smiles S (1859). *Self-Help*. John Murray, London
- Smith B, Clifford NJ, Mant J (2014). The changing nature of river restoration. *WIREs Water* 1:249–261
- Smith MW, Carrivick JL, Quincey DJ (2015). Structure from motion photogrammetry in physical geography. *Progress in Physical Geography* 40:247–275
- Stevens LE, Shannon JP, Blinn DW (1997). Colorado River benthic ecology in Grand Canyon , Arizona, USA: dam, tributary and geomorphological influences. *Regulated Rivers Research and Management* 13:129–149
- Tachet H, Richoux P, Bournaud M, Usseglio-Polatera P (2006). *Invertébrés d’eau douce - systématique, biologie, écologie*. CNRS Edition, Paris
- Tarolli P (2014). High-resolution topography for understanding Earth surface processes: Opportunities and challenges. *Geomorphology* 216:295–312
- Tarr EC (2008). The population structure and habitat requirements of the freshwater pearl mussel, *Margaritifera margaritifera*, in Scotland. PhD thesis, University of Aberdeen, Scotland
- Tena A, Batalla RJ (2013). The sediment budget of a large river regulated by dams (The lower River Ebro, NE Spain). *Journal of Soils and Sediments* 13:966–980
- Thoeni K, Giacomini A, Murtagh R, Kniest E (2014). A comparison of multi-view 3D reconstruction of a rock wall using several cameras and a laser scanner. *Proceedings of ISPRS Technical Commission V Symposium XL*:573–580
- Valovirta I (1998). Conservation of *Margaritifera margaritifera* in Finland. *Journal of Conchology Special Is*:251–256

- Varandas S, Lopes-Lima M, Teixeira A, Hinzmann M, Reis J, Cortes R, Machado J, Sousa R (2013). Ecology of southern European pearl mussels (*Margaritifera margaritifera*): first record of two new populations on the rivers Terva and Beça (Portugal). *Aquatic Conservation: Marine and Freshwater Ecosystems* 23:374–389
- Venditti JG, Dietrich WE, Nelson PA, Wydzga MA, Fadde J, Sklar L (2010a). Mobilization of coarse surface layers in gravel-bedded rivers by finer gravel bed load. *Water Resources Research* 46:1–10
- Venditti JG, Dietrich WE, Nelson PA, Wydzga MA, Fadde J, Sklar L (2010b). Effect of sediment pulse grain size on sediment transport rates and bed mobility in gravel bed rivers. *Journal of Geophysical Research: Earth Surface* 115:1–19
- Vericat D, Wheaton JM, Brasington J (2017). Revisiting the morphological approach: opportunities and challenges with repeat high resolution topography. In: Tsustumi D, Laronne JB (eds) *Gravel-Bed Rivers: Processes and Disasters*. Wiley, Tokyo, Japan, pp 121–158
- Walling DE, Owens PN, Leeks GJL (1998). The role of channel and floodplain storage in the suspended sediment budget of the River Ouse, Yorkshire, UK. *Geomorphology* 22:225–242
- Walling DE, Russell MA, Hodgkinson RA, Zhang Y (2002). Establishing sediment budgets for two small lowland agricultural catchments in the UK. *Catena* 47:323–353
- Webb RH, Griffiths PG, Melis TS, Hartley DR (2000). Sediment Delivery by Ungaged Tributaries of the Colorado River in Grand Canyon. U.S. Geological Survey, Water-Resources Investigations Report 00-4055
- Westoby MJ, Brasington J, Glasser NF, Hambrey MJ, Reynolds JM (2012). “Structure-from-Motion” photogrammetry: A low-cost, effective tool for geoscience applications. *Geomorphology* 179:300–314
- Wheaton JM, Brasington J, Darby SE, Sear DA (2010). Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets. *Earth Surface Processes and Landforms* 35:136–156
- Wheaton JM, Darby SE, Sear DA (2008). The Scope of Uncertainties in River Restoration. In: Darby SE, Sear DA (eds) *River Restoration: Managing the Uncertainty in Restoring Physical Habitat*. John Wiley & Sons, Ltd., pp 21–39
- Wheaton JM, Pasternack GB, Merz JE (2004a). Spawning habitat rehabilitation -I. Conceptual approach and methods. *International Journal of River Basin Management* 2:3–20
- Wheaton JM, Pasternack GB, Merz JE (2004b). Spawning habitat rehabilitation - II. Using hypothesis development and testing in design, Mokelumne river, California, U.S.A. *International Journal of River Basin Management* 2:21–37
- Whiting PJ, King JG (2003). Surface particle sizes on armoured gravel streambeds: Effects of supply and hydraulics. *Earth Surface Processes and Landforms* 28:1459–1471
- Williams DD (2005). *The biology of temporary waters*. Oxford University Press, Oxford, UK
- Williams GP, Wolman MG (1984). Downstream effects of dams on alluvial rivers. *US Geological Survey Professional paper* 1286:94

- Wilson AJ, Walling DE, Leeks GJL (2004). In-channel storage of fine sediment in rivers of southwest England. In: Golosov V, Belyaev V, Walling DE (eds) *Sediment transfer through the fluvial system*. IAHS Publication, pp 291–199
- Wohl E, Angermeier PL, Bledsoe B, Kondolf GM, MacDonnell L, Merritt DM, Palmer MA, Poff NL, Tarboton D (2005). River restoration. *Water Resources Research* 41:1–12
- Wolman MG (1954). A method of sampling coarse river-bed material. *Transactions, American Geophysical Union* 35:951–956
- Wood PJ, Armitage PD (1997). Biological Effects of Fine Sediment in the Lotic Environment. *Environmental Management* 21:203–217
- Young MR (2005). A literature review of the water quality requirements of the freshwater pearl mussel (*Margaritifera margaritifera*). Scottish Natural Heritage Commissioned Report No. 084 (ROAME No. F01AC609d): 18p.
- Young MR, Cosgrove PJ, Hastie LC (2001). The extent of, and causes for, the decline of a highly threatened Naiad: *Margaritifera margaritifera*. In: Bauer G, Wächtler K (eds) *Ecology and Evolution of the Freshwater Mussels Unionoida*, Springer-V. pp 337–357
- Young MR, Hastie LC, Cooksley SL (2003). Monitoring the Freshwater Pearl Mussel, *Margaritifera margaritifera*. Conserving Natura 2000 Rivers Monitoring Series English Nature2: 19p.

APPENDIX

A CD with relevant documents is attached to this thesis:

- 1- Electronic version (pdf file) of the thesis document;
- 2- Published version of Chapter 2: Marteau B, Vericat D, Gibbins C, Batalla RJ, Green DR (2016). Application of Structure-from-Motion photogrammetry to river restoration. *Earth Surface Processes and Landforms* 42:503–515
- 3- Published version of Chapter 3: Marteau B, Batalla RJ, Vericat D, Gibbins CN (2017). The importance of a small ephemeral tributary for suspended sediment dynamics in a main-stem river. *River Research and Applications* 33:1564–1574
- 4- Published version of Chapter 4: Marteau B, Batalla RJ, Vericat D, Gibbins C (2018). Asynchronicity of fine sediment supply and its effects on transport and storage in a regulated river. *Journal of Soils and Sediments*. doi: 10.1007/s11368-017-1911-1
- 5- Published Magazine article: Marteau B, Gibbins C, Green DR, Vericat D, Batalla RJ (2016). Photogrammetry aids River Restoration. *Geomatic World* 25(3):14-17
- 6- Electronic version (pdf file) of the general abstract.