Hydromorphological evolution of a restored river; a case study in the Upper River Eden catchment

Submitted in partial fulfillment of the requirements of the Degree of Master of Science

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Declaration

I certify that this thesis consists of my own work. All quotations from published and unpublished sources are acknowledged as such in the text. Material derived from other sources is also indicated.

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Abstract

River restoration has undergone a shift in approach from structural interventions controlling unwanted erosion to river naturalisation and the “re-meandering” of channels back to an historic planform. This is driven by acknowledgement of rivers as dynamic systems that, through restoring erosional and depositional processes and floodplain connection, can restore channel features. Restoring processes is expected to increase the long-term success of a restoration project. Swindale Beck is an example of such a natural flood management approach, where new active meandering channel was constructed, replacing the original canalised channel. Data acquiring by a small unmanned aerial vehicle (sUAV) facilitated topographical and photogrammetric data (at the centimeter scale), used to characterise habitat, assess sediment and sediment flux within the restored reach. The results show rapid initial response; erosion and deposition at the site show rates in line with levels expected of an active meandering system. Hydraulic modelling and habitat availability (through Froude numbers) determined and compared biotope presence and diversity in the channel pre and post restoration. Results show an increase in the diversity of biotopes present within the restored reach, transitioning from a run dominated river system. Bed shear stress was investigated across the reach to determine levels of entrainment with the majority of the reach subject to bed shear stress above the critical boundary for entrainment, significantly enhancing the post-restoration channels geomorphology, habitat and variability.

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1. Introduction

1.1 Background

River management in the UK has undergone a major shift in approach over the past decade. This change in approach includes a move away from structural engineering and green bank deflectors, aimed at controlling unwanted erosion, towards river naturalisation projects (Palmer *et al.,* 2005). These river naturalisation projects include natural flood management schemes and the restoration of rivers; all of which aim to work alongside the natural river processes, as opposed to controlling and constraining the channel. This is in stark contrast with the previous management techniques such as channelisation and other methods of 'technical flood management'. Technical management of rivers was previously favoured for effective flood management, particularly as the decision making processes and policies were dominated by economic factors and engineering science; rather than holistic river management seen today, that is largely driven by environmental and ecological science (Waylen *et al.,* 2017). This approach to river management may also be described as process-based. With the regard to the restoration of rivers, a processed-based approach is one in which the processes within a river system which have previously been disturbed and altered are reestablished back to normative or natural rates (Beechie *et al.,* 2010).

The term river restoration refers to returning a stream to pristine or 'pre-disturbance' conditions, recreating a river channel that resembles its natural state (Rosgen, 1997). A successful restoration project, therefore, takes into account the entire geomorphological system, with measures in place to restore the channel morphology, ecology, flow regime and sediment regime of the river (Newson & Newson, 2000; Rosgen, 1997). River restoration as both a science and in practice is growing in importance as a necessary measure to conserve rivers. Within the UK this is driven by legislation such as the EU Water Framework Directive (WFD) and funding from government bodies such as DEFRA (Department for Environment, Food & Rural Affairs) (Smith, Clifford & Mant, 2014). The inclusion of the term hydromorphology within the WFD has driven the importance of the inclusion of river processes and landforms within the study, analysis and management of river systems (Belletti *et al.,* 2017). The term 'hydromorphology' itself was introduced and defined in the Water Framework Directive (Boon, Holmes & Raven, 2010). It refers to both hydrological and geomorphological features and processes of surface waters. The hydromorphology of rivers directly influences their ecology and is stated in the water framework directive as key to achieving 'good ecological status' in UK Rivers by 2027.

Restoration is necessary for negating and reducing the detrimental impacts past human interference has had on rivers and their ecosystems. River restoration schemes often have a wide scope of benefits, having economic and social implications in addition to the environmental benefits, such as reducing the frequency and magnitude of flooding and creating recreational spaces (Janes *et al.,* 2017; & Lake, Bond, & Reich, 2007). Without such intervention the health and functioning of river systems will continue to degrade (Wohl *et al*., 2005).

The shift in approach to river management can be attributed to the understanding and acknowledgment of rivers as dynamics systems rather than objects (Nienhuis & Leuven, 2001; & Rosgen, 1997). A healthy functioning river, often described as being 'in-regime' has a channel that is constantly adjusting in response to local changes to maintain its equilibrium. Channels that are in disequilibrium, often as a result of previous management, may be channels that are aggrading or incising, this would be an 'un-healthy' river channel (Gomez *et al.,* 2001). This understanding of rivers as constantly changing and adapting systems rather than as singular objects is important for the implementation of an effective management scheme that works with the natural features and processes of the river to achieve long term, sustainable improvement (Beechie *et al.,* 2010; Guneralp *et al.,* 2012 & Wohl *et al.,* 2005).

There is a general consensus among academics that the chances of long term success of a river restoration project increase when the focus is on allowing the river to function dynamically, and in line with its natural processes and through the reintroduction of hydrological variability (Bechtol & Laurian, 2005; Wohl *et al.,* 2005 & Woolsey, 2007). Through this consensus and understanding, the term 'river naturalisation' was coined within river management. River naturalisation focuses on the alteration of rivers back to an historic planform. Whilst similar to river restoration the term naturalisation has an increased focus on returning the river to a state as close to reference conditions as possible, therefore, establishing rivers with varied morphological and hydrological conditions that support healthy and diverse ecosystems (Rhoads *et al.,* 1999). The focus of natural conditions is of particular importance in current river restoration and is direct opposition with many previous restoration schemes that were often centered around fisheries and artificial habitat creation, often creating habitats that were unnaturally static (Beechie *et al.,* 2010., & Smith, Clifford & Mant, 2014). Returning rivers back to this historical planform or towards pre-disturbance conditions is not always straight forward, and due to the scope and complexities of previous engineering and structural river management can be difficult to achieve (Bechtol & Laurian, 2005).

The aim of returning a river to its historic planform is a common goal of river restoration. For example, the re-meandering of a channel is one of the most visual and frequently implemented methods of river restoration, and is a common goal for many rivers in the UK and developed world; previously straightened for agricultural use (Kondolf, 2006). There are numerous problems associated with previous management technique of river straightening. Many channels were historically straightened to increase the extent of human utilisation of the floodplain and to control the river. The purpose of such was, for example to make more arable land for farming, for clearing land to build settlements, and for irrigation (Brookes, 1987; Richter & Richter, 2000 & Werrity, 2006). The negative impacts associated include a reduction of biodiversity as a result of lack of flow variability, such as that found in a pool-riffle system (Brookes, 1987). Biodiversity is also reduced on the floodplain as a result of its disconnection from the river channel in many straightened reaches also featuring artificial levees (Bechtol & Laurian, 2005; & Tockner, Sheimer, & Ward, 1998). Furthermore through the straightening of the river channel increases downstream flood risk through increased flow efficiency, decreased storage within the channel and a reduced lag time (Dixon *et al.,* 2016, & Janes *et al.,* 2017).

Natural flood management is a relatively new concept, growing out of the river naturalisation concept and acknowledgement that as rivers are dynamic systems that are always adjusting and therefore it is difficult to control and constrain them (Howgate & Kenyon, 2009). Natural flood management is described as being a sustainable alternative to the traditional methods of managing flood risk; involving the storage and slowing of flood waters through restoring rivers to a naturalised state (Janes *et al.,* 2017 & Lane, 2017). Techniques of natural flood management include full scale river restoration projects, and more localized land management techniques such as upland drain blocking and the introduction of large woody debris (SEPA, 2015).

1.2 Aim & Objectives

The focus of this thesis is to study the hydromorphological evolution of Swindale Beck, Eastern Lake district, in response to a river restoration project. The aim of this thesis is to quantifiably monitor the river response to restoration at Swindale Beck. To achieve this aim a number of objectives are set focused on the hydromorphological changes to channel planform and river processes. These objectives are to include an in-depth review of pertinent literature regarding river restoration and natural flood management, in which areas of consensus and disagreement between academics is identified. The morphology of the channel will be studied using repeat sUAV (small unmanned aerial vehicle) surveys to create digital elevation models of the channel and floodplain; these DEMs will be used to identify temporal changes to channel morphology, characterise riverine habitats and volumetrically calculate sediment flux. The results of which will be used to establish the response of the river to the restoration, drawing conclusions on the success of the project. TUFLOW hydraulic modelling is also completed to identify biotope presence and availability through an analysis of Froude number within the reach; this is used to show a comparison between pre and post restoration conditions. The sedimentology of the restored reach is assessed through sediment sampling along the restored reach and the use of TUFLOW modelling of the bed shear stress within the reach, again comparing between pre and post restoration conditions. The outcome of the restoration will be discussed in terms of its impacts to the overall river health and ecological status of the river, as well as its impacts on flood management.

It is expected that the repeat sUAV surveys will reveal a period of rapid adjustment to the restoration, following on from which, the river is expected to exhibit patterns and levels of erosion and deposition in line with those expected from a natural, single thread, meandering channel (Guneralp *et al.,* 2012). Habitat diversity is also expected to increase, with the hydraulic modelling showing increased dispersion and variety in biotope quantity in the river channel at Swindale Beck. It is likely that the restored reach will exhibit a significantly different bed shear stress in comparison to the unrestored data.

The order of this thesis shown in figure 1 is as follows; an outline of the study area and details of the restoration project is provided, followed by a review of literature pertaining to the topics of river restoration, naturalisation and natural flood management. The methods used to study the hydromorphological restoration of Swindale Beck are then discussed, along with justifications for the chosen methods. Following on from this the results will be presented, discussed and conclusions drawn.

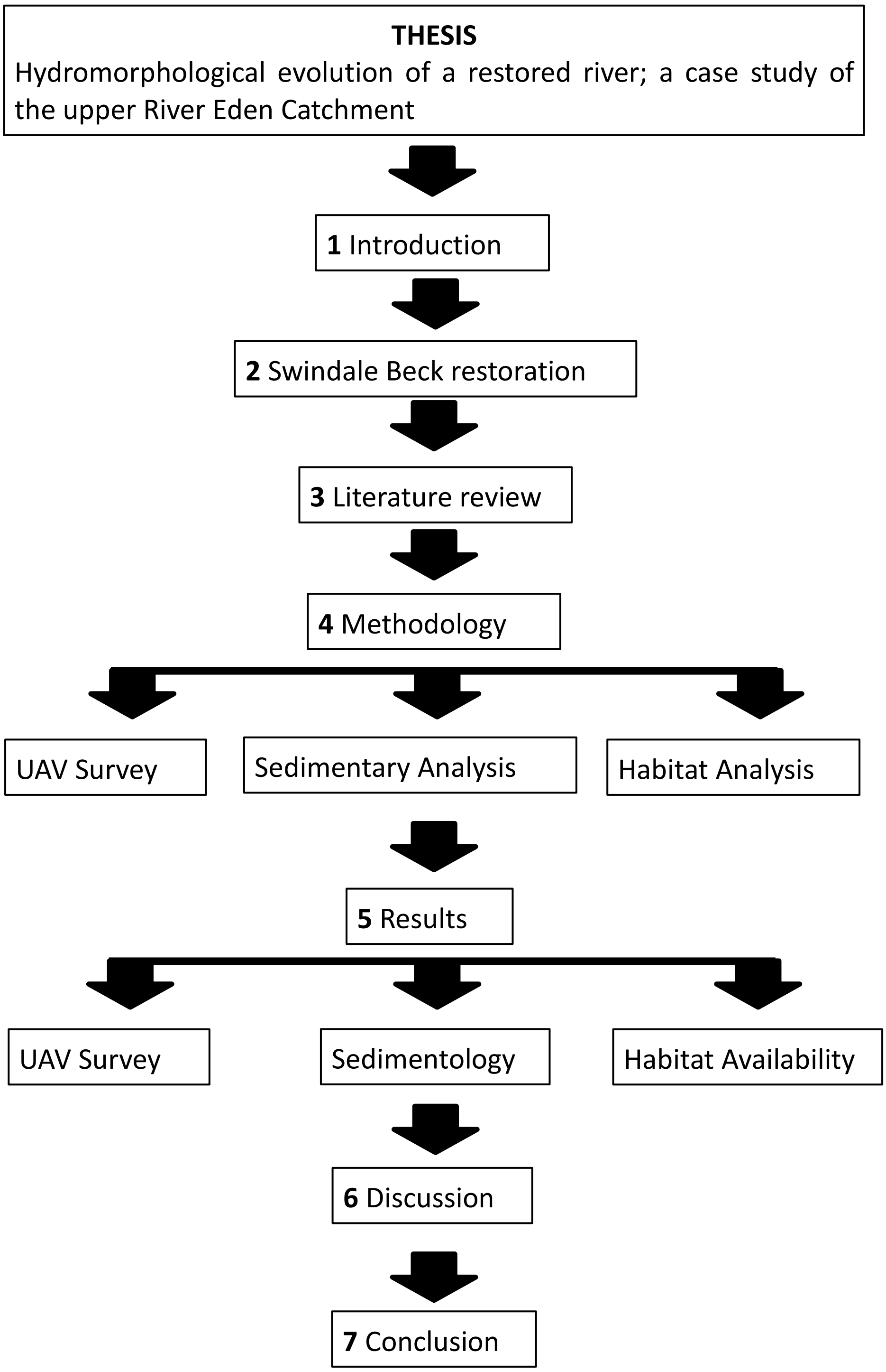


Figure 1 Thesis overview

2. Swindale Beck Restoration Project

2.1 Study Area

The reach studied flows through Swindale Farm in Shap Rural in the Eastern Lake District, UK. Swindale Beck is a tributary of the River Eden, located close to the Haweswater Reservoir (Figure 2). Swindale farm, along with nearby Naddle Farm, are on long-term lease from United Utilities by the RSPB, to be included as part of a project to improve farming and land practices. The land is leased by the RSPB and managed by a tenanted farmer, thus requiring cooperation between the landowner (united utilities), project operators (RSPB) and the land user (the farmer). The project aims to benefit farmers as well as improving wildlife conditions and river water quality. Additionally the grazing rights to 3 upland commons have also been acquired for this project (RSPB, 2015). The restoration of Swindale Beck is in conjunction with this demonstration of sustainable land management (CIEEM, 2017). Located downstream of the study reach is the united utilities drinking water intake (Figure 3).

Figure 2 Google Earth imagery showing the location of Swindale Beck, Eastern Lake District. Showing; 1. Location of the Haweswater Reservoir. 2. The study Reach. 3. The river Eden.

Figure 3 Google Earth imagery of the United Utilities drinking water intake at Swindale

The channel at Swindale Beck had been heavily modified, similarly to many rivers and watercourses in the UK, and other developed countries. The natural stream flow of rivers have been altered or constrained to create more useable floodplains for agriculture and settlements (Richter & Richter, 2000). Swindale Beck had been straightened at least 160 years ago, evidenced by historical maps showing the straight course of the river. Figure 4 illustrates the course of Swindale Beck after straightening, like many rivers Swindale beck was straightened to create usable meadows for agriculture (CIEEM, 2017).

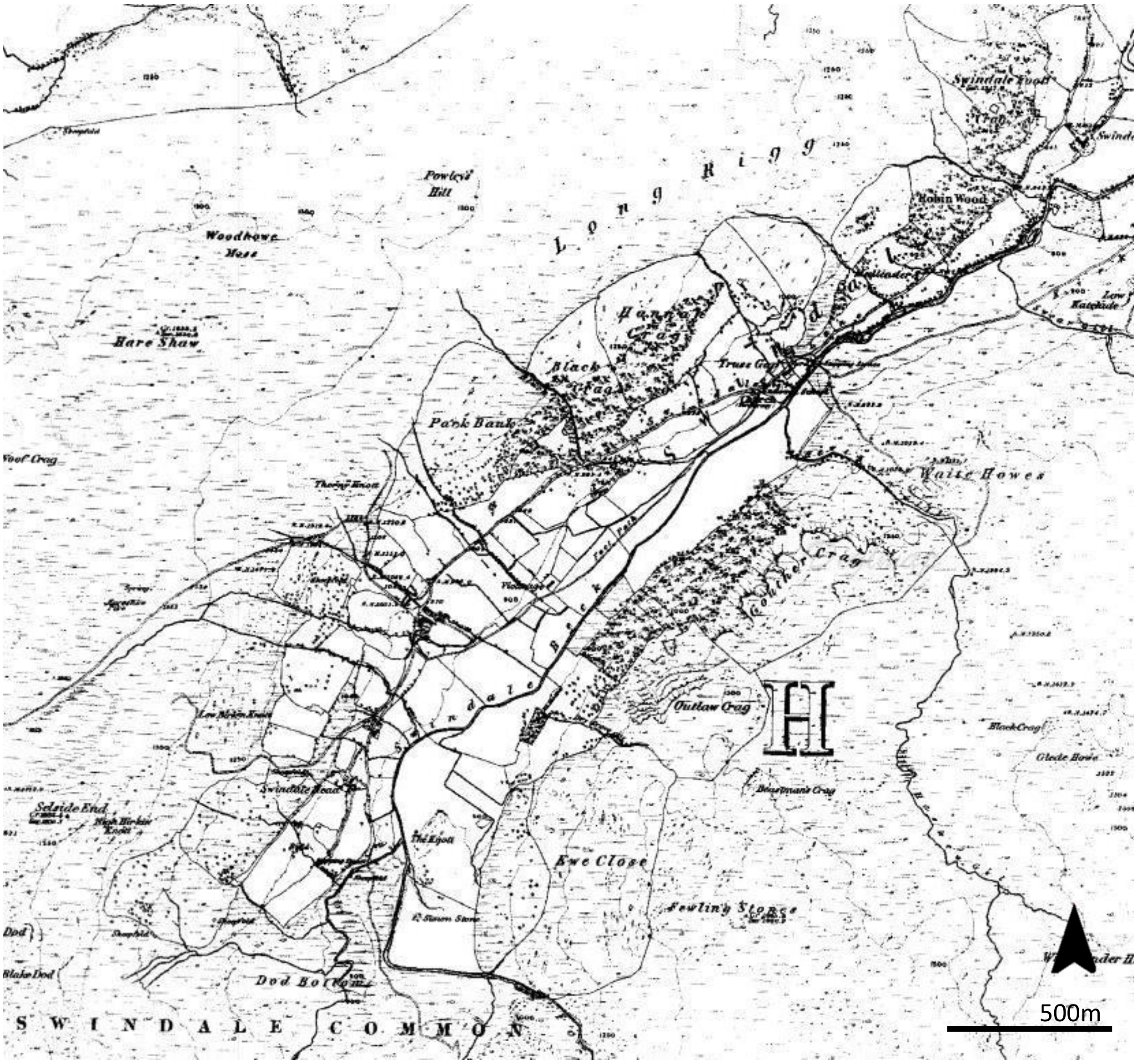


Figure 4 Historical Ordnance Survey map of the Eastern Lake District, showing the straightened course of Swindale Beck in the 1860s (Source: Ordnance Survey, 2018).

The straightened channel at Swindale beck was largely uniform in width, depth and flow; with few in-stream habitats present. The lack of channel variability and habitat diversity of Swindale Beck was evidenced by the absence of pool-riffle system, with a uniform flow being present in the channel and the absence of gravel bars. The lack of flow diversity and a pool-riffle sequence is commonly attributed to the loss of aquatic species, particularly fish in rivers (Brookes, 1987). It is widely acknowledged that the natural stream flow of rivers is crucial for maintaining a healthy river system; where rivers are unconstrained and the natural stream flow is allowed, rivers can constantly adapt to local changes (Mant & Janes, 2005; Richter & Postel, 2004). Accelerated stream flow present in the rock armoured Swindale Beck caused problems at the united utilities drinking water intake; with smaller gravels and silts regularly being entrained and deposited at the drinking water intake calling for regular maintenance (CIEEM, 2017). This accelerated flow also posed issues for downstream flood risk, reducing the length of the channel and the time taken for a unit of runoff to reach downstream areas where flooding is likely (Dixon *et al.,* 2016).

2.2 Restoration of Swindale Beck

The river restoration project at Swindale Beck was undertaken and completed in 2016, as part of a partnership between the RSPB and United Utilities, the land owners. The project created a new sinuous, single thread channel, to replace the previous straightened channel, shown in figure 5. The new channel measures at 891m in length, 140m longer than the original channel as a result of the meanders. The constructed channel is also approximately 2m wider than the previous channel. Reconfiguration of river channels and the reintroduction of meanders is a reasonable and achievable restoration goal that has been widely used (Kondolf, 2006). For the goal of restoring the river at Swindale Beck to 'pristine' or 'pre-disturbance' conditions the remeandering of the channel was crucial; combatting the uniform flow, channel planform and lack of in stream habitats to create a channel that reflects the natural conditions expected (Rosgen, 1997).

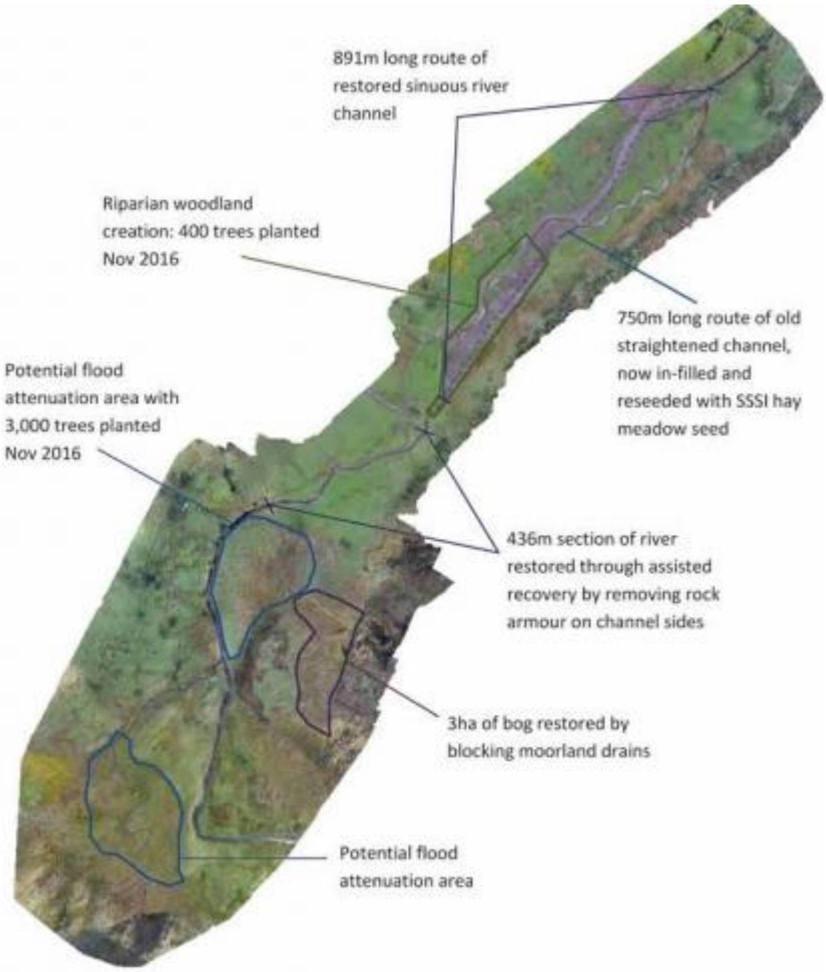


Figure 5 Restoration of Swindale Beck

The new channel was designed to be as natural as possible, reflecting its pre-disturbance conditions. The new course of the river was designed using evidence from paleo channels, which are areas of lower lying, wetter land, where the river previously flowed to. These paleo channels were used as a 'blue print' to aid in Swindale Beck's restoration. The use of paleo channels is well established in paleofluvial studies and the study of the evolution of fluvial systems (Dollar, 2004). The new channel also promoted lateral connectivity between the river and the floodplain, where the previous channel had levees along the river bank preventing water spilling out of the channel and onto the floodplain, decreasing floodplain biodiversity and increasing downstream flood risk (Tockner, Schiemer & Ward, 1998).

The methods for carrying out the restoration work were developed and selected to cause as little damage as possible to the environment at Swindale Beck. This included electro fishing to remove fish from the straightened channel before construction work commenced; following the completion of the new channel the fish were reintroduced. Electrofishing is a simple and effective method for capturing fish that causes minimal harm to the fish; using an electrical current in the water that attracts and then immobilizes the fish (Bohlin *et al.,* 1998).

The goal of the new channel at Swindale Beck is to create a river channel, with lateral and longitudinal connectivity that mimics the natural form of a meandering river, with processes of erosion and deposition that adjust to local changes, moving the river toward a state of equilibrium (Mant & Janes, 2005). There are numerous goals of the restoration project which include improving the ecological status of the river, allowing for erosion and deposition to occur in line with natural processes, encouraging wildlife through increased habitat availability within the river and floodplain, and reducing the downstream flood risk. Reconnection with the floodplain will allow small natural floods to occur; this is essential to the maintenance of a healthy floodplain. Under natural conditions floodplains are highly diverse landscapes with high biodiversity (Bechtol & Laurian, 2005., & Tockner, Schiemer & Ward, 1998).

Either side of Swindale Beck on the floodplain is hay meadows, some of which have been designated as Sites of Specific Scientific Interest (SSSI) or Special areas of Conservation (SAC) (RSPB, 2015). Hay meadows a rare habitat and are isolated to the upland valleys of Northern England (Jefferson, 2005). At the unrestored Swindale Beck levees developed alongside the channel prevented water flooding out on to the floodplain and later reentering the channel. This created stagnant pools of water, which had a negative impact on the health of the hay meadows and reduced biodiversity (CIEEM, 2017). Small flood events, where the water can reenter the channel when flooding subsided are essential to shaping and maintaining high levels of biodiversity of the floodplains (Tockner, Schiemer & Ward, 1998). It is hoped that with the creation new channel and removal of the levees, the ecological quality of the hay meadows will improve, as water will be able to move between the channel and floodplain as the two are reconnected and the lateral connectivity is restored.

Hay meadows are significant as they are both a rare and distinctive habitat, home to species such as wood cranesbill, great burnet and lady's mantle (JNCC, 2017). In addition to the improvements to the hay meadows hoped to be achieved through the restoration project, land management practices (monitored by a farm contractor, working for the RSPB as part of the sustainable land use project) are aimed at further assisting the restoration of the hay meadows. The land use practices implemented mirror traditional agricultural techniques; this includes not using fertiliser on the ground and carefully managing the seasonal timing of sheep grazing on the land (RSPB, 2013).

Furthermore, the channel straightening and development of Levees also increased the downstream flood risk, with water moving quickly through the channel and without adequate areas of storage in times of high precipitation and high flows. The new sinuous channel increased the length of the river channel as well as slowing the flow of water, with backwaters providing additional storage of water (SEPA, 2015). Backwaters, implemented at Swindale Beck for water storage, are areas of water separate from the main channel but connected at the downstream end, allowing water to enter in an upstream direction (Wadeson & Rowntree, 1998).

In a further attempt to cause as little damage to the current biodiversity as possible the new channel was dug through areas that were permanently wet, or wet the majority of the time, and thus had a lesser biodiversity. Openspace, a specialist environmental contractor, oversaw the project and prior to commencement an impact assessment was undertaken to determine whether the project would have positive impacts on biodiversity, allowing the project to gain support from Natural England.

A reforestation project was also implemented as part of this wider scheme with over 4,000 trees planted in the winter of 2016- 2017, it is hoped that this will be beneficial to the river channel through shading of areas of the channel and as the trees mature, the addition of wooded debris to the channel.

3. Literature Review

3.1 Introduction

This literature review will compare and contrast the pertinent literature regarding to river restoration, its significance, and common goals. The newly emerging field of Natural Flood Management (NFM) will be explored, and the long terms goals and monitoring of such projects discussed with a view to establishing grounding for this thesis studying the hydromorphological evolution of Swindale Beck in response to river restoration; and thus the success of the project.

At the forefront of hydrological science is the study and implementation of river restoration (Wohl *et al.,* 2005). Despite its importance and the general agreement between academics of its significance the term restoration itself is interpreted differently. Cairns (1990) define river restoration as having one finite goal, to completely transform the structure and function of a river to a pre-disturbance state. This view of a complete transformation of river systems is mirrored by Rosgen (1997) where restoration is defined as the return of a river to a dynamically stable channel, one which will not exhibit significant changes over an engineering timescale. However, other academics view river restoration as a process of enhancing damaged rivers and their ecosystems (Brookes & Shields, 1996; Kondolf, 2006; & Wohl, 2005). Though the difference between these definitions initially appears to be slight, the emphasis of the second group of academics is the vital approach of river restoration being an ongoing process, where conditions may be improved, yet the river may never be fully restored to pristine or pre-disturbance conditions (Kondolf, 2006; & Wohl, 2005). The later opinion has a strong focus on the process of improvement an enhancement and the ongoing nature of restoring a river. This approach to river restoration can be viewed as process based, where the focus lies in reestablishing normative rates of functioning in rivers, for example through the restoration of nutrient transfer, sediment transport and the storage and routing of water (Beechie *et al.,* 2010).

Furthermore despite political commitments to river restoration such as £110 million of funding from DEFRA and drivers from EU legislation such as the Water Framework Directive there is disagreement over the efficacy of methods for implementing successful restoration projects with long term implications, with a perception that the underlying science remains weak (Downs & Kondolf, 2002., & Smith, Clifford & Mant, 2014).

River restoration and natural flood management (NFM) are often closely associated. With common techniques and methods in river restoration such as re-meandering or the input of woody debris into channels, having positive effects for flood management; whilst also helping to achieve wider restoration goals, such as ecological improvement and increasing habitat diversity (Nienhuis & Leuven, 2001). The Scottish Environmental Protection Agency (SEPA, 2015) refer to natural flood management as an approach which is based on using techniques that work alongside the natural features and processes of a river; whilst typically focusing on storing and slowing the flow of flood waters. Furthermore they outline that the techniques and methods used in natural flood management, which may include large river restoration projects, have wide ranging benefits in addition to flood management including; biodiversity enhancements and improvements in water quality as well as social effects including the provision of recreational spaces and improved access to wildlife (Janes *et al.,* 2017; & SEPA, 2015).

3.2 Significance of river restoration

As rivers and their floodplains are important natural systems, their health and quality is of high importance. River restoration is a focus across the UK and many developed counties where riverine systems have been heavily modified (Richter & Richter, 2000). This modification of rivers over the past 2,000 years, through river management practices focused on the control of water to mitigate floods and the utilisation of water for society (for example through, irrigation, water supply, hydroelectric power), is agreed by many to be the leading cause of degradation in riverine ecosystems, and in reducing the capacity of rivers to store water and attenuate floods (Kondolf, 2006., & Lake, Bond & Reich, 2007). In a discussion over the future of river restoration and its approaches Newson & Large (2006) outline that despite disagreements over the most effective, holistic way of restoring a river ecosystem there is consensus over the need to repair the current damaged river ecosystems. Approximately 85% of river restoration projects are carried out in lowland rivers, which are more likely to have experienced previous management and are often in close proximity to settlement sites and population centers (Smith, Clifford & Mant, 2014). The term process-based restoration focusses on correcting these past interventions in river systems focusing on restoring processes within the river system to negate and undo previous management (Beechie *et al.,* 2010).

River restoration can be seen in two disciplines based on the above, restoration for ecology and restoration for flood management. Largely, these two goals overlap and are later discussed in more detail. Legislation is a key driver for both end goals of restoration. The EU Water Framework Directive aims to achieve ‘good ecological status’ of all surface waters by 2027, restoration to meet this goal is focused on aquatic ecology and water quality (Hering *et al.,* 2010). Similarly river restoration schemes often involve channel modifications to create habitats favourable to desired species (Clarke, Bruce-Burgess, & Warton, 2003). River restoration has developed from its early form with a large focus upon fisheries to restoration that has an ecological focus but is broadly based (Smith, Clifford & Mant, 2015). This shift in river restoration largely accounts for the overlap in the two general themes of river restoration with ecological goals being achieved through the implementation of schemes such as channel reconstruction and remeandering which have outreaching implications on the hydromorphology of the river, thus impacting flow regime, sediment transport, and flood risk (Werrity, 2006).

The ecological restoration of rivers is of particular importance in response to past human alterations and at combatting extinction rates; which are five times higher than terrestrial extinction rates (Ricciardi & Rasmussen, 1999). The second overarching theme is river restoration for flood management. Combatting the impacts of channels that had previously been straightened, deepened and disconnected from their floodplains, water storage capacity has been reduced, as has the transit time of water, both altering the flood hydrograph, exacerbating flood frequency and magnitude (Dixon *et al.,* 2016). Natural flood management schemes, overlapping with river restoration are seen as a cheaper and more sustainable way to manage flood risk, whilst also presenting benefits to the overall health of the river and floodplains (Bechtol & Laurian,2005; & Werrity, 2006). The results of field study and modelling, by Dixon *et al.,* (2016) supports the potential of this sustainable and natural method of flood management, suggesting its favour over hard engineering and structural defences.

3.3 Engineered River Restoration & Re-meandering

As the restoration project at Swindale beck features the creation of a new sinuous channel, designed based on paleo channel evidence, academic perspectives on engineered river restoration and the re-meandering of river channels is discussed.

The most visual form of river restoration is channel reconstruction, to mimic the natural state of the river, for example through re-meandering the river channel (Kondolf, 2006). This is driven by societal pressure to create a river channel that is aesthetically pleasing and fits in with the typically desired form of a healthy river. A river that is meandering appears to the majority of people as a natural, healthy river, as such this form of river restoration often garners widespread public approval (Kondolf, 2006). However, re-meandering a river provides more than just aesthetic benefits. Meanders, which are inherent in river flow, naturally form in rivers where the slope and width-depth ratio is sufficiently low at formative discharges (Leopold & Wolman, 1957; & Parker, 1976). Supporting this further is the acknowledgement that a meandering river is natural and within it has a pattern of sediment transport and introduces habitat variability to a river (Garcia, Shnauder & Pusch, 2012). As meandering rivers inherently contribute flow and habitat variability, where river restoration is concerned, re-meandering of a river should create a channel where natural processes can occur, allowing the river to reach equilibrium where its dimensions and features will remain significantly unchanged over engineering timescales, yet will respond to local changes (Thorne *et al.,* 1996).

Engineered river restoration and re-meandering also includes alterations to the river channel to enhance lateral connectivity. Through this lateral connectivity floodplain health is increased and downstream flood risk reduced (Bechtol & Laurian, 2005; Fischenich & Morrow, 2000; Guida *et al.,* 2015; & Tockner, Schiemer & Ward, 1998). One way in which downstream flood risk is reduced through channel reconstructions and reestablishing floodplain connectivity, such as levee removal, is the provision of water storage. At high flows water is able to overflow river banks onto the floodplain, this in-turn, reduces the discharge and velocity of the water, and in comparison to a constrained river significantly reduces the impact and frequency of downstream flooding (Guida *et al.,* 2015). Additionally, many academics stress the importance of small, frequent flooding on to the floodplain, which by name is an area of land susceptible to flooding. This agreement between academics states that natural flooding is essential to the health of floodplains. Frequent and small flood events replenish and sustain ecosystems, encouraging biodiversity (Bechtol & Laurian, 2005; Lane, 2017, Marteau *et al.,* 2017).

Moreover, in a study of river flows and floodplain forest restoration, the importance of nutrient transfer between floodplain and river is cited as essential for the health of both the river and floodplain, (Rood *et al.,* 2005). The importance of this nutrient transfer is widely agreed upon by academics for the ecological health of the river channel and the floodplain (Bechtol & Laurian, 2005; Guida *et al.,* 2015; Junk, Bayley & Sparks, 1989; Lane, 2017; & Tockner, Schiemer & Ward, 2005). Government and environmental authorities are also in agreement with the importance of a natural flood regime, stating floodplain connection as a common and significant goal of many restoration schemes (Environment Agency, 2007).

A study of the restoration of two lowland German rivers, The Schwalm and The Gartroper Mühlenbach provides case study evidence of the above. The restoration projects involved the remeandering of the channels and lowered floodplain levels to increase connectivity with the floodplain. In the post project study and monitoring of these two restoration projects, it was observed that flow diversity had increased, as well as the variability in channel substrate and features. Within the river channel the restoration had also lead to increased presence in macrophytes and increased population and diversity of macro-invertebrate families, genera and taxa. In addition, the health of the floodplain and its ecosystems had also increased, as evidenced by increased species diversity of floodplain flora (Lorenz, Jähnig, & Hering, 2009).

3.4 River restoration goals

The aim of river restoration is to create, enhance and improve conditions, structures and functions of a river channel and its floodplain, aiming to achieve conditions that resemble the natural, or pre-disturbance state expected of the river (Brooke & Shields, 1996; Cairns, 1990; Kondolf, 2006; Rosgen, 1997; & Wohl, 2005). For a river restoration project to be deemed a success the project should take a holistic approach, and consider the entire watershed. This is due to the complex interconnection of physical, chemical and biological process within the watershed over varying timescales (Wohl *et al.,* 2005). Furthermore the chances of achieving success in river restoration are greatly increased when the difficulties of doing past structural works are considered alongside the desired outcomes (Bechtol & Laurian, 2005). Indicators of successful river restoration include, providing an enhanced service to society, and improved river ecosystem attributes such as; morphological and hydrological variability, near-natural sediment transport and a near-natural temperature regime, species abundance and diversity and vertical, lateral and longitudinal connectivity (Lake, Bond & Reich, 2007). The ecological, morphological, and floodplain-centric restoration goals are discussed as well the factors presenting challenges to their achievement.

3.4.1 Ecology

Ecological improvements are a common goal of restoration projects, based on the loss of diversity and ecological degradation caused by centuries of human interference and alteration of river systems (Janes *et al.,* 2017; Wohl *et al.,* 2005). Process-based river restoration focusses on the improvement of processes in a river to reestablish normative rates, and is in contrast with previous methods of ecological river restoration which focused on the creation and engineering of artificial habitats (Beechie *et al.,* 2010).

The alteration of flow has been observed to have negative impacts on species diversity. Dam construction, for example, which decreases flows in rivers and alters sediment supply has a direct impact on the macro-invertebrate species assemblage. By examining hydrological and macro-invertebrate assemblage data for the Green River in Utah, Vinson (2001) assessed the impacts of the Flaming Gorge Dam on the river. The study reveals that as a result of the dam the annual mean minimum daily discharges, water temperature and sediment transport all decreased significantly. Moreover, the study found that after the closure of the dam, with the river following a more natural course the mean macro-invertebrate density increased by 9,000 species per square metre, from 1,000 m/s^2 to 10,000 $m/s^{2.}$ This shows the importance of factors such as discharge, water temperature and sediment transport of river ecology.

Smith *et al.,* (2014) supports the findings of Vinson (2001) acknowledging that habitats are declining and fragmenting as a result of human alterations on river systems and river processes. To combat this re-establishment of biotic substrate and a focus upon restoring invertebrate communities is suggested (Lorenz, Jähnig & Hering, 2009). The importance of ecological improvements is widespread, however, a narrow focus on ecological improvements for example the artificial creation of habitats and species reintroductions may have short lived effects, failing to achieve long term success and change. This is due to an increased focus given to the end result of habitat creation and species introductions and less focus on the underlying geomorphological processes that can sustain this long-term (Clarke, Bruce-Burgess & Wharton, 2003). Through the example of the Green River, the re-establishment hydromorphological processes within a river is crucial to achieving long term success for river restoration (Vinson, 2001; Woolsey, 2007). Furthermore, within the UK most river and floodplain restoration is modest in scale, thus, limiting the extent of ecological success, with often ecological success being limited to small areas and reaches within a watershed (Adams, Perrow & Carpenter, 2004).

3.4.2 Morphology

Morphological changes to a river are common in restoration; this may be through the creation of a new channel or through the formation of gravel bars. Much of the discussion regarding morphological diversity as a river restoration goal has been previously discussed under the heading of ‘Engineered River restoration and re-meandering’. However, achieving a functioning and morphologically diverse river requires more than just the construction of a new channel; schemes and adjustments need to be designed appropriately with individual conditions considered (Pretty *et al.,* 2003).

Successes in this area of restoration include the Kissimmee River Restoration Project in Florida, where the re-establishment of a meandering planform in response to channelisation in the 1960s successfully improved sediment transport and point bar development (Anderson, 2014). A fluvial audit post restoration on the River Cole, UK revealed an increase in geomorphological features when compared with the pre-restoration channel. As mentioned this morphological diversity creates habitats, resulting in ecological benefits to the river (Kronvang *et al.,* 1998).

Not all restoration projects are successful in creating morphologically diverse channels that have wider benefits. Contrastingly to the findings of Anderson (2014) and Kronvang *et al.,* (1998); Pretty *et al.,* (2003) observed a weak response of fish to river restoration across the UK, attributed to a lack river specific planning resulting in poorly designed restorations across inappropriate scales in many low gradient restored rivers. Therefore highlighting the importance of considering the individual characteristics present in a watershed prior the implementation of a river restoration scheme.

The restoration, enhancement and reconnection of the floodplains is increasingly viewed as an imperative fragment of a successful river restoration. It is viewed as more challenging than that of traditional in-channel restoration. This challenge is posed by the uncertainty of the pre-disturbed state of the floodplain, the ability to create, maintain and improve the linkages between river and floodplain; along with additional complexities arising from landowner and stakeholder interference often wanting floodplain land to be usable (Adams, Period & Carpenter, 2004). Similarly the interconnection of processes is made more complex with the scale of impact increased across the river and floodplain, leading to difficulties in restoring floodplains (Wohl *et al.,* 2005). Despite the challenges, and gaps in understanding of floodplain restoration best practice, there is widespread agreement that through the reconnection of rivers to their floodplains, re-naturalisation of the channel and flow, ecological improvements to the floodplain will result (Bechtol & Laurian, 2005; Marteau *et al.,* 2016; Tockner, Schiemer & Ward, 1998).

3. 5 Natural Flood Management

Floodplain restoration and reconnection will also impact on flood risk. The concept of Natural Flood Management and its successes and challenges are discussed in the framework of restoration. Natural flood management with river restoration is likely to have developed through the understanding of how channel and floodplain topography and geometry impacts on flood wave propagation. River restoration and flood risk practioners are implementing schemes that alter the morphology of the river channel, or through the creation of new channels and floodplain restoration and reconnection that alters the flow and storage of river systems to reduce the frequency and magnitude of downstream flooding (Dixon *et al.,* 2016).

Table 1 Natural Flood Management techniques and actions (SEPA, 2015)

Measure Group	**Measure Type**	**Main Action**
Woodland Creation	Catchment woodlands	Runoff reduction
	Floodplain Woodlands	Runoff reduction/floodplain storage
	Riparian Woodlands	Runoff reduction/ floodplain storage
Land Management	Land and soil management practices	Runoff reduction
	Agricultural and upland drainage modifications	Runoff reduction
	Non-floodplain wetlands	Runoff reduction
	Overland sediment traps	Runoff reduction/sediment management
River and floodplain restoration	River bank restoration	Sediment management
	River morphology and floodplain restoration	Floodplain storage/sediment management
	Instream Structure (e.g. large woody debris)	Floodplain storage
	Washland and offline storage ponds	Floodplain Storage

Natural Flood Management and River Restoration are closely associated; river restoration projects often have the goal of reducing flooding, through natural and sustainable measures, and natural flood management schemes include techniques used in river restoration projects, or include the restoration of a river itself as a measure to achieve flood management (SEPA, 2015). The techniques and actions that form NFM are shown in Table 1. Natural flood management refers to reducing downstream flooding, through the storage of water, and the slowing of flows of storm water into river channels (Janes *et al.,* 2017).

Further linking the two disciplines are the additional benefits that may be achieved from the implementation of natural flood management schemes, which have the potential to improve the functioning of river catchments, provide ecological improvements and an increase in habitat and species diversity (Janes *et al.,* 2017; Nienhuis & Leuven, 2001; & SEPA, 2015). Natural flood management is of increasing academic and practical interest due to its potential to provide these ecological benefits whilst also providing major social and economic benefits through the reduction to the cost of flood infrastructure and potentially reducing the costs and effects of flood damage (Janes *et al.,* 2017; Merz *et al.,* 2010; & Werrity, 2006). The input of woody debris into a channel, for example, will slow and store water in high flow conditions whilst also providing physical habitats and nutrients to the channel that benefit aquatic species (Dixon *et al.,* 2016). Natural flood management is becoming more widely incorporated into river restoration as projects move from the enhancement of individual and isolated reaches of modified rivers to the wider catchment scale projects (Smith, Clifford & Mant, 2015).

NFM appears to be a promising method for a more sustainable, efficient and cost effective strategy to managing flood risk. Flood risk in the UK is changing at a significant rate, which is associated with the changing climate and the potential increase in physical and meteorological conditions conducive to flooding (Dixon *et al.,* 2016; Kelman, 2001; & Merz *et al.,* 2010). As NFM is a relatively new discipline, there are gaps in the knowledge of the application and success of the techniques for flood management goals.

Despite the consensus for a new approach to flood risk management (Howgate & Kenyon, 2009., & Kelman, 2001) and legislation such as the Water Framework Directive and DEFRAs consultation 'Making Space For Water' there is still disagreement over whether NFM can successfully manage flooding. Werrity (2006) argues that NFM alone is not sufficient to manage flooding and protect settlements, property and people from flooding. Arguing that it is not as effective as traditional hard engineering and structural defences, and should not solely be relied upon for mitigating flood risk. Despite this claim that NFM is unreliable and deemed less effective at providing adequate protection from flood damage, many traditional flood defence schemes have failed and caused increased damage (Bechtol & Laurian, 2005). Kelman (2000) uses the case study of Lewes, Sussex on 13 October 2000 to highlight the potential of traditional flood defences to cause greater damage. Flood defences in the town of Lewes trapped breached flood water in properties in the October 2000 floods extending the duration of the flood of drastically increasing the amount of damage. However, the failings of previous schemes and commonly used methods in case study example alone, does not provide any evidence to suggest that the implementation of NFM schemes would be more successful at preventing flooding and mitigating flood damage. Furthermore, despite concerns over impact caused by the failure of structured flood defences, when social and economic interests must be considered when flood infrastructure is designed; as structured, hard engineering methods of flood management can be more precisely designed, implemented and managed allowing for areas of high social and economic importance to be effectively protected from flooding (Werrity, 2006).

Many of the basic principles and theories undermining NFM are widely understood; with the basic principles focusing on slowing the flow of water and providing increased storage in times of high flows (Janes *et al.,* 2017). Re-meandering of river channels, whilst being one of the most commonly and frequently used methods of river restoration, is further useful in natural flood management (Kondolf, 2006). Through increasing the length of the river channel and reducing the velocity of water within the channel downstream flooding is reduced, increasing the amount of time taken for a runoff unit to travel through the river system to a point in which flood risk is experienced (Bechtol & Laurian, 2005 & Dixon *et al.,* 2016). Furthermore a meandering river channel, allows a variety of flows and intense sediment transport to occur (Garcia, Schnauder & Push, 2012).

Downstream flood risk is reduced significantly through reconnection with the floodplain, allowing water to leave the river channel into the flood plain in times of high flow. This reduces the discharge and velocity of water in comparison to constrained rivers, thus reducing the amount of water and the speed of which the water will travel downstream leading to reduced frequency and magnitude of downstream flooding (Guida *et al.,* 2015; Kronvang *et al.,* 1998). Furthermore, natural flood management has wide-ranging benefits, for example the storage and slowing of water through reconnection with the floodplain is needed to sustain and replenish floodplain ecosystems (Bechtol & Laurian., 2005).

Whilst the mitigation of downstream flooding through the NFM methods of floodplain reconnection and river channel re-meandering is promising in the science and application of flood management, the impacts of differing flood management or lack of management across sub-catchments and the convergence of peak flows must be considered. This is due to the effect of waters from sub-catchments with different management will have on the overall downstream flood risk; which may reduce the signifance of any benefits provided by the implementation of NFM within parts of the catchment. The convergance of flows from unmanaged catchments will minimize the impact of NFM techniques on downstream flooding as large amounts of fast flowing water will still enter the river channel (Werrity, 2006). This may particularly be a problem in agricultural areas as farming land management has often reduced the connection between river and floodplain and in many cases has included the straightening of the river channel (Holstead *et al.,* 2017).

Legislation such as the EU Floods Directive (2007) and the UK Water Management Act (2010) encourage the use of techniques that provide sustainable flood mitigation, such as those encompassed within NFM; focusing on restoring the natural function, and the hydrological and morphological processes of rivers, and the benefits that this will have upon water quality and riparian areas in addition to reducing flood risk (Bechtol & Laurian, 2005; & Janes *et al.,* 2017). Additionally, natural flood management techniques may be favoured as they are cheaper to implement than traditional hard engineering and structural flood defences (Addy & Wilkinson, 2016; & Howgate & Kenyon, 2009). However at present time the uncertainties in the effectiveness of NFM schemes and techniques mean they are rarely suggested in favour of structurally engineered techniques (Waylen *et al.,* 2017).

3.6 Post Project Appraisal

To determine whether a river restoration scheme (or NFM scheme) has been a success, there needs to be post project appraisal and monitoring, with the longer the timescale of monitoring, the greater the learning potential (Downs & Kondolf, 2002). Within the UK the principle source of data on monitored river restoration projects is the National River Restoration Inventory (NRRI) created and curated by the UK River Restoration Centre (RRC). Whilst this inventory is inherently positive, storing and disseminating the outcomes of restoration projects, a major flaw lies within the data stored in the inventory. As the NRRI is an archive of data, the data has been collected by different bodies such as the Environment Agency, independent rivers trusts and community groups; meaning the scope, scale and level of detail widely varies between each of the monitoring projects archived (Smith, Clifford & Mant, 2014).

Frequently with projects of this nature there is a lack of published work to monitor the successes or failures of a river restoration project, despite its agreed importance within academia (Woodward, 2015). It is likely that financial constraints limit the extent to which river management projects can be monitored and studied in a scientific manner. Research into new concepts and ideas raises more revenue in funding than applied research and monitoring projects can achieve (Wohl *et al.*, 2005). Bash & Ryan (2007) and Dickens & Suding (2013) identify constraints to finance and labour as the key obstacle limiting the implementation of long-term monitoring projects of river restoration schemes. Without the monitoring and appraisals of river restoration schemes over varying timescales (short-term, intermediate term, and long-term) river restoration practioners cannot learn from previous schemes, thus limiting the advancement of river restoration theory and practice and ultimately the rate of success for current and future restoration schemes (Smith, Clifford & Mant, 2014). Given the nature of current river restoration projects, schemes often have a holistic ‘vision’ opposed to a strategic brief with clearly stated aims and objectives that can be quantifiably measured. Thus the completed restoration project becomes a live experiment for the combination of techniques used resulting in many of these projects often going un-quantified and the successes and failures of the scheme unmeasured (Newson & Large, 2006).

Despite the difficulties in implementing such schemes, long-term monitoring and continual learning is necessary for the advancement of river restoration, flood management and general river management practice and policy (Downs & Kondolf, 2002; & Roni *et al.,* 2008). Studying and critically evaluating the outcomes of river restoration projects provides the necessary knowledge to guide future projects, evaluate the efficiency of projects and the techniques used. All of which is necessary for the continual improvement of practices and for gaining public acceptance and support (Woolsey *et al.,* 2007). The study of the Kissimmee River, Florida, spanned a 10 year timescale. The hydraulic conditions of the reach were studied 10 years post completion, and revealed that re-meandering and closure of the Flaming Gorge Dam improved conditions and processes, such as sediment transport; providing importance evidence of the success of the project (Anderson, 2014).

The long term effects of restoration are fundamental to determining its success, therefore monitoring schemes long term is critical for lessons to be learned and best practice established. In a study of the German lowland rivers The Schwalm and the Gartropper Mullehnbach, the rivers were studied 2 years post completion and followed up with monitoring 10 years post completion, as well as a comparison with local anthropogenically straightened rivers to assess the effects of the scheme long term. It is also suggested in the study that the rivers should be revisited and re-studied once monitoring projects have ceased (Lorenz, Jähnig & Hering, 2009). The necessity of monitoring from a scientific perspective is well outlined, however monitoring projects are also necessary with regards to practical implementation issues of river restoration project, sound scientific evidence supporting methods of river restoration is paramount to gaining stakeholder support and gaining funding and acceptance of future river restoration projects (Palmer *et al.,* 2005 & Smith, Clifford & Mant, 2014).

The importance of monitoring schemes supports this thesis' study into the hydromorphological restoration of Swindale Beck following river restoration, aiming to show the initial and intermediate response of the river channel. The effect this restoration has on the ecology, hydrology and geomorphology of the river will be used to determine the success of the scheme, on which lessons can be learned and incorporated into future schemes.

Along with the necessity of creating a scheme to monitor such projects, important questions arise regarding what constitutes a successful river restoration project, and which outcomes should be monitored in order to determine these successes. Within this thesis the following are monitored over a 16 month period following the completion of the restoration project to determine the hydromorphological changes which constitute success; topographic change and sediment flux, sedimentology and bed shear stress, biotope characterisation and availability. Regarding the concept of success, in keeping with common restoration goals, this is determined by the extent to which the channel resembles pristine or 'pre-disturbance' conditions such as channel morphology and ecology and natural flow and sediment regimes (Beechie *et al.,* 2010; Newson, 2000; Rosgen, 1997).

4. Methodology

This chapter outlines the methodology chosen to study the hydromorphological evolution of Swindale beck in response to restoration activities. In addition to providing an outline of the methods used, the selection of these methods will be justified. The methods include repeat sUAV surveying of the Swindale Beck and its floodplain, the creation of DEMs of difference to assess morphological changes and hydrological modelling to assess habitat availability and sedimentary analysis.

4.1 Topographic surveying of Swindale Beck

The primary method of data collection used in this thesis is the acquisition of high resolution topographic data in the form of Aerial photographs remotely sensed using an sUAV. The following section outlines the methodology from data collection to presentation. This data was used to detect topographic change through time, assess changes in sedimentation, characterise habitat and volumetrically calculate sediment flux. The data was later used for habitat and sedimentary analysis, discussed in the following sections.

4.1.1 Image Acquisition

The study area was surveyed 6 times over a 16 month period using an sUAV to obtain high resolution topographic data in the form of aerial photographs. Surveys were conducted in the following months October 2016, November 2016, April 2017, November 2017, December 2017, and February 2018. Digital photographs are the most common type of data acquired using UAVs. Previous successful applications of sUAV obtained topographic data support the choice of this method of data collection and formatting and support its validity and reliability for use in this project. Flener et al., (2013) used UAV remote sensed aerial photography in the mapping of river channels at high resolution, finding UAV photography to be suitable of obtaining high resolution data suitable for acquiring a suitable level of detail for the study of river channels despite the use of this technology being in its infancy at the time of writing. Table 2 outlines key studies that have successfully employed this method of data acquisition.

Table 2 Key studies using UAVs to obtain high resolution topographic data

Lejot *et al.,* 2007	Very high spatial resolution imagery for channel bathymetry and topography from an unmanned mapping controlled platform
Hervoue *et al.,* 2011	Analysis of post-flood recruitment patterns in braided-channel rivers at multiple scales based on an image series collected by unmanned aerial vehicles, ultra-light aerial vehicles, and satellites
Flener *et al.,*2013	Seamless mapping of river channels at high resolution using mobile LiDAR and UAV-photography
Fontstad *et al.,* 2013	Topographic structure from motion: a new development in photogrammetric measurement
Tamminga *et al.,* 2015	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
Woodget *et al.,* 2015	Quantifying submerged fluvial topography using hyperspatial resolution UAS imagery and structure from motion photogrammetry

Outside of fluvial studies UAV surveys have been used to collect topographic data for studies of agriculture, landslides, costal processes and the study of glaciers (James *et al.,* 2017). The use of UAVs allows for the data collection to be rapid, inexpensive and flexible, especially when compared to traditional data collection methods, such as LiDAR and traditional surveying. The collection of high resolution topographic data is generally associated with high costs of expertise and equipment (Westoby *et al.,* 2012; & Woodget *et al.,* 2015).

Table 3 DJI phantom 4 quadcopter specification.

Weight (Battery & Propellers Included)	1380 g
Max Wind Speed Resistance	10 m/s
Max Flight Time	Approx. 28 minutes
Camera Sensor	1/2.3" CMOS Effective pixels:12.4 M
Gimbal Stabilisation	3-axis (pitch, roll, yaw)

For the repeat surveys of Swindale Beck a DJI phantom 4+ quadcopter UAV fitted with a 4k camera was used. The DJI Phantom 4+ has a maximum flight time of 28 minutes and a 5km range (Figure 6; Table W). The camera captures high resolution photos at a resolution of 4384 x 3288 MP and 1080p HD recording. The camera is fitted to the UAV with a remotely operated 3 axis gyroscopic gimble, ensuring stability of the camera and accuracy of the angle, necessary for accurate data collection. For each of the 6 surveys the UAV was flown at approximately 35m in height, the flight path following the banks of the river on each side. The photos were taken at 3 second intervals to ensure the necessary overlap required for image processing. All surveys were flown within the guidelines of the UK Civil Aviation Authority (CAA) with a licensed drone pilot and spotter present at all times.

Figure 6 DJI phantom 4+ Quadcopter UAV

Prior to each survey, before flying the UAV, the weather conditions were considered to determine whether the survey will obtain accurate and reliable data. This includes assessing the wind speed, as speeds higher than 5-10 m S^{-1} are problematic, due to the potential to create errors with the aspect of the photographs and reducing the control of the UAV during the flight. As shown in table 3, the specification of the drone indicated a maximum wind resistance of 10 m S^{-1}. Furthermore the light conditions and degree of cloudiness need to be considered to ensure that photographs taken will be clear, of good quality and contain sufficient detail, this meant flying the drone with suitable levels of daylight and never in overly cloudy conditions which may interfere with the validity of the data collected (Flener *et al.,* 2013). With the use of sUAV obtained data and its processing and analysis ensuring the data collected is of sufficient quality to meet the study aims is paramount (James *et al.,* 2017).

4.1.2 Ground Control Points

To begin each survey, preceding flying of the UAV, a series of ground control points (GCPs) were marked and measured at the survey site. The GCPs for the October 2016 survey (survey 1) are shown in Figure a, though the locations of GCPs changed for each survey as they were replotted the pattern and frequency for each survey remained the same. Semi-permanent survey paint was used to spray paint a circle, approximately 50cm in diameter on the ground. The semi-permanent paint was chosen for its ease of use, as no markers have to be collected post-survey. The white colour is also easily identifiable during the image processing, in which the ground control points need to be manually located. As the paint is semi-permanent it will have no lasting effect on the land and will be removed through natural weathering and rainfall.

As can be seen in Figure 7 the GCPs are located along both banks of the river channel, spaced approximately 50m apart and cover the entire length of the survey. The GPS locations of each GCP were recorded with Real Time Kinetic-GPS (RTK-GPS) using a Total Station EDM theodolite.

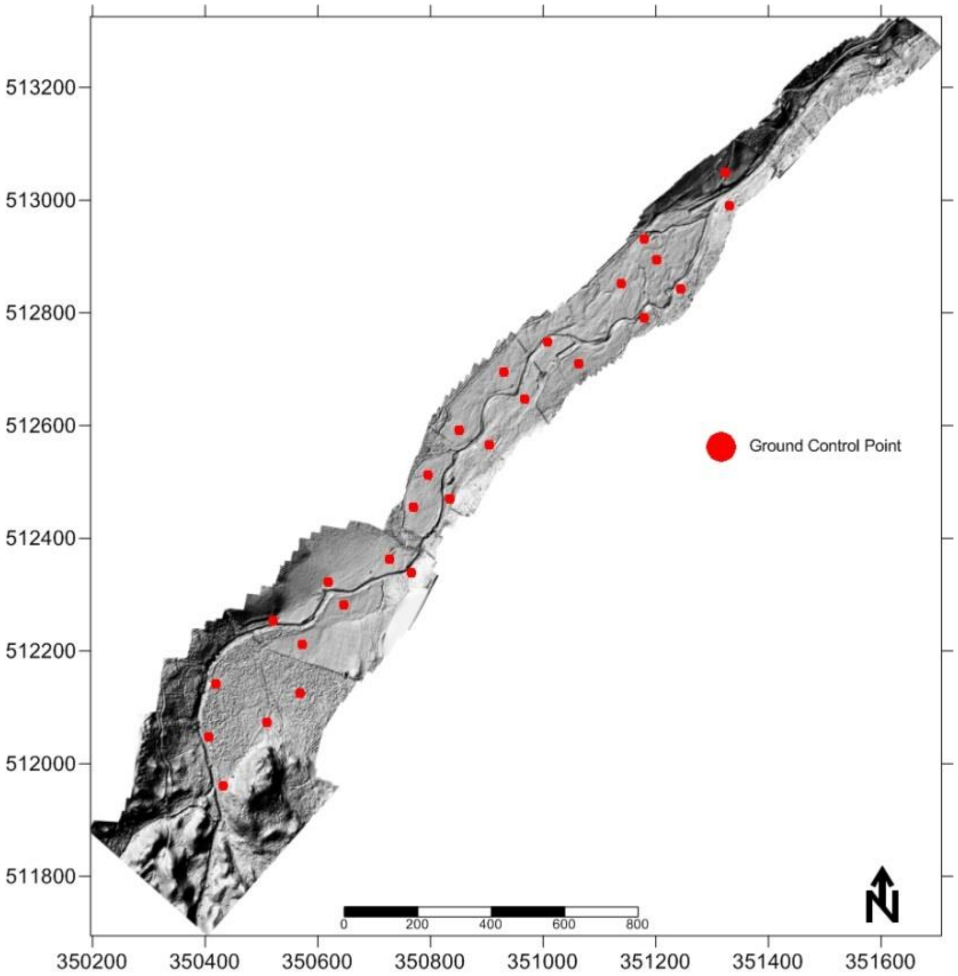


Figure 7 Digital Elevation Model of Swindale Beck, October 2016 survey with locations of plotted ground control points.

The purpose of the GCPs is to allow for the images to be constructed into a Digital elevation Model and orthophoto that is transformed using real world coordinates, rather than based on an arbitrarily scaled 3d Point cloud that would otherwise be created (Javernick, Brasington & Caruso, 2014). For the creation of DEMs of difference (DoDs) the use of ground control points was essential, as they allow for the model to be projected accurately, and on to a real world location, from which the 2 DEMs used in each DoD could be accurately subtracted and compared.

4.1.3 Image Processing and Analysis

The data collected through the UAV surveys was processed using Structure from Motion (SfM) photogrammetry. SfM is similar to traditional photogrammetry in its method of reconstructing 3D scenes using images acquired from multiple viewpoints (Fonstad *et al.,* 2013).

One key difference between SfM Photogrammetry and traditional photogrammetry is that with SfM the collinearity equations can be solved prior to the input of real world locations derived from GCPs and camera locations. Furthermore SfM is capable of matching imagery obtained from widely differing angles, viewpoints and orientations that is not possible using traditional photogrammetry methods, giving SfM an advantage (Woodget *et al.,* 2004). A further advantage of SfM over traditional photogrammetry is that the process is largely automated and requires minimal user input; this allows for rapid and low cost image processing with a reduced level of human error, whilst also making it widely accessible. The accuracy levels of SfM photogrammetry are on-par with LiDAR, which is widely used in topographic studies and by environmental bodies such as the Environment Agency (Fonstad *et al.,* 2013). The main drawback with SfM data lies not in the application of SfM itself but with the inputted data. The algorithms within an SfM package facilitate an easy workflow and the creation of detailed topographic models, often in the form of Digital elevation models and orthophotos. The main factor affecting the validity of these outputs is the image and survey quality, which is highly variable in practice (James *et al.,* 2017).

Agisoft Photoscan was used to employ SfM to create DEMs and orthophotos from the high resolution topographic data, collected in the form of aerial photographs with the sUAV. Used by Javernick, Brasington & Caruso (2014) in modelling of shallow braided rivers, Agisoft Photoscan provides a software package that includes a ‘friendly’ user interface, allows for the control of numerous parameters, and has an inclusive transformative ability. Figure 8 shows the workflow from Data Input to output within Agisoft Photoscan. Digital elevation models were created by inputting the photos into the software and aligning the photos using the algorithms built into the software. After which the GCPs are manually located and the coordinates for the GCPs recorded with the RTK-GPS are inputted, this geo-references the photos to real-world locations. The alignment is then optimized. For all surveys the maximum error was set at a maximum of 5cm. The software’s workflow is then followed to create a dense point cloud, following this a mesh is built, with a texture layer then created resulting in an accurate DEM ready for exporting. Orthophotos for each study, providing an overall image of the study site were also generated and exported using the SfM workflow in Agisoft Photoscan, to create the orthophotho the workflow as above was followed with the additional steps of building and exporting an orthophotho. Orthophothos and DEMs were generated for each survey.

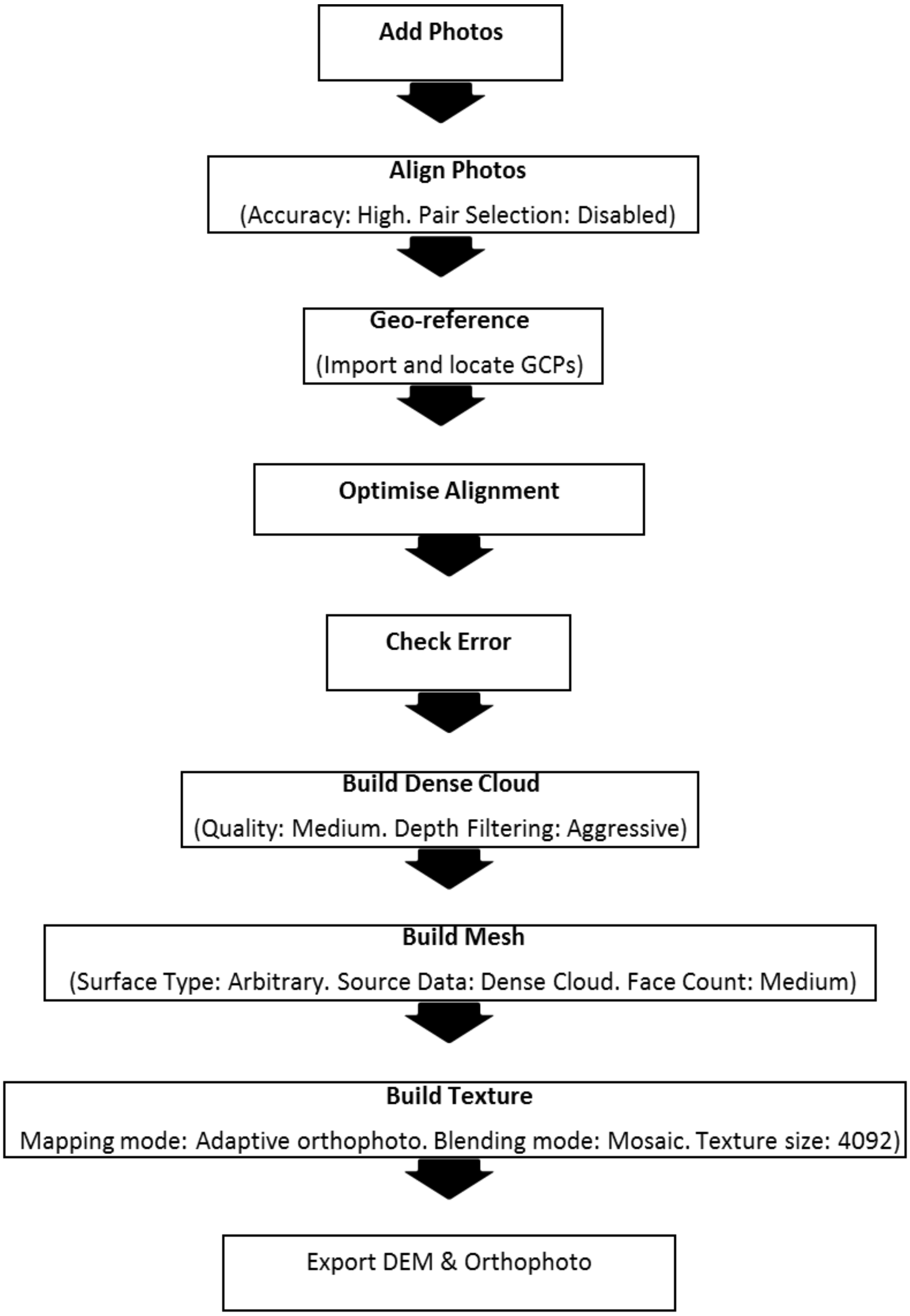


Figure 8 Workflow for the creation of DEMs & orthophotos within Agisoft Photoscan; from data input to DEM export

Following the creation of the DEMs for each survey of the study site, further processing was carried out for analysis of the data. Initially this was the creation of DEMs of difference, which show the areas of erosion and deposition. DEMs of difference have been widely and successfully used in a number of studies. The process involves the subtraction one DEM from another DEM to reveal topographic changes between the two surveys (Kincey *et al.,* 2017). Negative values represent areas of erosion and positive values areas of deposition.

Within DEM differencing there is an element of vertical error present, which is common across its many applications (Kinsey *et al.,* 2017). For the purpose of analysing these surveys and the based on the data provided a 10cm error is accounted for. The DoD creation was completed in ESRIs ArcGIS using the ‘Minus’ geoprocessing tool, with the two individual DEMs being inputted as Raster layers. From the implementation of the geoprocessing tool ‘minus' the Z value of one DEM is subtracted from the subsequent DoD and an output raster layer, containing the difference in elevation between the two DEMs, is created.

The DoD can be used to calculate the overall sediment flux, through calculating the net erosion and deposition occurring in the river channel. Using Golden Software’s ‘Surfer’ programme the river channel can be isolated. The function grid volume is used, outputting values of cut and fill values and net balance; from which levels of erosion and deposition can be deduced.

The DoD provide a visible representation of changes to the river channel, showing areas of erosion and deposition, from which inferences about the functioning of the river can be deduced. For example, development of gravel bars and undercutting of meander bends will be shown on a DoD, this can be determined by the levels of erosion or deposition and where in relation to the channel they occur. For assessing the geomorphological changes the creation and analysis of DoDs is vital.

4.2 Sediment sampling and bed shear stress

Sediment samples were taken at 5 sites along the reach measured on the a, b and c axis, from which the D_{50} was calculated. The sampling method used is based on Wolman Sampling, which requires 60-100 samples from each site to be recorded to establish the mean population sediment size (Rice & Church, 1997). The D_{50} is the median sediment size calculated from the measurements of sediment on the b axis (Bunte & Abt, 2001). Site 1 is located at the downstream end of the reach and site 5 located in the middle of the reach (Figure 9). The purpose of collecting 100 samples at all five sites along the reach is to allow a comparison is sediment sizes and D_{50} values downstream throughout the reach. The D_{50} can be calculated through the Wolman's curve which was the traditionally preferred method (Wolman, 1954). With the use of widely accessible computer software such as Microsoft Excel, the D_{50} can be computed quickly. Using the function 'PERCENTILE.EXC' within Microsoft Excel, which returns the 'k-th percentile of values in a range' the D_{50} for each site can be calculated quickly and efficiently (Office Support, 2018). For the calculation of the D_{50} the k-th percentile is the 50th percentile fraction of surface bed materials.

The D_{50} is used for the calculation of critical bed shear stress and a comparison of sediment size along the reach. Though 5 sites were sampled with a total of 100 samples taken at each site, the D_{50} used for the purpose of calculating the bed shear stress was taken from site 5, which is located half way along the reach and is therefore representative of the entire reach.

Figure 9 Diagram of Swindale Beck channel at the restored reach showing the location of the 5 sediment sample sites.

To calculate the bed shear stress the following equation was used

$$\tau_c = \emptyset_c \times (\frac{Ps - Pw}{D_{50}}) \times g$$

Where;

- τ_c is the critical boundary shear stress
- $\emptyset_c$ is the critical dimensionless shear stress
- Ps is the density of sediment at 2650 kg m^{-3}
- Pw is the density of water (1000 kg m^{-3}),
- g is the acceleration due to gravity (9.81m s^{-2})
- D_{50} is the median sediment size.

The value for critical boundary shear stress is dependent upon the sorting of sediment included, those that are well sorted will use the critical boundary shear stress value of 0.06; and those sediments that are poorly sorted will use the value of 0.047. The critical boundary shear stress is the shear stress required in the channel to mobilise bed material, therefore is the boundary for entrainment (Milan *et al.,* 2001).

The critical shear stress, which is required for the imitation of motion, is likely to increase with discharge (Gordon *et al.,* 2004). To study entrainment within the study reach at Swindale beck the critical boundary shear stress is calculated twice, to assume for well sorted or poorly sorted sediments. The values will then be used in conjunction with TUFLOW modelling, discussed later, of the bed shear stress within the river channel in two flow conditions, low flow and bank full. A comparison of sediments entrained in these two flow conditions is expected to reveal an increase in entrainment at bank full. Furthermore, the spatial variability in entrainment along the river channel will be used alongside the values of D_{50} moving downstream in the channel to assess sediment size and transport.

4.3 Biotope characterisation

In addition to studying the morphological changes in the river, and a study of sediment sizes and entrainment; biotopes in the reach were measured and compared across the study period. From the initial pre-restoration LiDAR data and throughout the 6 repeat UAV surveys conducted from October 2016 to February 2018. Hydraulic models created with TUFLOW were used for this purpose. TUFLOW (Two-dimensional Unsteady Flow) is a 2D hydraulic modelling system, originally developed for tidal hydraulics. Since its creation TUFLOW has undergone developments, now described as an 'excellent' 2D/1D flood modelling package (Syme, 2001). For this investigation TUFLOW was used to create hydraulic models of the river, using the DEMs, from which the river was classified into biotopes based on the Froude number of the water. This method of modelling was also used for the sedimentary analysis through the modelling of bed shear stress, outlined above. This was done for each survey, showing the temporal change in biotope diversity in addition to a comparison with the baseline data obtained prior to river restoration.

Froude number of water calculated using the following equation;

$$Fr + \frac{v}{\sqrt{gD}}$$

Where;

- Fr is the Froude number,
- V is the average velocity of the water in the channel
- g is the acceleration due to gravity (9.81 m s^{-1})
- D the hydraulic depth.

Within TUFLOW the Froude number was calculated throughout the length and widths, using the DEMs of the river reach for each of the surveys and the pre restoration LiDAR data, this is calculated and modelled in Low flow and bank full conditions.

The Froude number of water is stated as an easy-to-measure index, and is useful for categorising and characterising habitat types (Jowet, 1993). As such, the Froude number has been chosen as a method for classifying habitat types allowing a comparison throughout the rivers adjustment to the restoration project and as a means of assessing habitat suitability at Swindale Beck and how the river and its available habitats have changed over the course of the study and in comparison to the pre-restoration conditions. Different surface flow types are a result of spatial variation in hydraulic condition, the distribution of these flow types is used to provide an assessment of habitat heterogeneity. This assessment can be done visual through the observation of characteristics presented in each flow type, however for this analysis the Froude number of water is chosen as a suitable parameter from which the biotopes present, represented by the different flow types can be quantified (Reid & Thoms, 2008). The interconnect nature of the relationship between surface flow type, near bed hydraulics and substrate characteristics suggests that this classification based on Froude number is an effective way to characterise the physical habitat in a river system. Moreover, classification by surface flow type is suggested as valuable, time and resource effective measure of habitat heterogeneity and thus a suitable measure of potential biological diversity and productivity of a river (Reid & Thomas, 2008).

Using the data generated from the TUFLOW hydraulic modelling the data was classified using Surfer software (Golden Software). The data was analysed through the creation of Classed post maps within the software. The classed post maps were used to categorise the data by Froude number to its corresponding habitat. The habitats present are categorised as hydraulic biotopes. The biotope classifications were taken from Entwistle, Milan & Heritage (2010) which studied the mapping and identification of in-stream ecological units. The 5 categories of used and the corresponding habitat types, with a visual representation in the form of a photograph for each category along with a description of characteristics and the Froude number are outlined in Figure 10. Water surface roughness delimiters used for terrestrial LiDAR are also included, though were not used (Entwistle, Milan & Heritage, 2010).

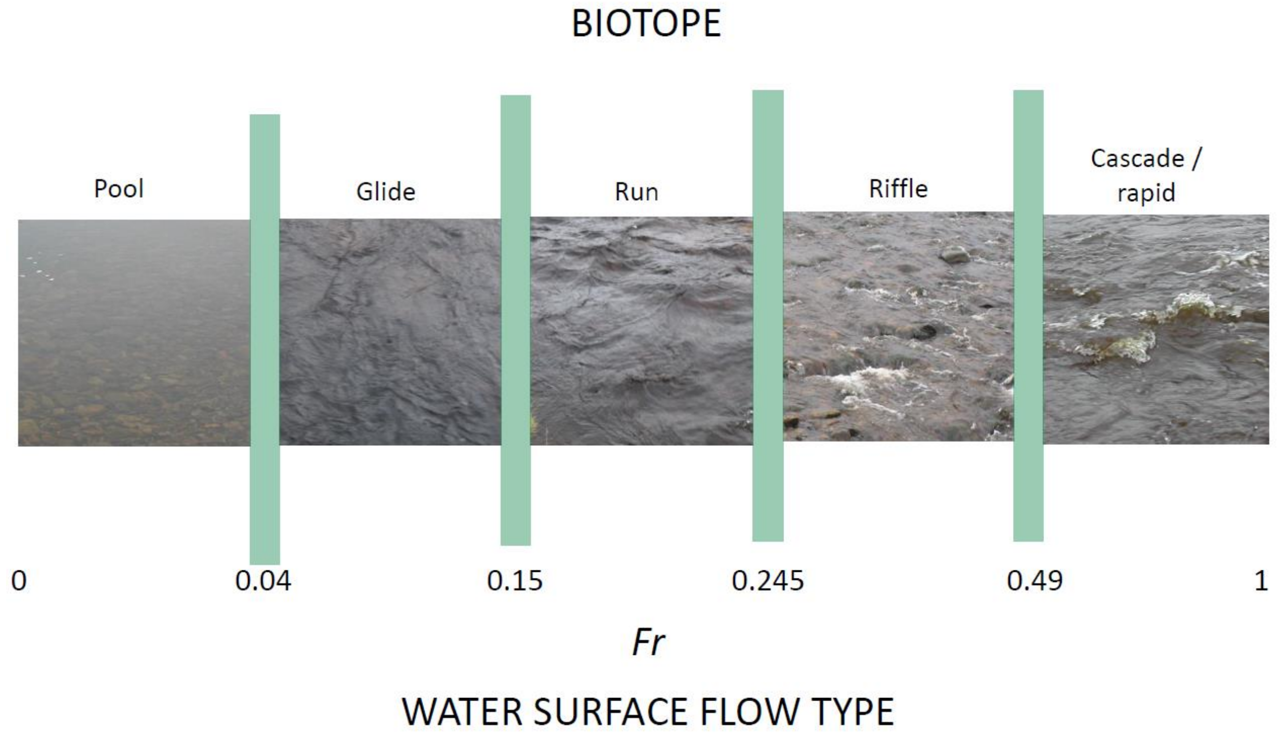


Figure 10 Biotope and water surface metrics and Froude Number(Source: Entwistle, Milan & heritage 2010)

The term biotope as opposed to the term habitat is chosen for this analysis. This choice was made to differentiate between the abiotic environment required for a community (biotope) and the abiotic environmental requirements for a species, the habitat (Wadeson, 1994). As river restoration has developed the goals of restoration projects have also developed, for example with a move away from habitat enhancement schemes focused on a certain species to general biodiversity enhancements (Smith, Clifford & Mant, 2015). This change in approach further validates the choice of the terminology 'biotope' as the restoration at Swindale Beck is aiming for widespread biodiversity enhancements as a result of the restoration project. Pool, Glide and margin biotope is characterized as having a Froude number between 0.009 and 0.016, a pool is described as having a barely perceptible flow, as opposed to a glide which exhibits a flow that is clearly perceptible. Pools, glides and margins are all without surface disturbance and can occur over any substrate dependent upon the depth of the water being sufficient to reduce roughness (Wadeson & Rowntree, 1998). In comparison, water in riffles, runs and cascades is much rougher, and therefore has a higher Froude number. A run is characterized as having a ripples flow, all the way up to cascades which are free flowing water over substrate such as large rocks and boulders (Wadeson & Rowntree, 1998).

The results from the classed post maps were transferred into tabular form, presented in the results section, to show the percentage of the reach in each category and how these values changed following the restoration and throughout the study period, and also across the 2 flow conditions. The presence of different biotopes present is used as an indicator of the effect the Swindale Beck Restoration project has had on the aquatic biotopes and ecological standard of Swindale Beck.

5. Results

5.1 Topographical channel change

The results of the repeat UAV surveys are presented below, for the evaluation of success at Swindale Beck the surveys from November 2016 to February 2018 are included. This is as a result of the scope and detail of the surveys being sufficient to present the hydromorphological changes present, from which conclusions about the impact and success of the restoration can be drawn.

The new channel is a sinuous single thread channel visible features within the channel are shown in figure 9 an orthophoto constructed at Swindale Beck using aerial photographs obtained in the November 2016 survey. Visually observable from figure 11 is the shallowing of water towards the mid-section of the reach, with the upstream and downstream ends of the reach having visibly deeper water. Gravel bar formations inside meander bends can also be seen, with smaller sediments accumulating in these areas. Deeper waters, with higher discharge and velocity can be seen on the outer meander bends where erosions should be occurring. A backwater is visible in the orthophotho which also exhibits a visibly deeper channel depth. Throughout the majority of the channel areas of shallow water and sedimentation can be seen, as well as areas of deeper, likely faster flowing water.

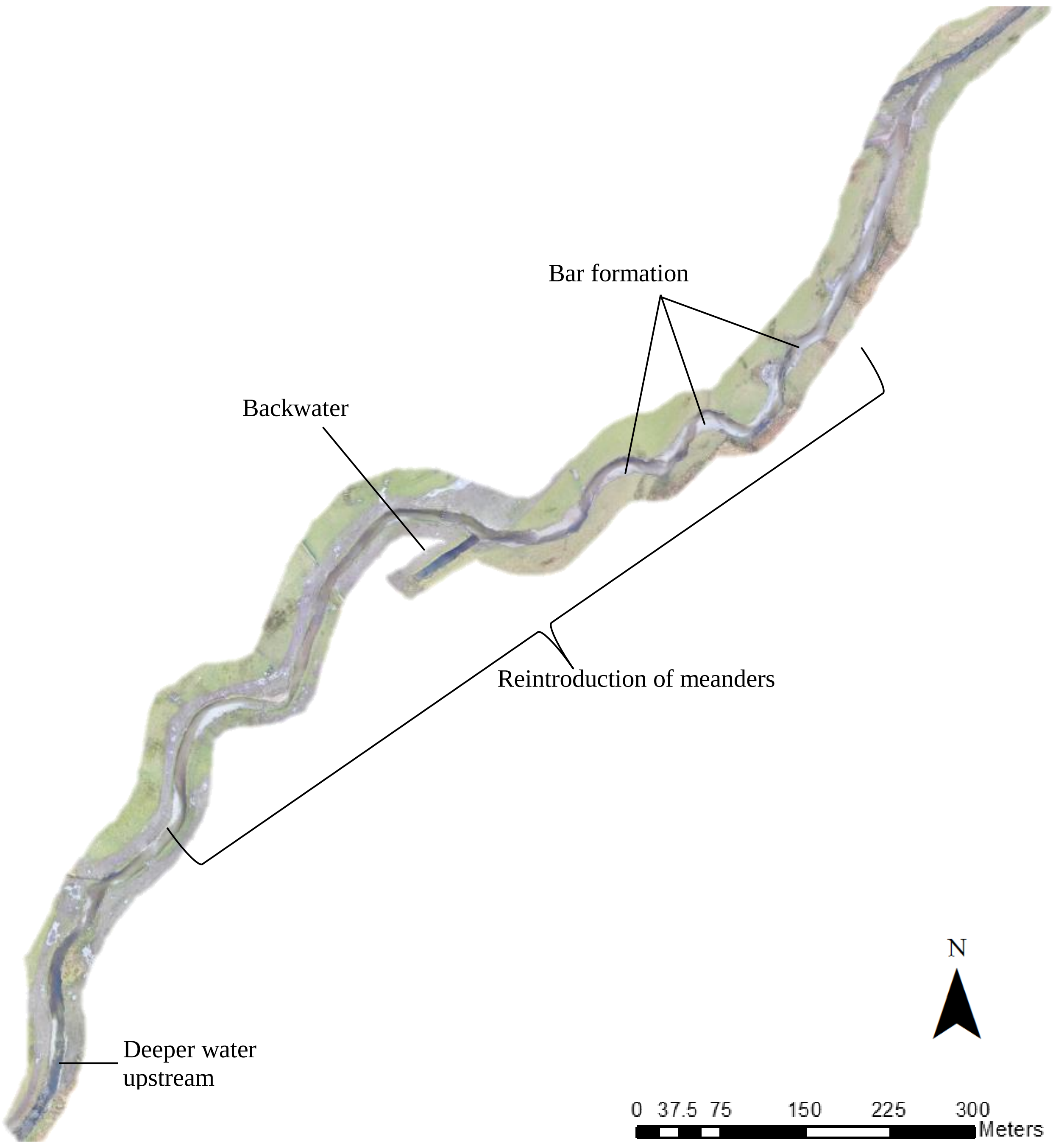


Figure 11 Orthophoto of Swindale Beck study reach constructed from November 2016 Survey data.

Initially the focus is on the immediate response in the first 6 months of data collection, with the absence of the October 2016 survey. The morphological changes from November 2016-April 2017 are shown in Figure 12, showing areas of significant change with topographical change higher that 10cm difference with the previous survey. The majority of elevation change is occurring around meander bends and in areas where gravel bar formation may occur.

Many areas of the river channel show no significant topographic change, particularly within the middle section of the reach, showing white colour on the DoD (Figure 12). This shows that elevation in these areas changed by a maximum of 0.1m above or below the starting value, this level of change is stated as not being a significant elevation change as it is within the bounds of error within the DEM differencing.

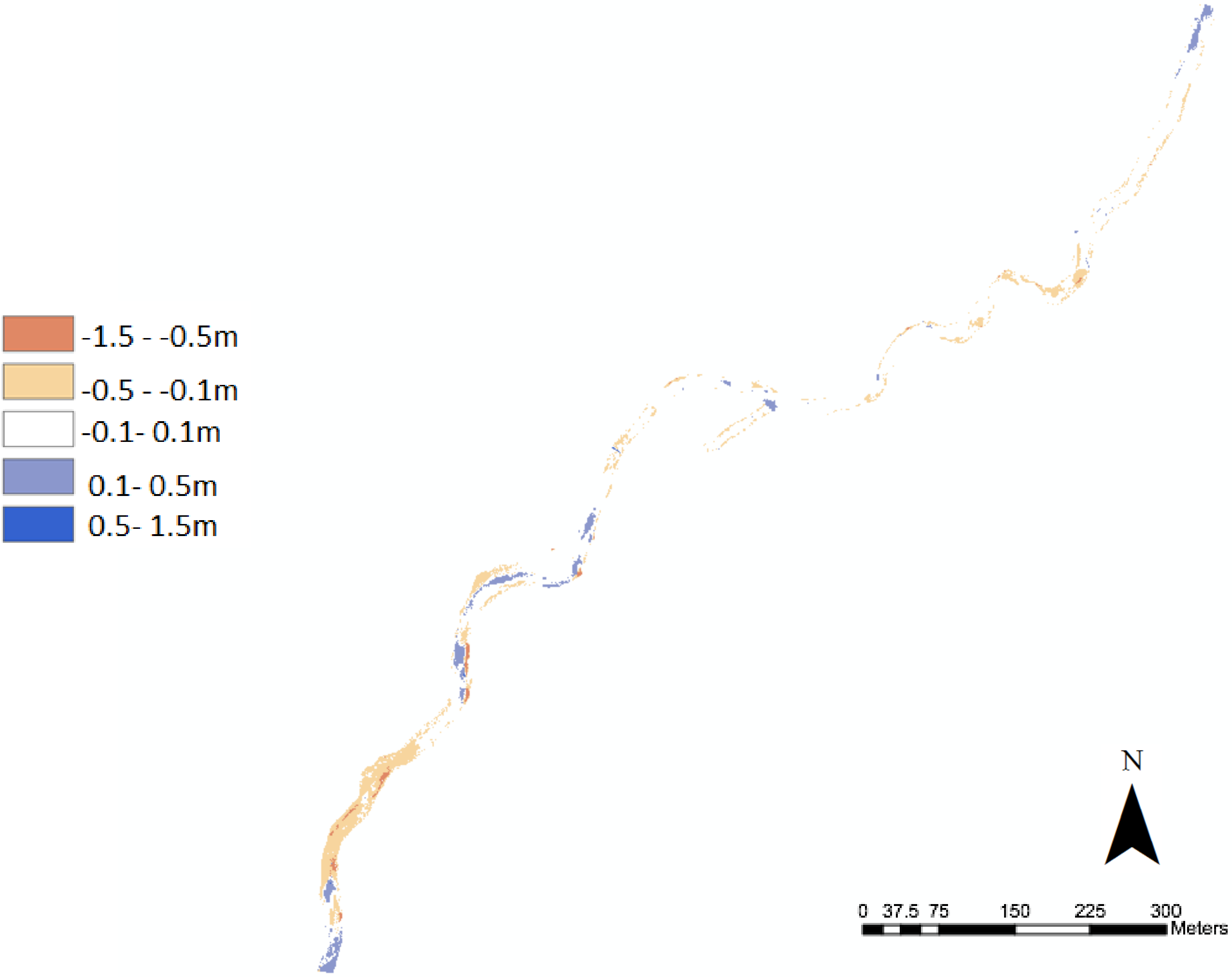


Figure 12 DEM of difference showing elevation change detailing erosion at deposition occurring at Swindale Beck between November 2016 and April 2017

The highest levels of erosion, shown in Figure 12, with the presence of the darkest shades of red are mainly isolated to areas along the outer bends of meanders. Erosion is more widespread over the study reach, with deposition being limited to certain areas, particularly in the upstream end of the middle portion of the reach. This DoD shows significant deposition of materials mainly located between 150-250m along the reach. This deposition is occurring along a large meandering section, with significant levels of deposition on the outer bend where erosion is likely to occur. Based on field site observations this deposition is likely to be a result of bank material being undercut and falling into the channel, and therefore as a result of erosional processes. Deposition can also be seen to occur on the input to the backwater, an area that is separate from the flow processes of the main channel, this difference likely explains the deposition of materials up to 0.5m occurring here

Figure 13 shows a more detailed image, covering a selection of 3 meanders towards the downstream end of the reach. The DoD shows erosion, of between 0.1 to 0.5m, occurring along the outer bends of these meanders. Smaller areas with erosion reaching up to 1.5m can also be seen. This coincides with what is visible on orthophotho, in which smaller gravels can be seen on the inner bends with visible areas of deeper water at the outer meander bends.

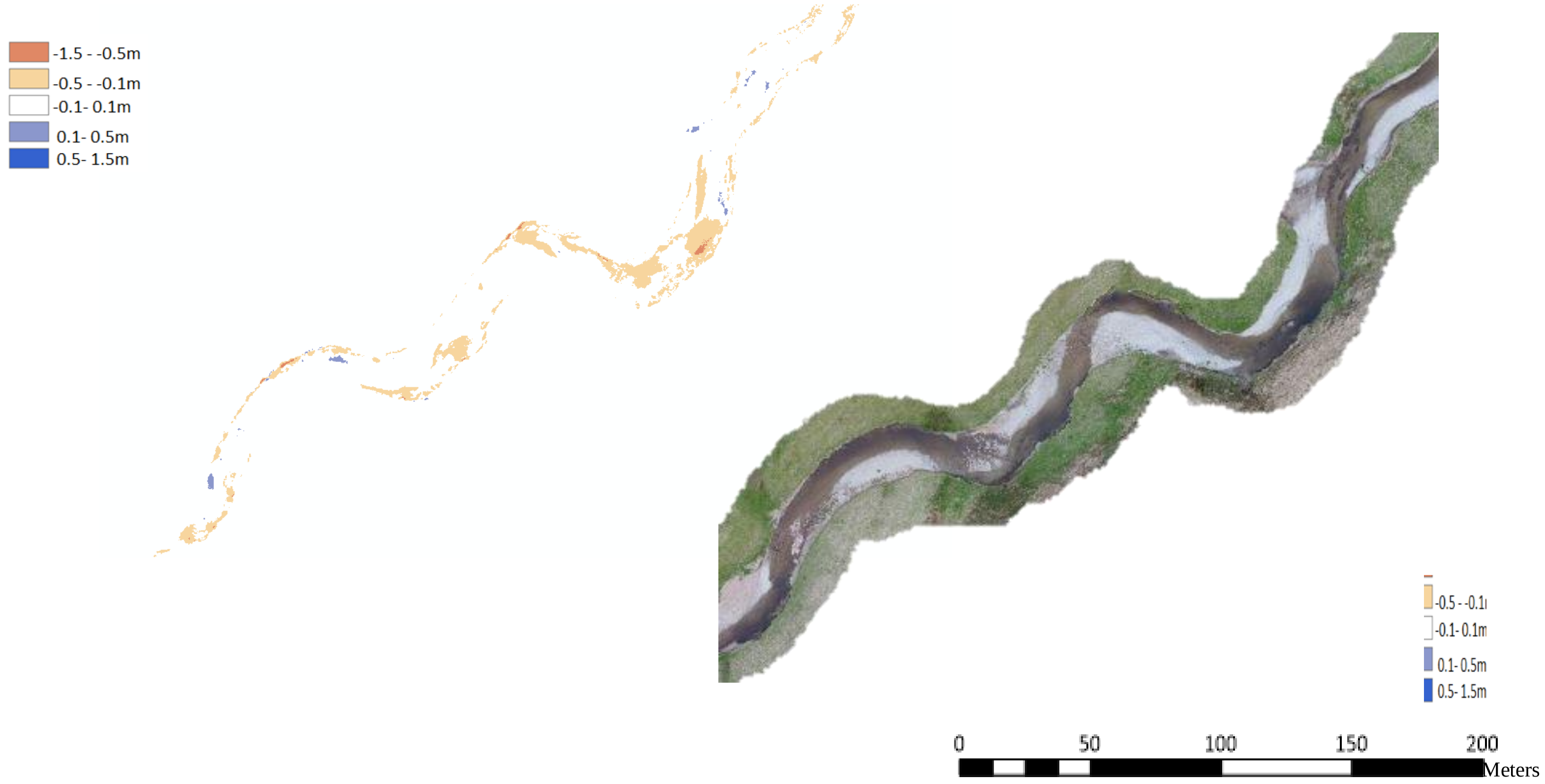


Figure 13 DEM of Difference and orthophotho of downstream meandering section at Swindale beck. DoD from November 2016 to April 2017, orthophotho from April 2017.

Table 4 Volumetric sediment calculations at Swindale Beck November 2016 to April 2017

	Volume deposited	**Volume eroded**	**Volume Balance**	**Areal equivalent**
	(m^3)	(m^3)	(m^3)	(m)
Swindale Beck Channel (Bank to Bank)	177.05	558.07	381.01	0.46

Table 4 shows the volumetric changes at Swindale beck between November 2016 and April 2017, with more materials deposited, than eroded within the channel itself with a positive net volume balance of 381.01 m^3.

The second DEM of difference created for the April 2017 to November 2017 period is presented in Figure 14. Patterns of erosion and deposition are similar to that of the November 2017 to April 2017 survey. In this second DoD there is a greater portion of the channel showing little to no significant change in elevations, showing that in these areas there is little erosion and deposition taking place.

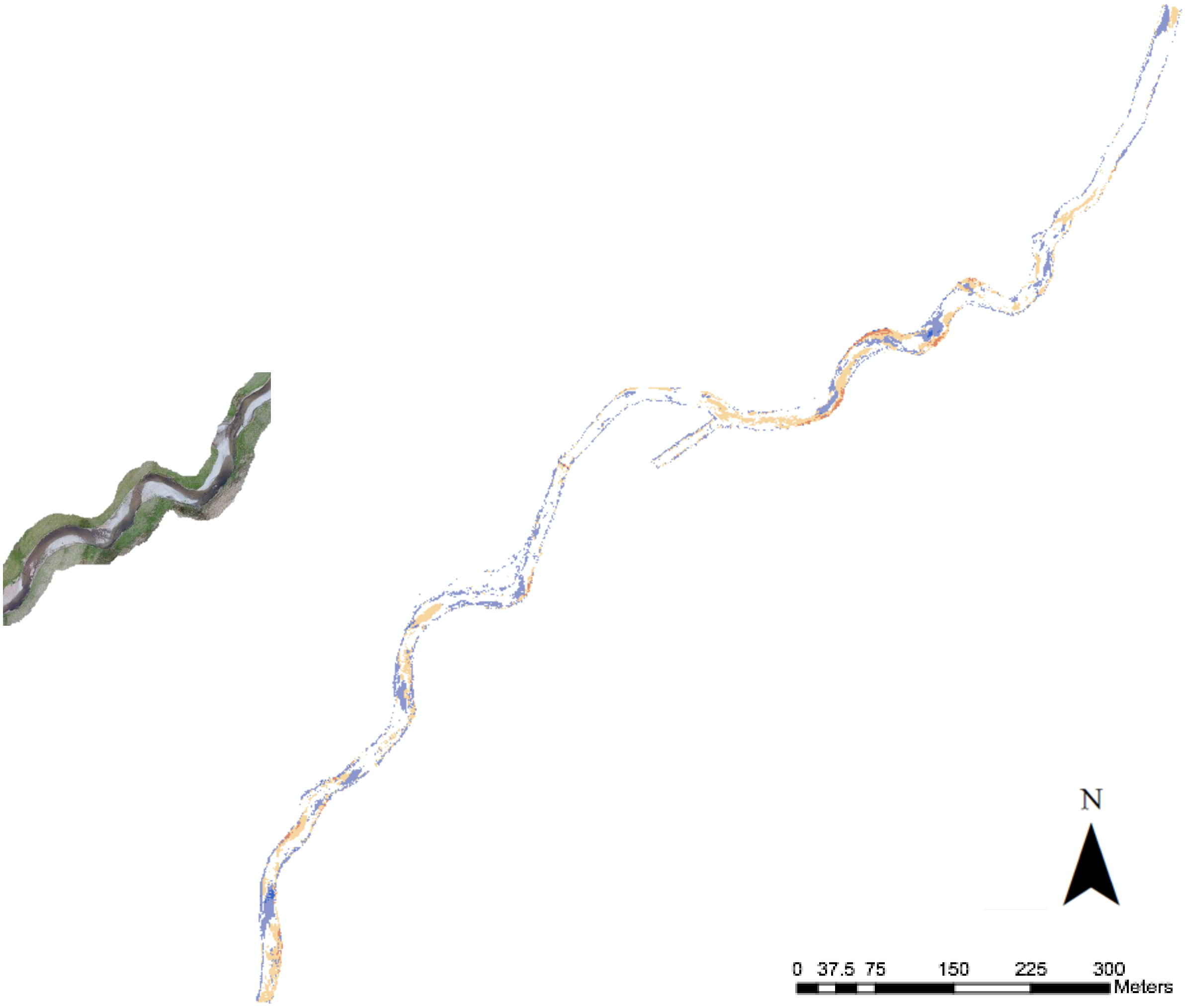


Figure 14 DEM of difference showing elevation change detailing erosion at deposition occurring at Swindale Beck between April 2017 and November 2017.

Compared with Figure 12 of the DoD for November 2016-April 2017, figure 14 showing channel changes between April 2017 and November 2017 shows deposition occurring in a larger portion of the reach, with particularly prominent areas along outer meander bends. The processes of erosion and deposition are occurring at a much similar rate in the April 2017- November 2017 Survey compared with the initial November 2016- April 2017 survey. In the upstream meanders there are higher rates of both erosion and deposition occurring, than that of the November 2016-April 2017 survey.

Figure 15 presents a closer view of the rates of erosion and deposition occurring between April 2017 and November 2017 isolated to a single meander bend.

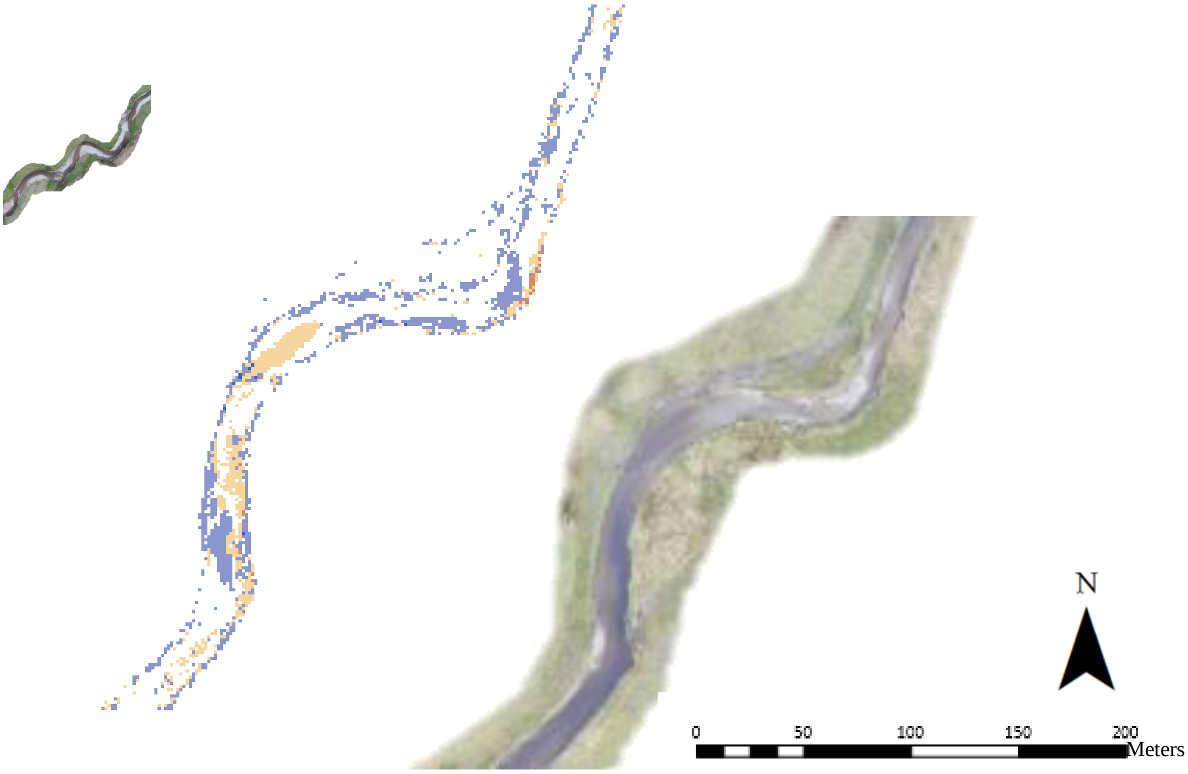


Figure 15 DEM of Difference and orthophotho of upstream meandering section at Swindale beck. DoD from November 2016 to April 2017, orthophotho from April 2017.

Up to 0.5m of erosion can be seen occurring at the outer meander bend, this can be seen in the orthophotho as an area of deeper water, shown by the darker colour of water in the orthophotho. The deposition seen occurring on the banks of the channel may be a result of vegetation growth.

Table 5 Volumetric sediment calculations at Swindale Beck April 2017 to November 2017.

	Volume deposited	**Volume eroded**	**Volume Balance**	**Areal equivalent**
	(m^3)	(m^3)	(m^3)	(m)
Swindale Beck Channel (Bank to Bank)	344.17	343.47	0.69	0.0008

The volumetric changes in sedimentation for the period from April 2017 to November 2017 are shown in table 5 the levels of erosion and deposition within this 7 month period are almost level with a net balance of $0.69m^3$ and an areal equivalent of less than 1mm of elevation change (0.8mm) per metre of the channel within the reach.

The next DoD shows the levels and pattern of erosion and deposition occurring over a 1 month period between November 2017 to December 2017 (Figure 16). During this period there is much of the channel in the study reach which is not experiencing significant elevation change, showing no erosion or deposition occurring in these places.

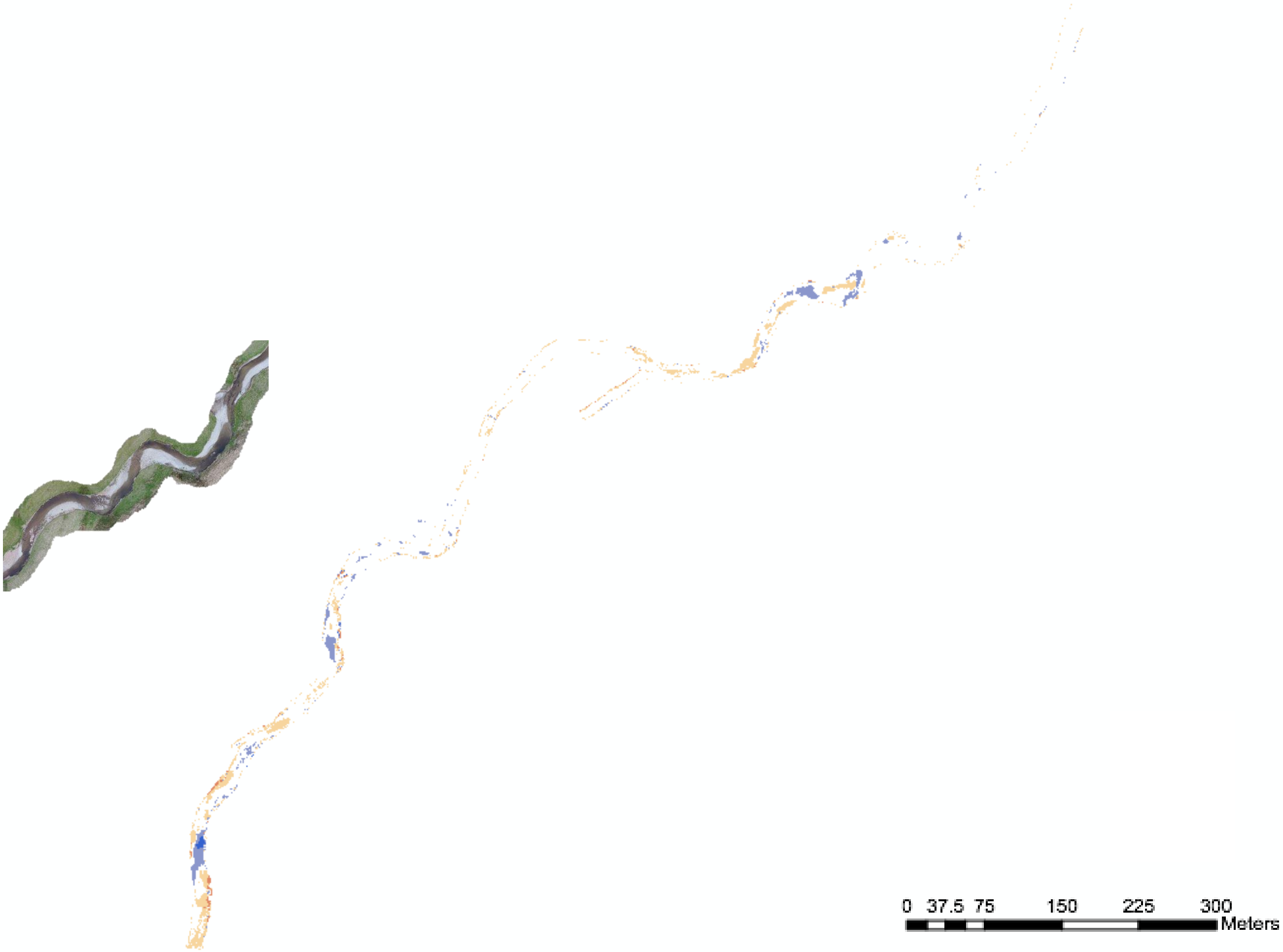


Figure 16 DEM of difference showing elevation change detailing erosion at deposition occurring at Swindale Beck between November 2017 and December 2017.

As mentioned, much of the DoD is whited out showing no significant elevation change. Erosion is the dominant process as shown by the widespread coverage on the DoD, with deposition occurring in limited areas. Table 6 shows this numerically, with a negative net balance of -614.97m^3 showing that much more erosion than deposition has occurred at this time.

Table 6 Volumetric sediment calculations at Swindale Beck November 2017 to December 2017.

	Volume deposited	Volume eroded	Volume Balance	Areal equivalent
	(m^3)	(m^3)	(m^3)	(m)
Swindale Beck Channel (Bank to Bank)	122.15	737.12	-614.97	0.74

The final DoD presented also falls in the winter period of 2017-2018. Similarly in Figure 17 much of the channel in the study reach is not experiencing high levels of erosion nor deposition. In this DoD from December 2017 to February 2018 shows the majority of erosion and deposition occurring along the banks of the river.

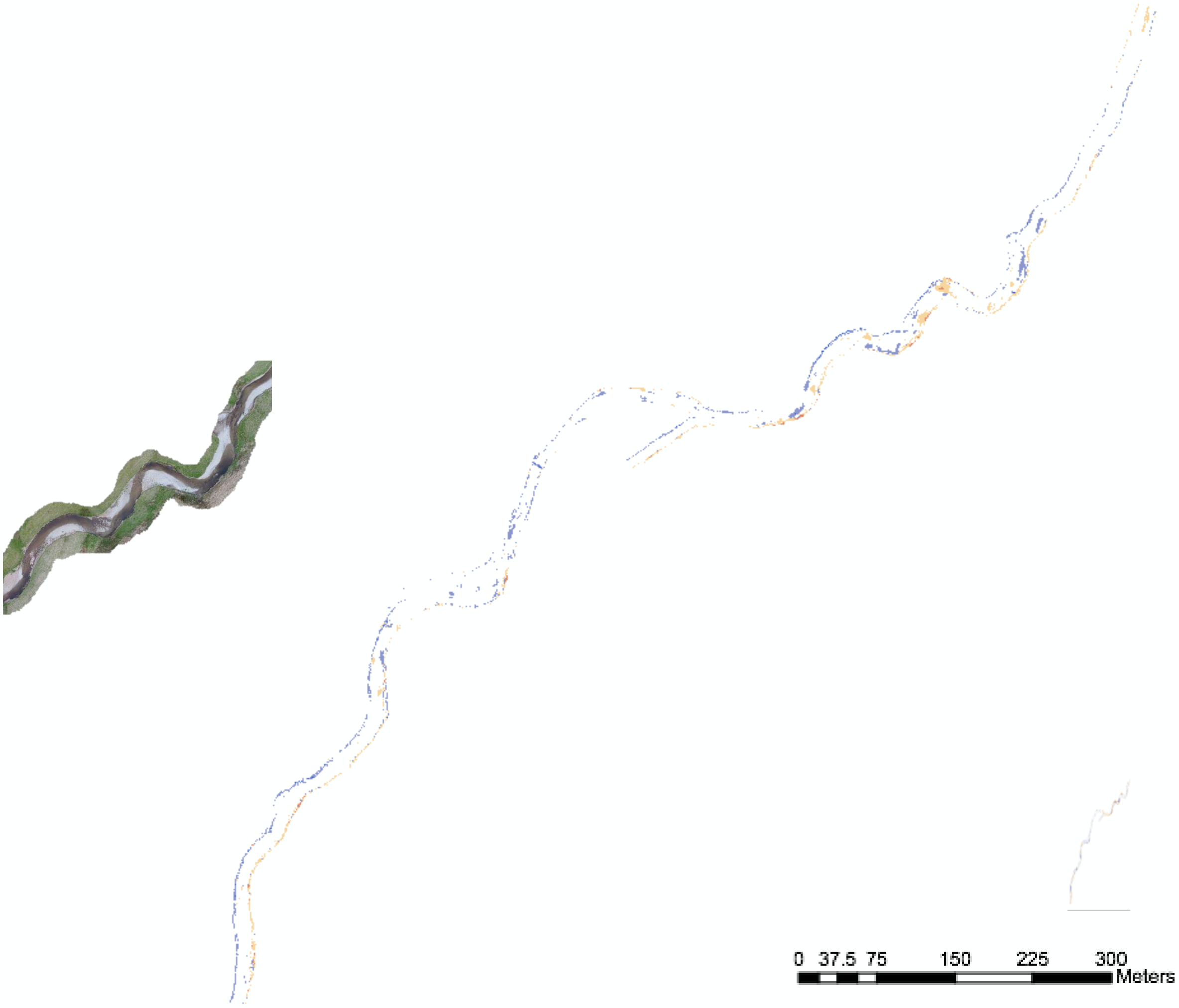


Figure 17 DEM of difference showing elevation change detailing erosion at deposition occurring at Swindale Beck between December 2017 and February 2018.

Table 7 states the volume balance between material deposited and eroded at 133.85m^3, showing a decrease from the previous DoD, along with this the areal equivalent of erosion and deposition has also reduced, with the final DoD results presenting an areal equivalent of 0.16m.

Table 7 Volumetric sediment calculations at Swindale Beck December 2017 to February 2018.

	Volume deposited	Volume eroded	Volume Balance	Areal equivalent
	(m^3)	(m^3)	(m^3)	(m)
Swindale Beck Channel (Bank to Bank)	324.30	192.45	133.85	0.16

5.2 Sedimentology

The results from the sediment sampling at the 5 sites within the study reach at Swindale Beck (Table 8); show a reduction in sediment size downstream, with the largest D_{50} values present at Site 5 and the smallest at Site 1.

Table 8 Mean sediment sizes and map of sample sites.

	D_{50} (mm)	
Site 1	32	
Site 2	35	
Site 3	40	
Site 4	53	
Site 5	65.5	

The D_{50} value has reduced in size by 51% from 65.5 mm at site 5, located in the centre of the reach and to 32 mm at site 1 at the upstream end of the reach.

The bed shear stress was also calculated, based on the D_{50} value from site 5, chosen to represent the reach as it is located at the midpoint along the reach. The critical boundary shear stress was calculated for both well sorted and poorly sorted sediments. For poorly sorted sediments the critical boundary shear stress for entrainment is 684.689 N m^{-2}. For well sorted sediments the critical boundary shear stress for entrainment is higher at 874.071N m^{-2}.

The results assuming for well sorted gravels are presented first. Figure 18 shows areas of entrainment in both low flow and bank full flow conditions for Swindale Beck in the reach prior to its restoration. This uses data calculated from the input of the baseline LiDAR data and the value of 874.071 N m^{-2} to calculate the critical boundary bed shear stress for entrainment within the reach, plotted in figure16.

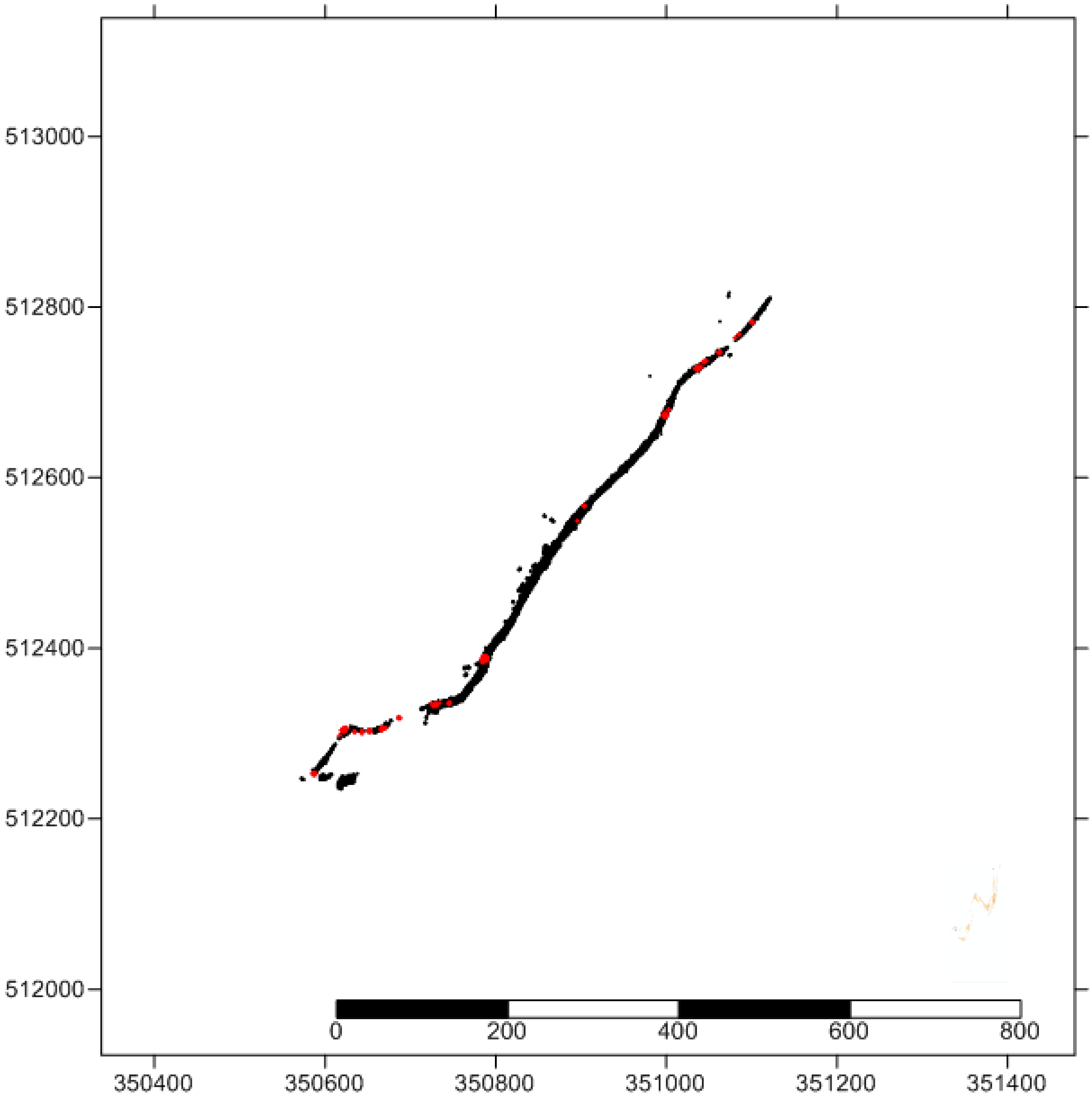


Figure 18 Plot of Critical Boundary Shear Stress in the unrestored Swindale Beck channel in Bank full (Black) and low flow (Red) Conditions assuming well sorted gravels.

From figure 17 it is evident that in bank full conditions much of the channel experiences a bed shear stress capable of entraining sediment for transport. Entrainment in bank full conditions for the data representing the unrestored reach of Swindale beck is 3 times higher than the levels present at low flow The spatial pattern of entrainment shows in the low flow conditions entrainment is mainly isolated to the upstream and downstream ends of the reach, with little entrainment occurring in the mid-section of the reach, whereas in bank full conditions areas of bed shear stress above the critical boundary for entrainment are present across the entire reach. The highest shear stress value recorded in bank full conditions using the baseline data for the unrestored reach is 95% higher than the critical boundary shear stress of 874.071N m^{-2}. For the baseline data at bank full 9.2 % of the channel experiences a shear stress higher than the critical boundary for entrainment. In low flow conditions 2.9% of the channel experiences a shear stress higher than the critical boundary for entrainment.

The results for the bed shear stress for the final survey taken in February 2018 are presented in Figure 19 plotted across the reach. Plotting the data for the ultimate survey, allows for a comparison to be drawn between the conditions present before the restoration took place and the conditions present in the channel at the end of the study period.

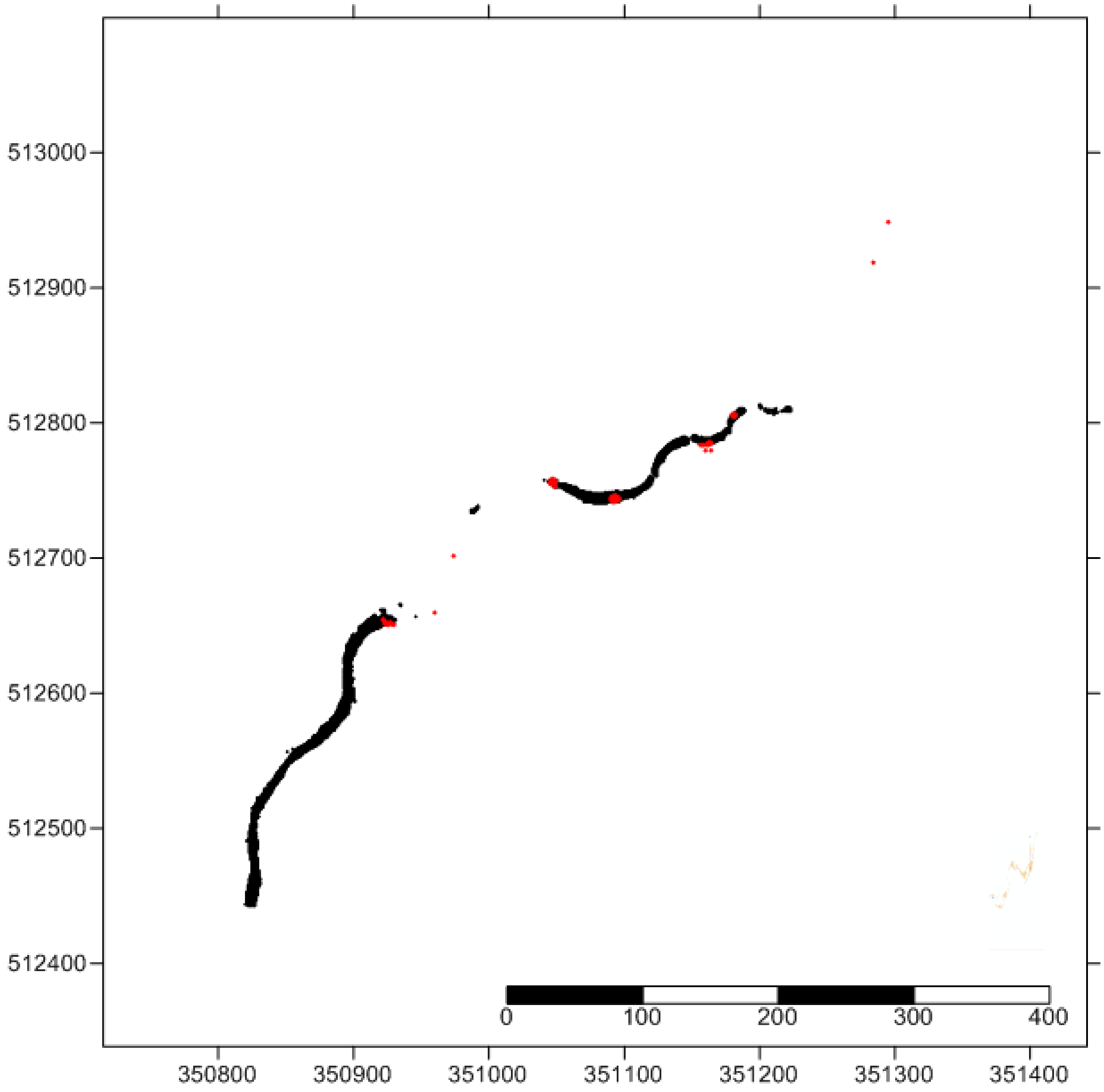


Figure 19 Plot of Critical Boundary Shear Stress in the restored Swindale Beck channel from the final February 2018 survey in Bank full (Black) and low flow (Red) Conditions assuming well sorted gravels.

In bank full conditions much of the reach is experiencing a Bed shear stress value sufficient for entrainment. The upstream end of the reach is experiencing high levels of entrainment, with this not being present in the downstream reach towards the united utilities drinking water input. In low flow conditions the areas of entrainment are isolated and much more limited in scope. Overall in bank full conditions the percentage of channel covered by a shear stress sufficient for entrainment is 33.6 %; in low flow conditions this is significantly reduced with only 1.3% of the channel area experiencing a bed shear stress above the critical boundary for entrainment. The furthest upstream 120m of the restored river channel experiences the most entrainment in bank full conditions; at low flow no entrainment is present here.

When comparing the results between the data from the unrestored reach and that of the restored reach it is interesting to note that the levels of entrainment for bank full conditions are similar; with 33.6% of the restored channel area and 36.8% of the unrestored reach channel area in entrainment. The least entrainment is occurring in low flow conditions within the restored reach, 1.3% of the total channel area has a value of shear stress higher than the critical boundary for entrainment, compared with 10% for the reach pre-restoration.

Entrainment across the channel is presented in figures 20 and 21 assuming for poorly sorted gravels, using the critical boundary shear stress value of 684.689 N m^{-2}. The spatial patterns of entrainment are similar to that shown in the plots using a critical boundary shear stress for well sorted gravels.

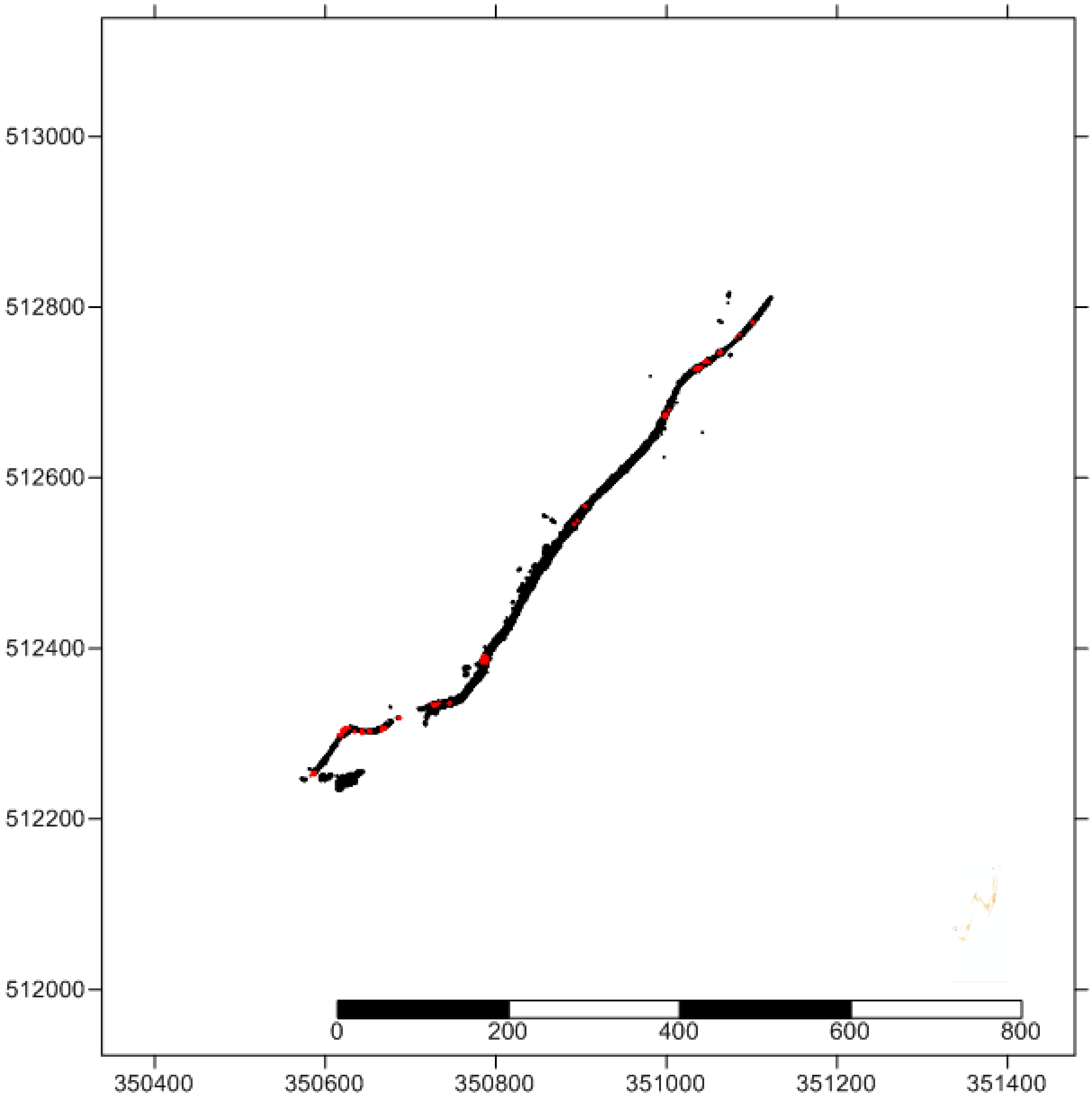


Figure 20 Plot of Boundary Shear Stress in the unrestored Swindale Beck channel in Bank full (Black) and low flow (Red) Conditions, assuming for poorly sorted gravel.

From figure 21 the baseline data for the reach in its unrestored form shows much higher levels of entrainment in bank full conditions that those present at low flow; this mirrors the results for the bed shear stress plotted based on the critical boundary for entrainment calculated using the values for well sorted gravel. When compared with the results for well sorted gravels, higher levels of entrainment occurred when assuming for poorly sorted gravels; with entrainment occurring over 1.18% more of the pattern and levels of entrainment in the restored reach, taken from the February 2018 survey present highly similar results for poorly sorted gravel (Figure 21) as they do with well sorted gravel (Figure 18). For poorly sorted gravels the percentage of the channel experiencing a bed shear stress of a high enough value for entrainment is higher at 3.4% at low flow and 37.7% at bank full than the values calculated from the critical boundary shear stress calculated for well sorted gravels.

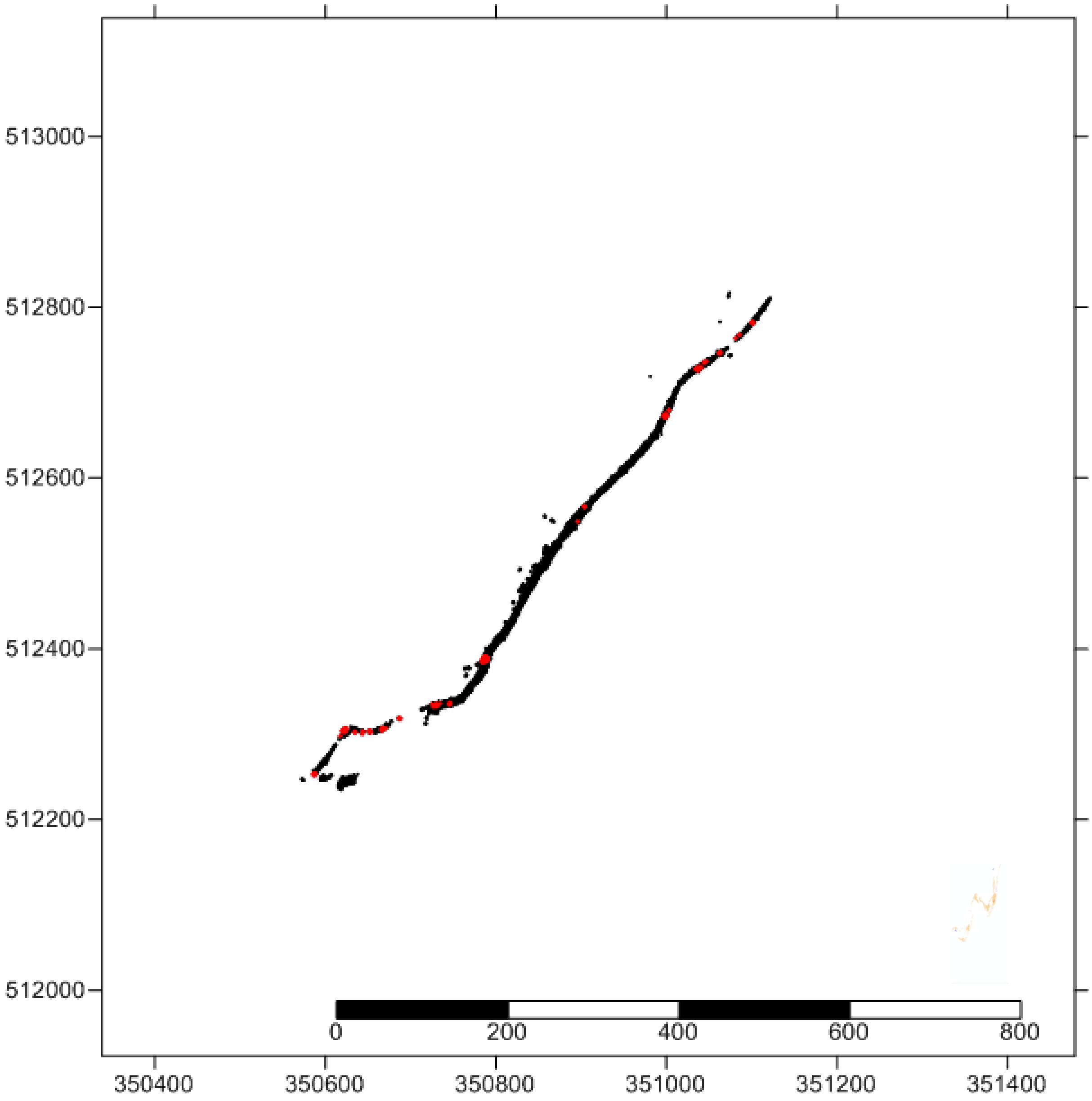


Figure 21 Plot of Critical Boundary Shear Stress in the unrestored Swindale Beck channel in Bank full (Black) and low flow (Red) Conditions, assuming well sorted gravels.

5.3 Spatial-temporal habitat availability

The result of the habitat analysis, categorising the study reach in to present biotopes is presented below. Initially the biotopes present in low flow conditions are presented for the reach in both its restored and unrestored conditions.

Table 9 Biotopes present at Swindale Beck in low flow conditions from baseline pre-restoration data to February 2018 survey data.

Biotope	**Froude**		**Percent**						
	Minimum	Maximum	Baseline	Sep-16	Oct-16	Apr-17	Nov-17	Dec-17	Feb-18
Pool/glide/Margin	0	0.04	0.5	4.3	4.9	6.3	6.6	4.8	5.8
Boil	0.04	0.15	9.2	9.3	11.1	21.1	23.7	27.4	26.9
Riffle	0.15	0.245	27.2	28.4	29	24.5	26.8	27.1	26.2
Run	0.245	0.49	48.9	51	47.1	40.5	34.6	33.2	33
Cascade/ Rapid	0.49	1	14.2	6.9	8	7.6	8.4	7.5	8.1

Table 9 shows the habitat types present and the concentration of each habitat for the baseline data, taken before the restoration began and for each subsequent survey. Showing the overall diversity and abundance in biotopes present in the study reach, and how this changed from the baseline data taken prior to the restoration and consequently through each survey up until February 2018.

The data shows that there has been a marked change in the Run biotope decreasing by 15.9. From covering almost half of the river channel (48.9%) in the baseline model, prior to river restoration, to occupying one-third (33%) in the most recent survey. Additionally the percentage of the river now classified as a 'Boil' has increased in frequency by 17.7 from initially accounting for only 9.2% of the river channel, to being present in 26.9% of the channel by February.

In the baseline study there was less than 1% of the channel being classified as a pool, glide or Margin (0.5%), by the ultimate survey in February 2018 this figure had increased more than fivefold to 5.8%. This change in biotope variability was seen immediately after the restoration in the first survey recorded in October 2016, and remained steady throughout the study period. The distribution change from the baseline data, to the final survey is shown in Figure 22.

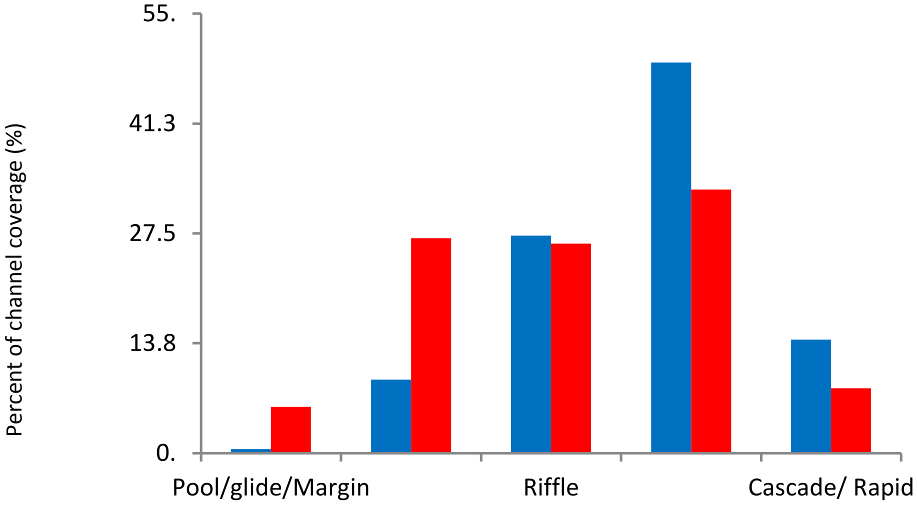


Figure 22 Bar graph showing Biotope distribution at Swindale Beck, baseline data (Blue) and February 2018 survey data (Red) for low flow conditions.

Figure 22 shows the distribution of biotopes present in the river channel, with a comparison between the baseline data and the final February survey. Figure 22 shows riffles and runs dominating the majority of the river channel in the baseline study; with the most recent survey having a more even spread of biotope types present in the river channel.

The following is also presented with the results from the modelling Froude number in bank full conditions.

Table 10 Biotopes present at Swindale Beck in bank full conditions from baseline pre-restoration data to February 2018 survey data.

Biotope	**Froude**		**Percent**						
	Minimum	Maximum	Baseline	Oct-16	Nov-16	Apr-17	Nov-17	Dec-17	Feb-18
Pool/glide/Margin	0	0.04	2.4	3.2	3	3	3.1	1.2	3.1
Boil	0.04	0.15	13.7	3.5	3.6	3.9	4.9	4.9	3.8
Riffle	0.15	0.245	20.4	19.3	17.9	21.7	24.4	15.3	15.5
Run	0.245	0.49	53.6	70.3	70.7	65.5	62.9	74.8	74.5
Cascade/ Rapid	0.49	1	9.9	3.5	4.8	5.9	4.6	3.9	3

Table 7 shows the biotopes present when the reach was modeled in high flow conditions, runs dominate the reach covering 74.5% of the channel in the final survey.

Table 11 Comparison of biotope abundance at Swindale Beck.

	Low Flow		Bank full	
	Baseline	Feb-18	Baseline	Feb-18
Pool/glide/Margin	0.5	5.8	2.4	3.1
Boil	9.2	26.9	13.7	3.8
Riffle	27.2	26.2	20.4	15.5
Run	48.9	33	53.6	74.5
Cascade/ Rapid	14.2	8.1	9.9	3

Table 11 above shows a comparison of biotopes between the baseline data and the final survey in February 2018 for both low flow and bank full conditions. From this table the changes in Froude between high and low flow conditions can be seen both pre and post restoration.

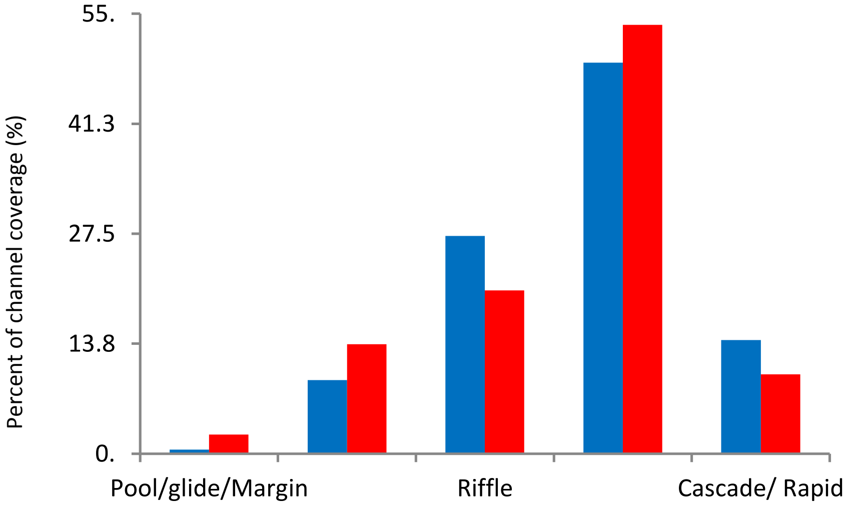


Figure 23 Bar graph showing biotope distribution at Swindale Beck, baseline data (Blue) and February 2018 survey data (Red) for bank full conditions.

Figure 23 shows the biotopes present in both low flow and bank full conditions at Swindale beck in the unrestored, straightened channel. The bar graph shows little variation in biotopes despite this difference in discharge. Figure 24 below shows difference in biotope variability in the restored reach.

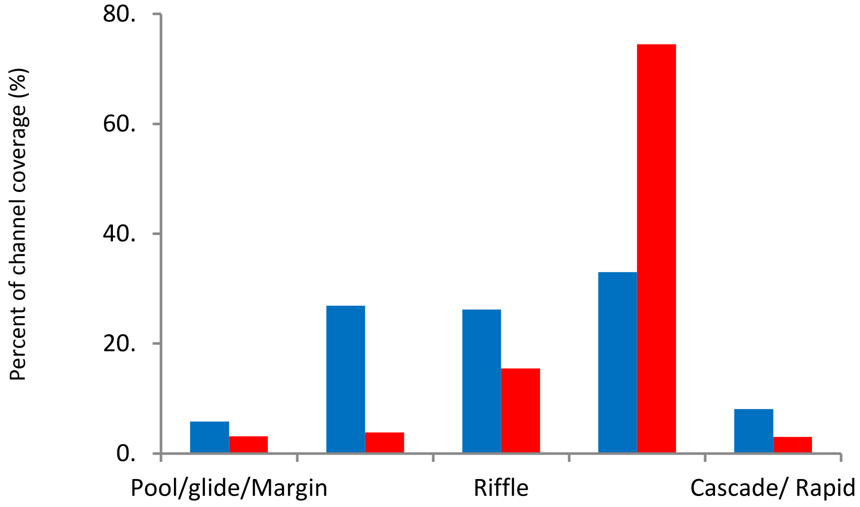


Figure 24 Biotopes present February 2018 in bank full (Red) and low flow (Blue) conditions.

In the restored reach there is a great difference in value for biotopes present, when comparing the two flow conditions. There is an increase in pool habitat compared with the pre restoration data and though the dominant biotope in both flow conditions are runs the percentage of the reach occupied by this in the post restoration data is significantly higher, covering 74.5% of the channel area. Furthermore, the change in flow conditions is seen to have a greater impact upon the biotopes present and their abundance within the reach, this was not the case with the pre-restoration data in which the variety and abundance of the different biotopes was similar regardless of the flow.

The implications of these results, along with the results of the UAV surveys and sedimentary analysis are discussed, prior to the summary and conclusion of this investigation.

6. Discussion

6.1 Topographical change at Swindale Beck

Based on the results provided form the repeat UAV surveying of Swindale Beck, the restored channel is acting in line with processes of erosion and deposition that would be expected of a natural, single thread, meandering channel. There is evidence of erosion and deposition occurring in areas they are expected to. With erosion on inner meander bends and deposition on outer meander bends, and the formation and growth of gravel deposits in the form of bars. This pattern of erosion and deposition suggests that the channel is adjusting to natural changes and has the potential to continue working towards reaching a natural equilibrium (Kondolf, 2006). As the restoration project was centered on the creation of a new river channel, which is designed to function in line with the conditions expected in a natural, sinuous, single thread channel these patterns of erosion and deposition are a promising result for the restoration thus far. Through the creation of a new channel, the previous intervention which constrained the river and prevented natural functions from occurring has been reversed showing a success for this process-based river restoration. The new channel has sediment deposits, and a continuing of deposition in areas in which sediments were placed. Evidence of the success of the project from a geomorphic standpoint is in the orthophothos post restoration which shows a heterogeneous channel (see Figure 11 pg 52).

It was initially assumed that the channel would undergo a period of rapid adjustment followed by a slowing of the rate of change in the channel. Evidence from the initial November 2016 to April 2017 DoD created supports this assumption with a positive net volume balance of 381.01 m^3 compared with 0.69 m^3 in the DoD for April 2017 to November 2017. This shows that following an initial period of readjustment with higher levels of deposition, the majority of the channel is no longer experiencing significant elevation change. This suggests erosional and depositional processes at Swindale Beck are functioning in a similar manner to that of a naturally formed, unconstrained river channel and at what may be considered to be normative rates of erosion, deposition and sediment transport as supported by the study of process-based river restoration (Beechie *et al.,* 2010).

The results show this immediate response as the river adjusts to the new engineered channel with the rate of change, and rate of erosion and deposition then slowing as the river moves towards equilibrium, with a net balance closer to zero. As the processes effecting morphology of the channel at Swindale Beck are reaching a steady rate, once the river has fully adjusted to its new course it can be assumed that the restoration, in terms of the morphological structure of the channel, has been successful. Though in order to fully assess this, repeat surveys post completion could be implemented at a time frame of between 5-10 years post project. Long term monitoring of river restoration projects reveals more about the long term channel conditions and increasing the learning potential from river monitoring (Downs & Kondolf, 2006). However, though the importance of longer term monitoring to assess the ongoing health and functioning of a river such as Swindale Beck would provide useful insight to individual schemes and wider restoration science and practice, the practicalities of implementing such a monitoring scheme are often hindered by a lack of resources and funding which often makes such schemes unfeasible to implement (Bash & Ryan, 2007; Dickens & Suding, 2018).

Furthermore, Bechtol & Laurian (2005) attribute increases in the ecological and biological quality of rivers to the presence of a more stable morphology and consistent patterns of sediment routing. As the project has been completed recently in hydromorphological terms, the overall success of the new channel on biological and ecological quality cannot be entirely defined. Yet, the results from volumetric changes show that the channel is experiencing a more stable morphology and consistent sediment routing, which would provide suitable conditions for habitat creation and the sustenance of aquatic life. In support of this, increased reports of wildlife sightings in the river, such as Brown Trout and Atlantic Salmon, suggest that the morphology and sediment patterns within the channel are becoming more favourable to supporting aquatic life than in the unrestored channel (RSPB, 2017).

The re-meandering of Swindale Beck provides complex hydrodynamics that favour high biodiversity. Within a meandering river system there is likely present a mosaic of close habitats supported by the flow patterns present in a meandering system with the provision of a diversity of geomorphic units (Garcia, Schnauder & Push, 2012). Furthermore this restoration through the re-meandering of a reach of river channel, using paleo channel evidence as a guide for creating a natural channel has resulted in the creation of a channel with a variable planform, velocity, discharge and sediment transport regime. The presence of such variability with in-channel structures and processes are described as being key to the functioning of natural, stable channels (Rosgen, 1997).

Within a straightened channel flood risk is higher, comparable to a meandering, single thread channel; with increased flow efficiency and water velocity, a reduction in water storage availability and reduced lag time (Janes *et al.,* 2017). The creation of a new meandering channel at Swindale Beck has increased lateral connectivity and the creation of meanders and backwaters has slowed water flow, increasing both lag time and water storage availability and reducing the downstream flood risk, unlike the previous straightened channel which was disconnected from the floodplain, with levees built up along the banks . Levees pose a risk for downstream flood risk as they prevent water from overflowing the channel on to the floodplain in times of high flow (Opperman *et al.,* 2009). This increase in lateral connectivity is likely to provide benefits to flood risk, reducing the downstream flood risk by allowing water to overflow the channel onto the floodplain. The restoration work at Swindale Beck has been observed to show an increase in flow types and an increase in geomorphological features present as a result of the re-meandering, suggesting the channel is functioning in line with the processes and functions of a naturally occurring sinuous, single thread channel. Pre-restoration data showed that the majority of the channel exhibited a run or riffle flow type, in comparison the February 2018 survey data showed a more even spread of flow types particularly with the increase of pool and boil flow types available. Natural flood management schemes centre on these techniques aimed at the slowing of flows within a river channel, and the increase in storage of water to negate downstream flooding (Holstead *et al.,* 2017; & Waylen *et al.,* 2017). In addition to the benefits to flood risk obtained through the re-meandering of the channel, the creation of backwaters may also decrease the downstream flood risk. The backwaters present have been created as storage areas, the purpose of backwaters is to allow for additional water storage in areas which are connected to the main channel but remain disconnected from the flow of the channel (Wadeson & Rowntree, 1998). The back waters will store water in time of high flow, holding this water upstream in the fields. This technique of adding backwaters into a channel will aid in preventing or reducing the frequency and magnitude of downstream flooding and reducing the extent of damage caused by floods (Nakayama & Watanabe, 2008).

As previously stated, the new channel is increasingly connected to its floodplain, unlike the previous channel where high levees had built up either side of the channel preventing water from flooding on to the floodplain in times of high flow. Disconnection of a river from its associated floodplain results in a diminished capacity of natural flood storage in the river system (Opperman *et al.,* 2009). This connection with the floodplain at Swindale Beck has further implications spanning wider than the benefits to downstream flood reduction. Natural, small and frequent flooding on to the floodplain is necessary to sustain floodplain ecosystems. Healthy and functioning are some of the most biodiverse ecosystems present. However as a result of river management practices such as channelisation and the implementation of levees, they have become one of the most threatened ecosystems with severe decreases in biodiversity and widespread habitat loss (Bechtol & Laurian, 2005, & Opperman *et al.,* 2009). On the floodplains of Swindale Beck is upland hay meadow habitat. The natural flooding of the river is expected to improve and sustain the health of these hay meadows. Hay meadows are rare habitats found only within certain regions, oftentimes found along river banks where the nutrient exchange from small river floods provides necessary nutrients for the health of the meadows. Additionally, as the hay meadows surrounding Swindale Beck are designated Sites of Specific Scientific Interest (SSSI) and Special Areas of Conservation (SAC), any benefits to these delicate ecosystems are welcomed. It is widely agreed that connectivity between a river and its floodplain will have benefits for riparian ecosystems, this is delivered through the nutrient exchange between the two (Pilotto *et al.,* 2018). Though riparian habitats were not assessed throughout this thesis' study, through the removal of levees and the increased lateral connectivity of the new channel it can be assumed that this would result in positive benefits to the health of the floodplain ecosystem. As part of the land management scheme at Swindale Beck sustainable grazing has been implemented, with the exclusion of sheep grazing from early May to late summer. The exclusion of grazing animals aims to benefit the health of the hay meadow habitat through allowing vegetation succession (Jefferson, 2005).

6.2 Sediment patterns and responses

The results of the sediment analysis at Swindale beck shows a reduction in mean sediment size in the downstream direction. This is shown in the differing D_{50} values from site 5 to site 1, with this value getting increasingly smaller as the sites move downstream. The reduction of sediment size in the downstream direction is known as downstream fining (Hoey & Ferguson, 1994). Downstream fining is common in rivers, and is a feature of a healthy and functioning gravel bed river (Frings, 2007; & Hoey & Ferguson, 1994). The smaller sediment size downstream, as a result of this fining, has implications on sediment transport with the smaller sediments becoming more mobile and more transportable impacting on increasing sediment transport rates downstream. However, this is not always the case with smaller particles such as silt, being harder to entrain due to the effects of hiding and protrusion (Ashworth & Fergusson, 1989). At Swindale Beck the mean sediment size recorded at site 1, at the downstream end of the reach was 32mm, described on the Wentworth scale as a pebble and therefore at a size which is easily mobile in sufficient flow conditions (Wentworth, 1922).

This fining of sediment may also have an implication on spawning fish habitat, with an abundance of smaller sized sediments potentially having a negative impact on the ability of spawning fish to find suitable gravel for redd formation (Frings, 2007). However within the context of the Swindale Beck study reach, the availability of different sediment sizes and grain structures in different areas of the channel promotes an abundance and variety of physical habitats suited to different species (Tockner, Schiemer & Ward, 1998). Furthermore, despite large fining occurring with sediment sizes approximately half that of the values present at site 5, sediments measured are sufficiently large enough to suggest that this is not occurring. This is due to the abundance of gravel clasts within the channel, as opposed to silt and clay. Gravels of different sizes and in accumulations seen at Swindale beck appear to be suitable for the provision of redds. The individual requirements of fish varies between species. Atlantic salmon and brown trout species are generally flexible in their requirements for spawning and nursery habitats within heterogeneous fluvial systems. However the presence of gravel of varied size for the creation of redds and the availability of pools and riffles is a necessity for these fish (Louhi, Mäki-Petäys & Erkinaro, 2008).

A gravel bed river in its natural state should experience entrainment of bed materials in high flow and flood events, with the majority of sediments being immobile in low to normal flow conditions (Fergusson, 1994). As the restored channel at Swindale Beck is a gravel bed river, where the bed material is dominated by gravels with the presence of a small amount of sand, sediment transport is expected only at high flows (Wadeson, 1994). The results from studying the critical boundary shear stress for entrainment in both conditions, and for both well and poorly sorted gravels, displays an increase in the amount of channel area experiencing a bed shear stress above the threshold for entrainment in the bank full, channel forming conditions compared to that of low flow. This is present in both the pre and post restoration data.

Notably, there are less areas of the channel experiencing this critical boundary shear stress at low flow in the restored reach compared to the unrestored reach data, from the February 2018 survey the percentage of channel experiencing critical boundary shear stress for entrainment drops from 33.6% of the channel at bank full to 1.3% in low flow conditions; in the unrestored reach in low flow conditions 2.9% of the channel is exhibiting a shear stress higher than the critical boundary for entrainment and 9.2% at bank full. Suggesting that in the unrestored channel extensive entrainment was occurring at low flow. Though the majority of the channel was not experiencing bed shear stress above the critical boundary for entrainment the area of the channel was higher than that of the restored reach. This represents a success of the restoration project in terms of assessing the scheme as a form of process based restoration, indicating that variations in shear stress in the restored reach are in line with that of a natural channel. As such, short term channel evolution will occur as a result of the interaction between bed shear stress and the mobility of sediments (Lisle *et al.,* 2000).

A larger proportion of the reach is exhibiting a shear stress indicative of the transport of sediments in the higher discharge condition in the reach both pre-restoration and post restoration. With the increased discharge the level of entrainment is increased as the higher value of bed shear stress allows for the entrainment of larger particles (Ashworth & Fergusson, 1989). Furthermore in both conditions, downstream of the reach experiences higher levels of sediment transport. Smaller sediment sizes are present here, requiring less flow for entrainment and a lower shear stress for entrainment, though the mobility of sediment is not solely dependent of absolute size of sediment it is a pertinent contributing factor (Fergusson, 1994). Progressive fining of sediment downstream throughout a reach is also attributed to both abrasion of sediments during transport and weathering during periods of rest; as the fining of sediment within the reach at Swindale Beck is significant with sediment sizes reducing by up to 50% selective size entrainment is likely a larger influencing factor, as the effects of abrasion and weathering are not likely to be present in this condensed time frame. Therefore the fining of sediment shown is a likely result of smaller sediment sizes requiring a lower bed shear stress which is likely to be present over a larger portion of the river reach (Ashworth & Fergusson, 1989).

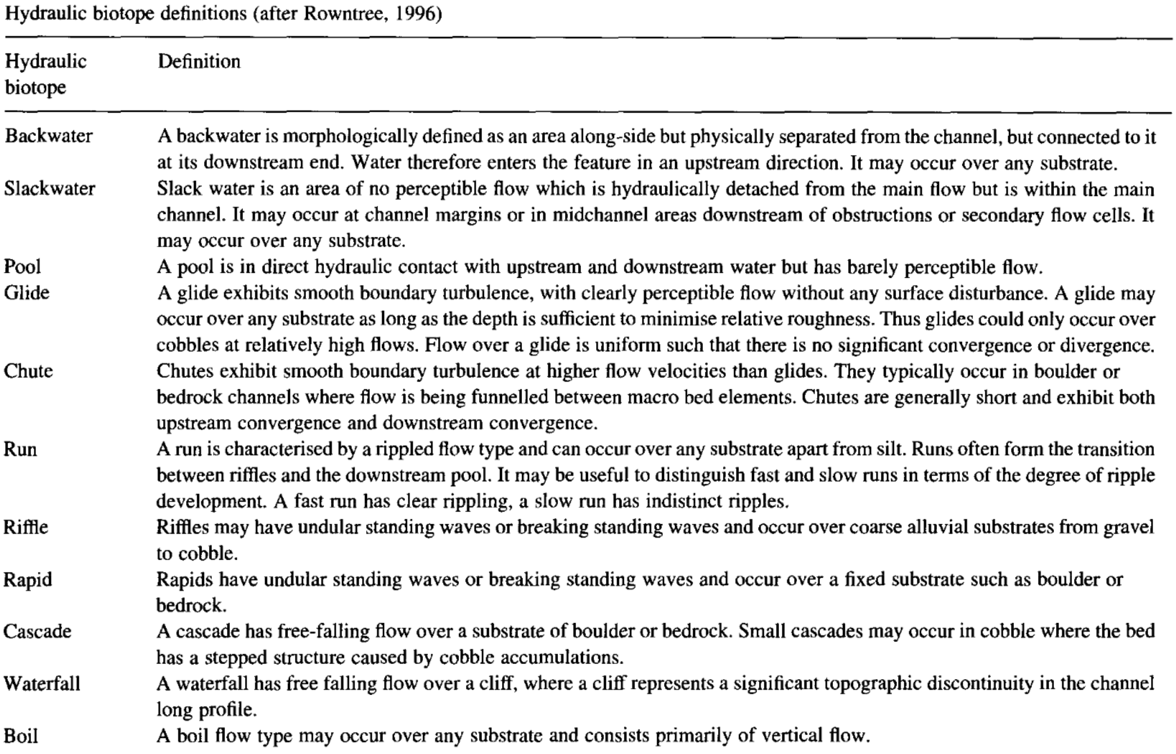
Short term channel evolution is largely driven by spatial variations in shear stress (Lisle *et al.,* 2000). The results of the shear stress plots show that in the restored reach there is a smaller portion of the channel experiencing a bed shear stress above the boundary for entrainment. This suggests that there is an increase in hydraulic variability in the new channel and the differing levels of shear stress, along with the results of the DoDs showing spatial variation in areas eroding or depositing materials. This supports the creation and evolution of channel features such as gravel bars (Church & Jones, 1982). Different bed shear stresses are also associated with differing flow characteristics and are present in different biotopes; the results of studying the biotope presence in the channel are discussed in the following chapter.

6.3 Ecological restoration of Swindale Beck

The results from studying the biotopes at Swindale beck are discussed here. This thesis studied biotopes in terms of their Froude number, classified in the following categories, with descriptions of flow type taken from Padmore (1998);

1) Pool, Glide and Margin. The water roughness is sufficiently low; in pools surface foam may be stationary. Reflections in glides are slightly distorted, in pools and margins reflections are not distorted.
2) Boil. Secondary flow is visible in a boil, circular horizontal eddies are present.
3) Riffle. The flow in a riffle has undular, standing, unbroken waves.
4) Run. Ripples in the water are present, not waves. These ripples are caused by surface turbulence.
5) Cascade & rapid. This consists of white water, and waves facing in an upstream direction.

The determination of flow type based on physical or visual characteristics of river flow is somewhat subjective, therefore the definitions and terms chosen are also reflected in figure 25, taken from Wadeson (1998).



Hydraulic biotope definitions (after Rowntree, 1996)

Hydraulic biotope	Definition
Backwater	A backwater is morphologically defined as an area along-side but physically separated from the channel, but connected to it at its downstream end. Water therefore enters the feature in an upstream direction. It may occur over any substrate.
Slackwater	Slack water is an area of no perceptible flow which is hydraulically detached from the main flow but is within the main channel. It may occur at channel margins or in midchannel areas downstream of obstructions or secondary flow cells. It may occur over any substrate.
Pool	A pool is in direct hydraulic contact with upstream and downstream water but has barely perceptible flow.
Glide	A glide exhibits smooth boundary turbulence, with clearly perceptible flow without any surface disturbance. A glide may occur over any substrate as long as the depth is sufficient to minimise relative roughness. Thus glides could only occur over cobbles at relatively high flows. Flow over a glide is uniform such that there is no significant convergence or divergence.
Chute	Chutes exhibit smooth boundary turbulence at higher flow velocities than glides. They typically occur in boulder or bedrock channels where flow is being funnelled between macro bed elements. Chutes are generally short and exhibit both upstream convergence and downstream convergence.
Run	A run is characterised by a rippled flow type and can occur over any substrate apart from silt. Runs often form the transition between riffles and the downstream pool. It may be useful to distinguish fast and slow runs in terms of the degree of ripple development. A fast run has clear rippling, a slow run has indistinct ripples.
Riffle	Riffles may have undular standing waves or breaking standing waves and occur over coarse alluvial substrates from gravel to cobble.
Rapid	Rapids have undular standing waves or breaking standing waves and occur over a fixed substrate such as boulder or bedrock.
Cascade	A cascade has free-falling flow over a substrate of boulder or bedrock. Small cascades may occur in cobble where the bed has a stepped structure caused by cobble accumulations.
Waterfall	A waterfall has free falling flow over a cliff, where a cliff represents a significant topographic discontinuity in the channel long profile.
Boil	A boil flow type may occur over any substrate and consists primarily of vertical flow.

Figure 25 Biotope classifications (Wadeson, 1998)

These biotopes are geomorphological units, with riffles, runs, glides and pools being cited as the principle geomorphological units in a fluvial system (Garcia, Schnuader & Push, 2017). Riffles and runs are areas of flow that exhibit high bed-shear stresses and usually coarse substrates, whereas pools, glides and point bars have a much lower velocity and bed shear stress (Garcia, Schnauder & Push, 2012). Through studying the biotopes present at Swindale Beck the presence of these different conditions is evidenced and the impact this has upon the ecological health of the river. As mentioned the term biotope was chosen as it represents the abiotic environment required for the sustenance of a community, rather than an individual species (Wadeson, 1994).

The results show an increase in the variety and abundance of different biotopes present in the restored reach when compared with the baseline, pre-restoration data. This variability of biotopes present is representative of flow variability. For example in both low flow and bank full conditions prior to restoration the river channel was dominated by water with a Froude number that coincides with the biotope of run. A run is defined as having a rippled flow type with fast flowing water. In a stream experiencing varied flow runs occur between upstream riffles and downstream pools (Wadeson, 1994). With the dominance of the run biotope which is present across 48.9% (low flow) and 53.6% (bank full) of channel area in the unrestored reach there is little habitat variability. Thus reducing the potential for aquatic species to live and reproduce in the channel (Horwitz, 1978).

When compared with the low flow data modeled in the restored reach the frequency of pools, boils and riffles is increased. The loss of pools and riffles, and reduction in flow variability, is a commonly stated cause for a reduction in fish species diversity and abundance in anthropogenically straightened rivers, and therefore directly impacts the biodiversity and ecological quality of the river (Brookes, 1987). Through the re-meandering of Swindale Beck, a variety of flow types have been reintroduced. The increased flow variability has increased the presence of a variety of biotopes. In low flow conditions the presence of pools has increased by 5.2%, boils by 17.7% and runs have reduced in abundance by 17.7% from the initial pre restoration baseline data to the final February 2018 survey data. The availability of different biotopes leads to an increase in the abundance of fish and benthic macro-invertebrate habitats.

This variability of habitat types is essential for the sustenance of species within the river. Taking brown trout (salmo trutta) for example, that have a preference for specific velocities. Brown trout, like many other species, will choose their preferred microhabitat regardless of the presence of other habitats within the river. Therefore the presence of numerous habitat types within a river encourages many species to inhabit the channel, increasing the ecological health and biodiversity of the river channel. As mentioned there have been increased sightings of salmonid species in the river, which can be accredited in part to the increase in habitats available through the increase in the variety of biotopes present (RSPB, 2017). Thus, suggesting success in the restoration project, with positive hydromorphological and ecological change through the emergence of fish species in the river. Furthermore, habitat heterogeneity is determined as a positive influencing factor on biodiversity, and though cannot encourage biodiversity independently provides a healthy basis (Wheaton, Pasternack &

Merz, 2004). Providing a range of habitat types is important for the biodiversity and species abundance of a river channel as without the provision of a physical habitat species cannot exist in that location (Maddock, 1990).

Gravel bars are also present at Swindale Beck, this along with the complex hydromorphology present in meanders provide benefits to supporting benthic communities. Around point bars, as well as pools and glides, there is a lower velocity and lower bed shear stress than riffle and run habitats within river channels (Garcia, Schnauder & Push, 2012). In-stream restorations are increasingly important for restoring aquatic communities, for example over the past 20 years, river restoration through meandering and the addition of sediments, boulders and large wooded debris has been used for trout fishery management, with the restoration, like that at Swindale Beck, providing flow refugia, refuge from predators and suitable feeding areas (Palm *et al.,* 2007). Within the channel at Swindale Beck there is also evidence of the creation of spawning habitat for salmonids, created through the reduction of erosion and equalising of erosional and depositional functions within the channel allowing for the development and sustenance of gravel feature formation, such as gravel bars and redds. This is shown in the final DoD, where areas of erosion and deposition are limited to more specific areas with clear areas exhibiting between 50-100cm of deposition along outer meander bends and gravel bars. Redds are depressions in gravel features within the river channel which are essential for salmonid species to spawn, the presence of gravel structures and redds is essential for the survival of salmonid embryos, and thus, the abundance of salmonid species within a river system (Palm *et al.,* 2007).

The study of the Froude number at the study reach also revealed that in the unrestored and anthropogenically straightened river channel reach, the flow conditions had little effect on the Froude number of the water and the biotopes present. The channel at Swindale beck was described as having a uniform flow and channel, in which there was little hydrological variability (CIEEM, 2017). The results revealed that the velocity and discharge of the water following the restoration had a greater impact upon the conditions in the river. When the restored reach was modeled in high flow conditions, where the discharge and velocity of water is increased, the Froude number of the majority of water in the channel was vastly different from that modeled in low flow conditions. In bank full conditions post-restoration the channel was dominated by runs with runs accounting for 33% of channel coverage in low flow conditions and 74.5% at bank full, and experienced less abundance and variability of other biotopes, with boils and riffles reducing in abundance by 23.1% and 10.7% of channel coverage respectively. Thus showing how the restored reach is a more dynamic river channel as the presence and variability of biotopes and flow characteristics changes in response to a change in flow conditions.

7. Conclusion

7.1 Managed Naturalisation of Swindale Beck

In summary the restoration work at Swindale Beck has been observed to exert a positive impact of the hydromorphology of the river channel. Kondolf (2006) states that the purpose of a river restoration project is to 'enhance aquatic and riparian habitat, and facilitate human uses' (Page 1); based on this definition the restoration at Swindale Beck can be viewed to be successful.

7.1.1 Topography

The results from the UAV surveying outlined in section 5.1 show the channel is experiencing stable levels of erosion and deposition, with the highest levels present in the areas where this is entirely expected; for instance the presence of higher levels of erosion at outer meander bends and deposition occurring around newly formed gravel bars. The new channel constructed, through its design, already imposed a more diverse topographic structure to the channel with the introduction of a sinuous meandering channel, backwaters and the presence of instream structures such as gravel bars.

The successive DEMs and DoDs of Swindale beck show the river is responding to its new course in a state of relative equilibrium, with the results of volumetric sediment flux calculations stating that the channel is neither aggrading nor degrading.

From the knowledge gained and presented through the review of pertinent literature regarding stable river channels, natural flood management and river restoration schemes, the output of Swindale Beck's restoration in terms of its topographical evolution indicate that in the short term the restoration has had a positive impact. The success with regard to the physical structure of morphology of the channel relates to the steady pattern of sedimentation and the rates of and pattern of erosion and deposition in the channel, and the increased storage of water and slowing of flows through the reintroduction of meanders, the creation of back waters and removal of levees to reconnect the channel with its floodplain.

7.1.2 Ecology

From an ecological viewpoint the increase in biotope variability in the constructed channel, compared with the previous channel shows a higher level of hydrological diversity, presented and discussed in sections 5.3 and 6.3 respectively. This hydrological diversity is presented in the presence and concentration of biotopes categorised by Froude number of water across the channel. The presence of varying flow and therefore varied biotope presence is important for the ecological health of the river, with a variety of flow types contributing to the habitat requirements of different aquatic species; thus the wider variety of flow types, the higher the potential for suitable habitat formation in the channel. The most notable change to flow types in a comparison between the anthropogenically straightened channel and the new restored channel is the reduction in the proportion of the river dominated by runs in the restored channel. The importance of this increased hydraulic variability and its positive impact on ecology is evidenced by the increased presence of salmonid fish within the channel.

The project was designed to work alongside farming practices, providing ecological benefits with the floodplain remaining viable arable land, as well as improving riverine conditions. Furthermore human impacts are considered and facilitated through the likely reduction of downstream flood risk through the slowing of flows and storage of floodwaters in the floodplain meadows and backwaters. The reduction of runs, coupled with the increase of flow types indicative of slower flowing water also provides evidence toward the goal of naturally reducing the downstream flood risk.

7.1.3 Sedimentology

Further assessment of the restoration project as a successful implementation of process-based restoration can be drawn from the results of the analysis of sediments and bed shear stress within the reach. Sediment sampling shows a progressive fining of sediment size in a downstream direction. Sediment fining is a natural process found within dynamic functioning gravel bed river systems caused by the process of abrasion mechanically reducing the size of individual clasts and selective deposition caused by the differential transport of grains as a result of their size.

The difference in bed shear stress between low flow and channel forming, bank full flow also indicates a quantitative success of the restoration at Swindale Beck, reestablishing normative rates of function within the reach. The previous, straightened channel, showed relatively small changes in bed shear stress between the two flow conditions. In the restored channel, the proportion of the river channel above the critical level for entrainment was reduced. This reduction was particularly evident in the low flow conditions, as such providing evidence of the healthy functioning of the river. Under these low flow conditions majority of sediments remain unmoved, which is typical of a naturally functioning, healthy gravel bed river. This therefore suggests that the response of Swindale Beck to restoration has created a channel that is functioning naturally.

7.2 Limitations and recommendations

The results presented show changes in the channel attributes for the restored reach at Swindale Beck, however further study and more widespread study of river restoration projects will increase the learning potential and provide a beneficial, ever expanding knowledge base for future river restoration projects. Smith, Clifford & Mant (2015) conclude that despite the legislative drive for river restoration implementation and the availability of data archives such as the NRRI there is still a need to improve the monitoring of restoration projects and implement the feedback of this monitoring to the design and implementation of future river restoration projects. In their study they state the feedback of previous river restoration projects is not widely incorporated in the design and implementation of future schemes with a lack of evidence available showing the response of intervening through river restoration and the changes to the physical attributes of a catchment as a result.

Following the restoration work at Swindale Beck the river channel has developed morphology and patterns of sediment transport that mimic that of the natural state of a single thread, sinuous, gravel bed river. Furthermore the river flow in the channel now has an increased variability that is indicative of a healthy river. Over an engineering time scale changes to Swindale Beck are likely to be minimal following this initial stage of readjustment. To further assess the suitability of the methods used for improving land use, river quality, reducing flood risk and an overall enhancement of river health, it is suggested that follow up surveys (including but not limited to; topographic surveys, species and macro-invertebrate surveys and hydraulic modelling) will be useful to assess the long term impacts and increase the learning potential of the project. This may include studying the river 5 and 10 years post completion, with additional surveys every 10 years thereafter. This need for monitoring is expressed by many academics and will prove useful for the advancement of river restoration in science and practice by monitoring how the river continues to change and the long term effects the restoration has had on the study reach and the wider catchment (Bash & Ryan, 2007, Dickens & Suding 2013; Smith, Clifford & Mant; & Woodward, 2015)

The addition of a survey of aquatic species within the reach may be useful to further quantify the effects of the restoration, for example through detailing the diversity and abundance of species of fish, macroinvertebrates, macrophytes and phytobenthos. The results of which can be compared with river reaches that have similar topographic and geomorphological characteristics that have been identified as having good ecological quality. Though this was not selected as a method for the initial monitoring of Swindale Beck, further examination such as this can only improve the learning potential of a river restoration project and provide further knowledge and examples of best practice to be used in the design of future projects, and reveal more detailed conclusions regarding the ecological health of the river post restoration. Furthermore, to study the ecological health of the river, a scheme of water quality sampling could be conducted to provide further evidence into the health of the river post completion studying the dissolved oxygen levels and nutrient composition which may be compared with reference sites within the catchment (Palmer *et al.,* 2005).

The use of UAV-SfM remotely sensed data for wider applications within the study of the reach in response to its restoration also provides area for future work to be completed with the goal of fully quantifying the effects the scheme has had upon the river. The use of UAV-SfM data for sediment sampling as opposed to the method chosen of field based site sampling would allow for more samples to be taken, covering a wider proportion of the river and accounting for smaller sediment sizes. The increased spatial extent of this method combined with the addition of smaller sediment clasts may reveal results not perceived from the sample method chosen, for example spatial patterns in smaller sediments. Additionally this method could be applied to each survey; the purpose of this would be to show temporal variations in sedimentation within the reach following the restoration which may compliment the results from the topographic surveying.

The methods used provide a holistic study of processes and impacts within the restored reach at Swindale Beck, allowing for a comparison of conditions between surveys, including pre-restoration data and across flow types. The additional methods outlined, may provide complimentary methods for further assessing certain aspects of the river system in response to the restoration project. Such methods may be incorporated in to a full scale scheme of monitoring restoration projects encompassing a much larger time scale.

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Appendix

A:1 Site 1 sediment size samples (a,b,c Axis)

Size (mm)		
A	**B**	**C**
52	22	30
60	53	38
50	20	30
100	70	47
50	20	22
42	38	19
55	30	30
55	25	10
65	35	25
28	22	10
50	35	5
52	46	11
52	40	22
36	34	12
42	35	9
17	16	12
55	25	30
49	32	28
50	28	28
56	34	23
65	40	16
65	31	14
80	32	38
64	84	34
52	43	27

48	33	24
43	27	18
38	20	9
55	47	17
39	30	5
40	32	26
57	40	30
70	40	31
49	33	20
46	35	29
57	30	21
42	30	40
61	31	21
40	20	15
46	32	18
60	38	28
51	20	13
52	28	18
29	15	11
50	26	8
37	27	25
56	20	38
67	43	35
67	42	22
72	48	20
40	37	27
52	41	30
55	35	30
39	25	22

60	20	11
28	62	35
35	30	6
50	40	7
53	34	20
27	28	20
70	40	30
58	41	33
60	35	37
15	12	5
35	22	30
55	24	24
50	30	22
42	32	25
57	30	12
53	32	8
50	30	37
33	32	16
60	27	20
50	41	7
34	25	20
114	36	16
60	40	30
41	29	24
92	40	18
62	32	11
52	20	15
40	27	24
62	22	30

54	32	21
40	33	20
54	41	23
50	35	18
73	26	23
56	30	22
70	43	8
46	32	30
63	32	15
58	25	25
42	36	24
52	26	38
54	48	15
60	36	20
36	26	20
56	21	9
74	32	28

A:2 Site 2 sediment size samples (a,b,c Axis)

Size (mm)		
A	**B**	**C**
70	60	40
39	32	31
65	50	20
74	46	27
50	40	38
67	40	26

70	40	17
65	35	28
60	44	36
93	33	17
52	34	19
39	33	12
60	45	16
41	32	29
40	22	28
53	49	21
66	26	34
55	41	32
51	34	17
81	53	17
117	52	38
62	40	19
66	28	35
25	24	18
70	42	19
53	45	33
40	36	22
50	42	9
86	46	38
56	41	26
60	30	32
65	19	16
66	36	30
67	46	17
52	42	48

75	60	53
58	28	24
82	35	29
64	34	30
56	37	16
52	45	18
70	40	18
52	32	26
45	44	28
70	30	15
88	42	23
75	30	26
57	26	15
70	40	17
83	47	37
66	36	18
97	45	41
52	36	24
63	52	33
45	42	16
65	47	16
70	32	24
26	17	8
76	28	26
57	37	17
60	42	24
83	65	50
74	20	34
53	45	19

56	10	32
42	28	20
32	22	21
74	34	38
72	44	28
74	30	30
58	35	25
55	35	30
75	46	36
55	28	35
64	51	9
72	22	24
62	34	17
45	30	32
93	44	29
70	30	40
29	20	18
65	35	35
68	38	17
65	22	40
83	45	32
70	41	9
72	30	42
81	35	17
54	30	22
41	26	19
58	30	40
24	22	9
68	28	34

13	12	10
70	45	30
52	37	27
50	30	30
26	18	7
58	22	20
50	26	7

A:3 Site 3 sediment size samples (a,b,c Axis)

Size (mm)		
A	**B**	**C**
70	40	40
72	42	21
80	34	44
53	35	14
45	22	32
62	30	31
40	22	40
21	18	9
82	28	50
65	51	37
62	40	20
52	34	21
60	30	30
19	69	32
90	18	40
80	71	20
89	48	15

65	47	13
92	56	60
59	44	25
70	60	55
72	55	16
62	34	35
45	41	25
60	40	10
94	39	40
77	61	28
78	50	17
72	40	40
67	53	22
62	30	28
36	24	11
70	42	32
36	29	15
80	54	14
17	12	6
90	55	20
38	56	33
78	40	32
75	37	36
105	70	45
60	51	19
56	40	20
66	40	27
60	51	50
34	27	13

56	40	34
79	37	36
90	36	15
56	47	19
78	28	10
90	57	16
62	32	30
31	25	19
65	35	25
41	52	18
65	46	40
57	41	17
60	40	35
55	40	45
95	56	40
90	35	38
50	35	22
40	36	18
46	42	15
55	35	20
59	48	23
70	30	27
61	51	42
58	20	32
47	34	21
92	45	60
66	31	25
55	47	14
40	42	18

47	42	16
70	30	40
60	33	21
62	42	40
80	65	39
56	50	30
62	40	18
70	40	35
69	45	21
64	25	24
78	40	36
60	30	30
78	41	31
64	40	50
92	47	21
65	35	20
68	40	9
60	40	25
64	48	25
60	42	30
60	43	15
62	40	30
51	46	18
50	44	40
90	32	24

A:4 Site 4 sediment size samples

Size (mm)

A	**B**	**C**
85	73	35
77	50	19
70	40	36
76	56	35
80	32	21
125	75	61
70	40	35
60	38	26
80	61	23
60	46	14
75	58	17
60	50	30
91	78	36
93	42	34
119	47	44
67	60	31
74	36	26
58	33	20
80	48	47
62	46	30
71	55	15
43	41	22
96	57	33
81	47	35
59	27	20
87	49	41
62	53	25
72	42	41

78	54	36
85	63	25
121	53	50
64	42	18
61	64	41
61	43	21
74	53	25
92	58	41
69	38	20
111	55	39
63	39	10
123	53	35
109	92	60
84	37	22
55	38	24
106	47	37
81	44	41
60	43	26
61	41	28
77	43	36
67	85	22
58	41	20
83	70	42
71	56	26
110	73	31
76	44	37
72	54	33
87	48	40
105	57	37

81	52	33
101	68	55
116	64	31
53	48	24
72	51	43
76	59	25
80	63	57
91	65	10
104	63	42
99	45	33
84	52	44
63	59	28
76	44	41
89	36	18
84	45	22
133	74	66
66	52	38
74	59	10
96	73	38
70	56	22
84	73	48
85	42	36
123	84	28
86	55	43
94	67	65
99	91	45
82	72	37
81	65	45
94	57	38

75	64	27
62	53	31
65	58	9
64	60	24
54	44	38
77	49	42
70	55	53
96	65	52
103	57	39
79	54	34
98	71	65
86	54	49
75	47	37
66	51	21

A:5 Site 5 sediment size samples

Size (mm)		
A	**B**	**C**
130	80	85
64	72	26
130	100	45
166	111	69
100	70	40
109	61	43
105	75	60
245	150	80
118	80	45
97	66	32

111	60	64
114	56	65
94	66	18
140	100	70
66	35	24
120	60	90
136	84	55
81	65	30
124	100	24
153	40	46
98	73	42
75	60	39
25	22	13
110	44	40
64	42	28
90	50	72
42	39	9
81	80	70
112	86	35
130	35	50
142	112	63
130	60	68
63	64	62
100	75	105
23	47	32
100	70	40
106	79	54
95	55	35
51	30	116

136	68	47
104	77	57
51	31	26
69	40	6
32	29	12
19	14	9
117	90	18
68	41	6
134	42	62
160	100	80
132	95	49
160	60	60
86	56	31
100	35	30
134	128	53
108	43	45
89	76	51
110	80	45
95	72	52
150	80	50
26	16	8
127	90	25
104	46	35
123	60	50
172	125	65
110	80	55
98	86	47
90	70	60
167	90	61

100	90	45
69	53	13
120	60	70
100	81	21
180	93	47
39	33	15
75	50	25
114	53	23
156	80	40
55	40	8
78	70	50
45	22	9
142	85	39
42	27	8
80	73	94
52	42	12
76	63	70
56	33	13
150	90	57
52	39	17
116	61	53
78	53	25
115	40	40
46	29	9
110	80	85
51	29	26
105	70	35
96	71	33
100	104	27

46	93	13
115	75	53
64	53	17

A:6 Average sediment sizes

Average	**Site 1**			**Site 2**			**Site 3**			**Site 4**	
	A axis	B axis	C axis	A	B	C	A	B	C	A	B
D16	39.16	22.32	11	45	26	16.16	47	30	15.16	62	42
D50	52	32	22	62.5	35	25.5	62	40	25	78.5	53
D84	63.84	40.84	30	74.84	45	35.84	80	51	40	99	66.68
D99	113.86	83.86	46.93	116.8	64.95	52.97	104.9	70.99	60	132.92	91.99