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A Riverine Ecosystem Service Cascade Model (RESCaM) framework for assessing ecosystem service provision as applied to English geomorphic river types

by

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Author's declaration

At no time during the registration for the degree of *Doctor of Philosophy* has the author been registered for any other University award without prior agreement of the Graduate Sub-Committee.

Work submitted for this research degree at the University of Plymouth has not formed part of any other degree either at University of Plymouth or at another establishment.

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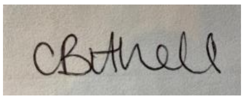
Signed: .

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Abstract

Claire Bithell

A Riverine Ecosystem Service Cascade Model (RESCaM) framework for assessing ecosystem service provision as applied to English geomorphic river types

Riverine ecosystems are considered the lifeblood of the Earth and because of this, have been exploited for centuries for social, agricultural and industrial development, resulting in their environmental degradation and simplification. This has led to a shift in the natural processes and functions and thus their ability to provide a full range and overall high levels of regulating, provisioning and cultural ecosystem services, which humans rely on. An ecosystem service and nature-based approach is being increasingly recognised as a useful tool to help evaluate, protect and restore river ecosystems for maximising the delivery of ecosystem services sustainably. Riverine ecosystem services are derived from riverscapes whereby "hydrological, geomorphological and ecological linkages and pathways of water, sediment and biogenic matter drive the relationship between river processes and physical habitat character and ecosystem services" (Large and Gilvear, 2015; Thorp *et al*., 2006). Better integration of this understanding is needed to inform sustainable river management in the 21st Century and maximise ecosystem services. This research aims to develop a bespoke riverine ecosystem service assessment methodology, for rivers in England, recognising the biophysical structure of river ecosystems as the template upon which ecosystem services are generated and is useful in guiding future river management. First, I start by critically evaluating an existing river ecosystem service assessment methodology using the Google Earth™ (GE ™)

platform, as proposed by Large and Gilvear (2015). The assessment is applied to a variety of rivers across England and Wales representing differing characteristics, scales and land cover uses and validated through field survey. I conclude that the L&G2015 methodology is not suitable for useful application across English and Welsh river networks and that significant advances and refinements are required. The research then focuses on developing a bespoke riverine ecosystem service assessment methodology for English and Welsh rivers that (i) accounts better for their geomorphological character, (ii) uses datasets are available in English and Welsh context and (iii) is underpinned by an evidence-based linkage matrix which recognises positive and negative linkages between riverscape attributes and land cover types, natural ecosystem functioning and ecosystem service provision. The linkages have been identified through an extensive literature review and each linkage has been assigned a confidence level. The linkages have been placed within a Riverine Ecosystem Service Cascade Model (RESCaM) framework. A geomorphic river type classification, recognising thirteen geomorphic river types commonly found in England, is further integrated within the approach to provide the template for which to evaluate ecosystem service 'performance' at the river reach-scale. The approach is tested across the spectrum of river types found in England and Wales and its significance for policy and river management is discussed.

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1 Introduction

"Fresh water is essential to all life and has played a central role in the development of human civilizations (Everard et al., 2001; Everard and Powell, 2002). River channels are fully interdependent with the landscapes of which they are a part (Newson, 1994). This connection with the landscape is essential for the functions performed by river systems, from which society derives many beneficial goods and services (Dugan, 1990)".

1.1 Research context

1.1.1 Riverine ecosystem services

The natural environment provides direct and indirect benefits, which have been valued by humanity for several millennia (Lele *et al*., 2013). Collectively, these benefits are recognised as *ecosystem services* and are simplistically defined by many as "the benefits humans receive, directly or indirectly, from ecosystems" (after Costanza *et al*., 1997; Daily, 1997; MEA, 2005). The ecosystem service concept provides "a means to integrate all possible direct and indirect benefits that accrue from an ecosystem to human society, including those that are not straightforwardly monetized" (Vermaat *et al*., 2015; MEA, 2005). Since the concept initially emerged in the 1970s, being described as *environmental services* by Wilson and Matthews (1970), interest has accelerated, and the concept is now high on national and international political agendas.

Riverscapes (defined as the river channel and adjacent floodplain) are highly valued freshwater ecosystems (UKNEA, 2011; Raymond *et al*., 2009; Morris *et al*., 2009; Naiman *et al*., 2005; Tockner and Stanford, 2002) and are recognised as "some of the most diverse ecosystems on Earth" (Palmer and Richardson, 2009; Strayer and Dudgeon, 2010). Riverine ecosystems provide direct benefits such as freshwater supply and indirect benefits such as recreational enjoyment, which contribute to human well-being (Ncube *et al*., 2018; Yeakley *et al*., 2016; Dufour *et al*., 2010; Naiman *et al*., 2005). These benefits are termed *riverine ecosystem services* and can be broadly defined as "those provided by rivers and the broader river-dependent landscapes that are hydrologically connected to rivers" (Hanna *et al*., 2018). Riverscapes have been crucial for the development of modern societies for centuries, as they provide prime locations for social, agricultural, and industrial development (Peipoch *et al*., 2015). Humans have exploited them for the consumption of water and energy, the extraction of gravel, their ability to regulate flooding, erosion and sedimentation, for tourism, heritage and education and other tangible and intangible benefits (Hanna *et al*., 2018; UKNEA, 2011; Yeakley *et al*., 2015; Penning-Rowsell *et al*., 2005). Not surprisingly then, rivers are deemed the ecosystem type most affected by humans worldwide (Nilsson *et al*., 2007) and their integrity is under threat in the face of climate change, population growth and the increasing demand on water resources (MEA, 2005b; Hanna *et al*., 2018).

Evaluating and quantifying riverine ecosystem services is challenging, not least because rivers are dynamic, complex ecosystems which display a high degree of variability across space and time (Ward, 1989). The interactions between hydrological, geomorphological and ecological processes ultimately result in the provision of essential riverine ecosystem services (Koopman *et al*., 2015). However, geomorphic and ecohydrological properties of river systems have undergone dramatic, worldwide and often irreversible transformations (Hossain *et al*., 2020; Hein *et al*., 2021) as a response to human activities, which thus limits the use of existing management frameworks to provide adequate solutions to current and future problems (Hein *et al*., 2021). Clearly then, humans must be treated as part of ecosystems (Newson and Large., 2006). Riverscapes are increasingly being viewed as "coupled and complex social-ecological systems (SES)" and we must improve our understanding of how riverscapes function in the 21st Century to allow us to effectively manage them for multiple benefits (Dunham *et al*., 2018; Crausbay *et al*., 2017; Naiman, 2013).

Eco-hydromorphology describes the interdisciplinary interface between ecology, geomorphology and hydrology and is defined by Vaughan *et al*. (2009) as "the interactions of the biological entities and ecological processes of a river with the hydrological and geomorphological form and dynamics". As recognised by Vaughan *et al*. (2009), "the linking of ecology to hydromorphology, via physical habitat characteristics, is a recent and on-going theme in river research and management". This linkage is expected to be an important basis upon which assessments of riverine ecosystem services can be undertaken. Fundamentally, hydromorphology provides the basis for which to describe the physical template of river networks (Poole, 2010; Maddock, 1999) whereby geomorphological processes create the physical structure within a river (Frissell *et al.*, 1986; Harper and Everard, 1998; Brierley *et al.*, 2000) and this structure in turn, provides a habitat matrix upon which biophysical processes occur (Montgomery, 1999; Brierley and Fryirs, 2000; Parsons and Thoms, 2007). It is therefore hypothesised that eco-hydromorphology could serve as a template for evaluating ecosystem structure, ecosystem functions and subsequently ecosystem services (Figure 1-1).

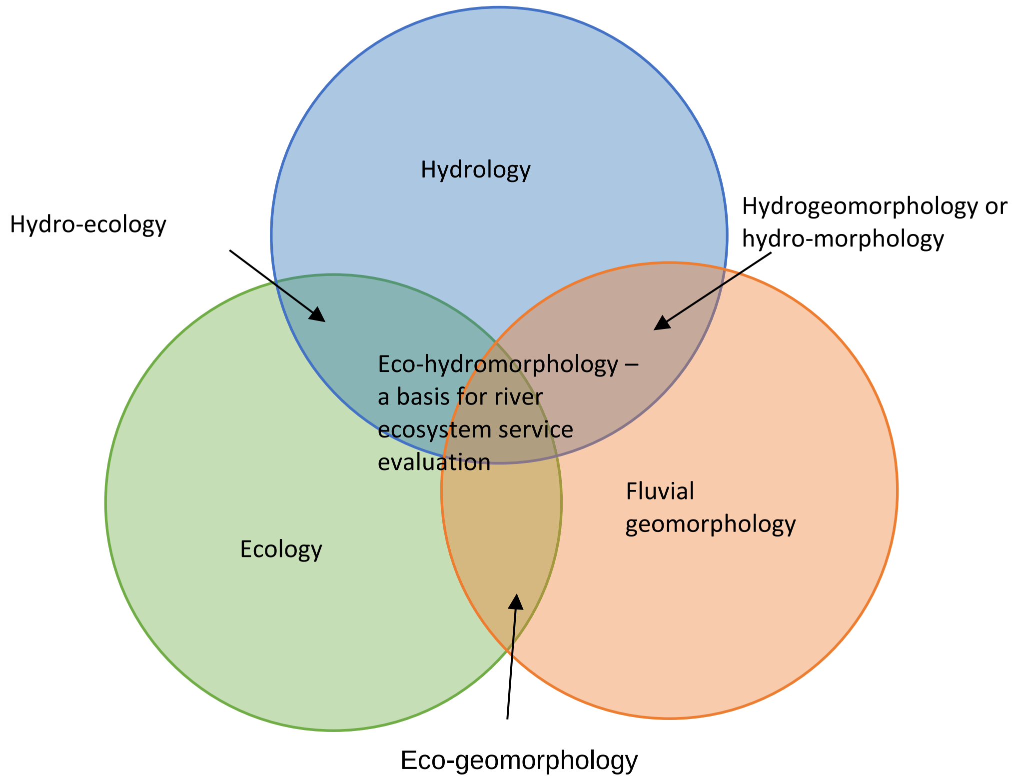


Figure 1-1 Conceptualisation of the interactions between hydrology, ecology and fluvial geomorphology which can provide a basis for river ecosystem service evaluation

The riverine ecosystem service concept emphasises the need for understanding the physical structure of rivers and the biophysical processes operating within rivers while recognising the benefits they provide to humanity (Large and Gilvear, 2015). Indeed, it treats 21st century rivers as socio-ecological systems. Few rivers globally, if any, are pure ecological systems. Thus, interdisciplinary research efforts are required for the sustainable provision of riverine ecosystem services.

In ecosystem service research, ecosystem service *cascade models* have been used to conceptualise the logic that underpins the ecosystem service paradigm (Haines-Young and Potschin, 2009, 2010, 2011; Potschin and Haines-Young, 2016; Large and Gilvear, 2015). The cascade is described as a "production chain linking ecological and biophysical structures and processes on the one hand and elements of human well-being on the other with potentially a series of intermediate stages between them" (Potschin and Haines-Young, 2011 and Potschin and Haines-Young., 2016) (Figure 1-2). Eco-hydromorphology then, provides the scientific basis for linking the biophysical structure or process and ecosystem functions in riverine ecosystems that ultimately yield ecosystem services which provide benefits to society. Thus, this thesis examines riverine ecosystem services through the lens of both eco-hydrogeomorphology and an ecosystem service cascade model framework, principally at the river reach-scale. Reach-scale analysis is central to river science although it is recognised that multi-scalar analysis is also coming to the fore (Seema *et al*., 2021).

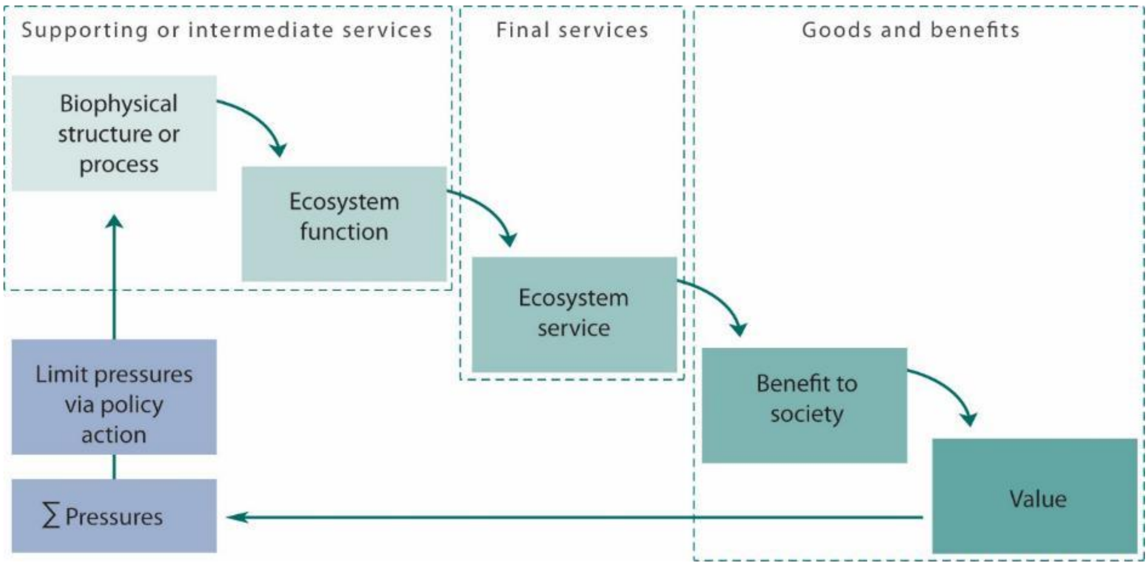


Figure 1-2 "The cascade model framework to clarify the terminology used in relation to the ecosystem service concept. The left hand side of the cascade (supporting or intermediate services and final services) represents environmental factors whereas the 'goods and benefits' represents social and economic factors" (Source: Potschin and Haines-Young, 2011 and Potschin and Haines-Young., 2016)

In hydromorphology research, many different frameworks have been proposed to understand and assess river ecosystems by organizing and interpreting information across a hierarchy of spatial scales (reviewed in Gurnell *et al*., 2016). Despite this, a comprehensive assessment of riverine ecosystem services does not exist, and it is acknowledged that the scientific literature lacks sufficient tools to assess and quantify the riverine ecosystem services generated across stream networks (Hanna *et al*., 2018).

One approach to assessing river ecosystem services has been proposed by Large and Gilvear (2015) to assess multiple ecosystem services at the river reach-scale. The methodology adopts principles encapsulated in the 'Riverine Ecosystem Synthesis' (RES) (Thorp *et al*., 2008) to "establish theoretical linkages between riverscape fluvial features, attributes and land cover types, and natural ecosystem functions and river ecosystem services" (Large and Gilvear, 2015). The methodology utilises the Google Earth™ (GE™) platform to measure riverscape features and attributes and implements a rules-based scoring system to generate a range of indices for scoring ecosystem service provision. Large and Gilvear (2015) said the methodology is "applicable across ecoregions and to rivers or varying size, level of human modification and character". However, it is recognised that the approach is based upon theoretical understanding of rivers, which often overlooks the importance of anthropogenic augmentation of the riverscape and the remote sensing approach using GE™ has not been appropriately tested or validated. The research herein shall critique and further test the robustness and suitability of the Large and Gilvear (2015) methodology for use on English rivers, it shall advance the methodology beyond theory, explicitly recognising the physical template upon which riverine ecosystem service interactions occur and it will generate an evidence-base to underpin linkages between riverscape attributes and ecosystem service provision in order to develop a bespoke geomorphologically-based riverine ecosystem service assessment methodology for English rivers.

1.1.2 Historical modification of rivers and ecosystem service impacts

Gurnell and Petts, (2002) stress that "natural is a difficult term to apply to any English river", whereby*:*

> *"The history of river channels in England…is one of progressive change from bedload-dominated wandering channels in forested catchments to suspended-load dominated, stable or incising, single thread channels. The Neolithic and later phases of deforestation and agricultural expansion and intensification were associated with soil erosion in the uplands and alluviation of river corridors. Brown (1987) considered that the resultant floodplain accretion and planform stabilization established the channel character for the next 2000–3000 years. The modern era has been characterized by a period of channel incision induced by dams, embanking, reafforestation, sediment-check structures, urbanization, and sand and gravel extraction…" (Gurnell and Petts, 2002, p. 582)*

Historically, river systems were highly connected to each other and catchment processes. Extensive management of river corridors, wetlands and catchments, particularly, throughout the English landscape, has resulted in partial or full disconnection of river channels from their floodplains and adjacent hillslopes, and a breakdown in the flow of ecological, social and economic benefits (UKNEA, 2011; Everard, 1997a, b). Our attempts to control dynamic river processes that determine natural channel mobility, flooding and sediment transfer, for example, have deeply degraded the integrity of river and riparian ecosystems (Dufour *et al*., 2010). Initially, perceived as a great achievement by humanity, this ability to control rivers and exploit them for a small range of ecosystem services has developed into a major environmental issue (Wostl, 2006). Conflicts typically arise where management of riverine ecosystems targets selective provisioning services without understanding the complex interactions between those and other ecosystem services provided. This normally results in immediate ecosystem responses (Nilsson *et al*., 2007) yet river management efforts have only come to the fore within the last several decades to restore or rehabilitate impacted rivers (Palmer and Allan, 2006, Jansson *et al*., 2007).

Recently then, river restoration which aims to enhance the hydromorphological and biological condition of rivers is being increasingly undertaken in developed countries (Deffner and Hasse, 2018; Smith *et al*., 2016; Wohl, 2015; Bernhardt *et al*., 2005; Shields *et al*., 2003). In England, much of this work has been undertaken by the efforts of the UK River Restoration Centre (RRC). However, efforts have predominantly focused on reach-scale river restoration rather than understanding wider catchment characteristics and constraints from large-scale catchment pressures. Numerous syntheses and meta-analyses have been published to appraise restoration efforts, most of which concentrate on the reach-scale (Bernhardt and Palmer, 2011; Violin *et al*., 2011; Doyle and Shields, 2012; Palmer and Hondula, 2014; Palmer *et al*., 2014a; Smucker and Detenbeck, 2014). Typically, these studies highlight that reach-scale interventions "fail to effectively restore river functional integrity with respect to water quality and biological communities" (Wohl *et al*., 2015). Knowledge on the effect of river restoration remains limited due to a lack of detailed monitoring (Bash and Ryan, 2002; Bernhardt *et al*., 2005; Wohl *et al*., 2015), in particularly quantifying the response on hydromorphology and biota, as noted by Kail *et al* (2015) who reported contrasting results. A key aim of restoration should be to optimise ecosystem service restoration for society rather than focusing on biodiversity alone, which has been the traditional focus (Gilvear *et al*., 2010).

Researchers in the field of river restoration have more recently been emphasising the need to think beyond the restoration of only river form at the reach-scale and instead, prioritise restoration of river function and natural processes at a larger scale (e.g. Kondolf, 1998; McDonald *et al*., 2004; Bernhardt and Palmer, 2007, 2011). Studies published include those that promote hydrological connectivity between river and floodplain (Tockner *et al*., 1999; Paillex *et al*., 2009; Shields *et al*., 2011; Gumiero *et al*., 2013; McMillan and Noe, 2017; Fischer *et al*., 2021), longitudinal connectivity and partial restoration of water and sediment fluxes (Shafroth *et al*., 2010; Konrad *et al*., 2011; Fuller and Death, 2018) and ecological productivity (Lepori *et al*., 2005; Palmer *et al*., 2010a, 2010b). Evaluation of biotic response to these process-based restoration approaches are increasing (e.g. Helfield *et al*., 2007; Walther and Whiles, 2008; Lorenz *et al*., 2009; Tummers *et al*., 2016) which is required to inform ecologically successful restoration (Wohl *et al*., 2015). Whilst it is important that river restoration efforts are scaled up and should target restoration of natural processes such as flooding, bed mobility and sediment transport, it is important to recognise that ecologically degraded rivers may still have attained social value (Adams, 1997; Junker *et al*., 2007) and in some communities, particularly in urban settings, process-based restoration is not always favourable (Dufour *et al*., 2010). Che *et al* (2014) report that:

"…elements that a river restoration scientist might view as necessary for a successful restoration in biophysical terms may not be the same as those that a community might value."

The ecosystem service concept provides a promising framework for modern river management (Gilvear *et al*., 2017) allowing us to evaluate the varied ways in which ecosystems contribute to human well-being in a holistic manner (Dufour *et al*., 2010; Schindler *et al*., 2014; Schröter *et al*., 2017; Hanna *et al*., 2018). Some researchers have raised concern that the ecosystem services concept could "encourage restoration projects to focus on a subset of processes that create a desired service rather than on the entire river ecosystem" (Palmer *et al*., 2014a; Wohl *et al*., 2015), however, tools for assessing ecosystem services should seek to alleviate these concerns as the science underpinning the concept advances.

In England, which is the focus nation of this study, the ecosystem services concept will be a central part of the move towards green recovery and nature-based solutions as advocated in the UK Government's 25 Year Environment Plans[1], demonstrating the UKs commitment to long-term, holistic river management. The hope is it will make 21st century rivers more sustainable, resilient ecosystems that better meet the needs of society, achieving the over-arching goal of improving the environment within a generation. At the global level, the "*UN Decade on Ecosystem Restoration 2021-2030*, declared on 1 March 2019 by the UN General Assembly", also aims to "massively scale up the restoration of degraded and destroyed ecosystems as a

[1] https://www.gov.uk/government/publications/25-year-environment-plan - Accessed on 03.03.2022

proven measure to fight climate change, and enhance food security, water supply and biodiversity".

1.2 Thesis aims and objectives

The overarching aim of this research is to develop a desk-based riverine ecosystem services assessment methodology for application across English river networks. Underpinning the aim is the presumption that integrating eco-hydromorphological principles and concepts and geomorphic river typing approaches within an ecosystem service cascade model will provide a sound template for establishing linkages between ecological processes, river structure and function and riverine ecosystem services across England and as a framework for assessments elsewhere in the world. Specific objectives to fulfil the aim are outlined below.

The specific objectives are:

Objective one: To critically evaluate the Large and Gilvear (2015) methodology for assessing reach-based riverine ecosystem services using GE^{TM}.

Objective two: To further test and validate the use of GE^{TM} for gathering spatial data on fluvial features, attributes and land cover classes characteristic of English rivers based on the methods described in Large and Gilvear (2015)

Objective three: To develop an evidence-based linkage matrix recognising the confidence in linkages between riverscape attributes, natural processes and functions and ecosystem services and place this within a RESCaM (Riverine

Ecosystem Service Cascade Model) framework, underpinned by eco-hydromorphological principles and concepts.

Objective four: To build upon objectives one – three, to develop a bespoke river ecosystem service assessment methodology suitable for river types commonly found in England, using a geomorphic river typing framework based on information extracted using the GE™ platform and national hydrological and asset datasets.

Objective five: to demonstrate the applicability of the proposed methodology across four pilot study sites representing the spectrum of geomorphic river types found in England.

1.3 Thesis structure

This thesis consists of six chapters, including this introductory chapter. Chapter 2 comprises of a literature review, chapters 3, 4 and 5 describe the experimental research which addresses the main aim and objectives of the thesis and finally, chapter six summaries the overall findings of the research and discusses its significance for river management considering its relevance to national and international policies.

Chapter 2 begins with an introduction of the ecosystem service concept, summarising key definitions and classifications and then discusses the concept of ecosystem cascades. It then specifically discusses ecosystem services provided by riverine ecosystems and finally highlights eco-hydromorphology (a discipline integrating ecology, hydrology and geomorphology) and key river science concepts as a template for improving understanding of river ecosystem services.

Chapter 3 critically reviews the L&G2015 methodology for river ecosystem service assessment using GE™, focusing on its suitability to English rivers. Limitations in the methodology and further research needs are identified to allow for refinement and development of a bespoke assessment methodology suitable for application across English river networks.

Chapter 4 further explores some of the weaknesses and limitations identified in Chapter 3 and assesses the validity of the use of GE™ as the platform for undertaking the L&G2015 methodology through field-based assessment, focusing again, on issues relevant to English river types.

Chapter 5 develops an evidence-based linkage matrix recognising the level of confidence in linkages between twenty-seven riverscape attributes and ten provisioning and regulating ecosystem services and places these linkages within the wider RESCaM framework. It uses current eco-hydromorphological understanding as a basis for developing a bespoke river ecosystem service assessment methodology for English river types. The assessment involves extracting information from GE™ and a suite of national hydrological and asset datasets and uses this information to derive ES scores on a reach-scale. Comparison between the ES scores derived and the potential maximum scores according to geomorphic river type is discussed as a means of identifying reaches where river management can be implemented to maximise ES provision. The methodology has been piloted on four study sites encompassing the spectrum of river types found in England.

Chapter 6 discusses the key findings from the research, the significance of its relevance to policy and river managers and provides recommendations for future research.

2 Literature Review

2.1 Introduction

This chapter summarises the scientific literature supporting the research themes relevant to this thesis. Firstly, the chapter introduces the ecosystem service concept: definitions and classifications systems are described, the concept of the cascade model (proposed by Haines-Young and Potschin, 2010) is introduced and the ambiguous and complex relationship biodiversity has regarding the provision of ecosystem services is discussed. These are then discussed in the context of river ecosystems, which are of the focus of this research. The literature review emphasises the importance of eco-hydromorphological understanding to underpin the basis for assessing riverine ecosystem services. It briefly outlines some of the key conceptual frameworks and classification systems used in river management and restoration and discusses the need to consider river ecosystems as both social and ecological systems. The chapter concludes by summarising the literature in the context of the experimental chapters.

2.2 The Ecosystem Service Concept

Anthropogenic activity (e.g. land conversion, water abstraction, carbon emissions, species introductions) has accelerated both the amount and intensity of environmental change within ecosystems, altering their composition, structure and function and thus their capacity to provide necessary ecosystem services to society (Oliver *et al*., 2015; Steffen *et al*., 2015; Krausmann *et al*., 2013; Simberloff *et al*., 2013; Palmer *et al*., 2004; Vitousek *et al*., 1997; Daily, 1997). It is also considered one of the major contributing factors to the loss of global biodiversity (Bullock *et al*., 2011). The ecosystem service concept dates back to the 1970s, initially described by Wilson and Matthews (1970) as *environmental services* and then later termed *nature's services* by Westman (1977). Westman (1977) further explained that "the effects of the development and physical change imposed by human beings on ecosystems could potentially be quantified in order to inform society and, thus, influence policy and management decisions in order to mitigate ecosystem degradation". As ideas and understanding evolved, the term *ecosystem services* emerged from the early 1980s (Ehrlich and Ehrlich, 1981; Ehrlich and Mooney, 1983). In the mid- to late 1990s, the concept developed into a potential framework for evaluating, protecting and restoring ecosystems and their biodiversity (Costanza *et al*., 1997). A widely accepted definition of ecosystem services simplistically describes them as "the benefits humans receive, directly or indirectly, from ecosystems" (after Costanza *et al*., 1997, Daily, 1997, MEA, 2005). In the academic literature, numerous ecosystem service frameworks exist (Nahlik *et al*., 2012; Hanna *et al*., 2018), many of which were motivated by the Millennium Ecosystem Assessment (MEA, 2005).

2.2.1 Ecosystem service definitions and classification systems

Any ecosystem service framework should include a suitable definition of ecosystem services and a classification system which allows for identification and categorisation of ecosystem services (Nahlik *et al*., 2012). Despite all the advances over the last four decades, the term *ecosystem services* has been broadly applied used in scientific studies leading to concerns around a general lack of consistency and meaning (Seppelt *et al.* 2011; Nahlik *et al.* 2012). Multiple approaches exist which adopt a wide range of terminology, definitions and classifications (Koopmnan *et al.,* 2015), however many are described as vague and require interpretation by those applying them (Nahlik *et al*., 2012). This has tended to complicate rather than simplify scientific progress in ecosystem service research. Three commonly used international classification systems are: *The Millennium Ecosystem Assessment*' (MEA, 2005), *The Economics of Ecosystems and Biodiversity* (TEEB, 2010) and *The Common International Classification of Ecosystem Services* (CICES, 2013). Furthermore, a national classification has been adopted in the UK, *UK National Ecosystem Service Assessment* (UK NEA, 2011).

The MEA (2005) is considered "one of the most comprehensive transdisciplinary efforts to date, documenting the global status and trends in ecosystem condition and services and the consequences for human well-being". The MEA (2005) provides a basic division of services into four categories namely *Provisioning, Regulating, Cultural* and *Supporting* services*.* These are outlined in Figure 2-1 (Source: MEA, 2005). It should be noted that supporting services, such as primary production play a different role to the other three types in that their contribution to society is indirect. Instead, they are "part of the often-complex mechanisms and processes that generate other services" (Haines-Young and Potschin, 2010).

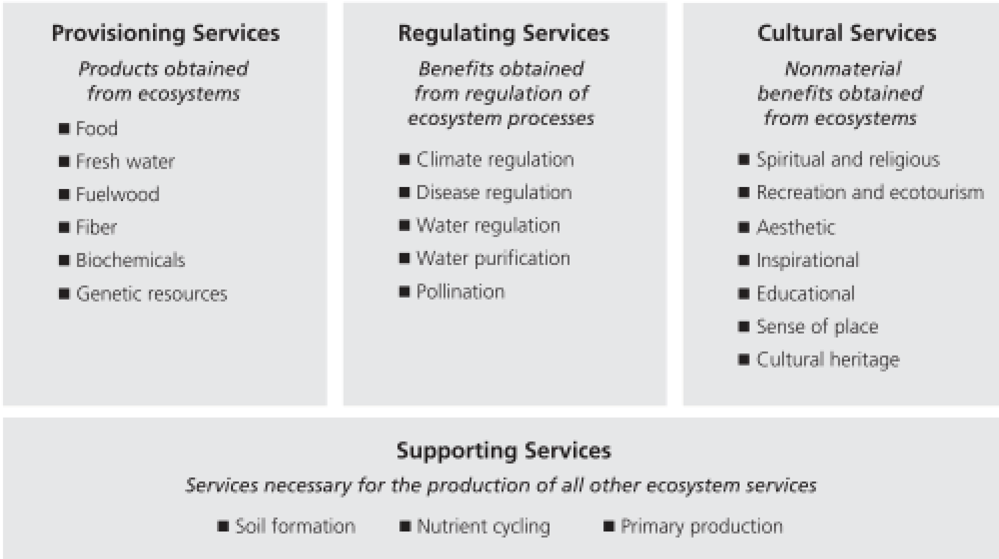


Figure 2-1 "The four ecosystem service categories" (Source: MEA, 2005)

The distinction between the mechanisms and processes by which services are generated and the actual services themselves, has been discussed by many (Boyd and Banzhaf, 2007; Wallace, 2007; Costanza, 2008; Fisher and Turner, 2008; Fisher *et al.,* 2009; De Groot *et al.,* 2010; Haines-Young and Potschin, 2010; Burkhard *et al.,* 2010; Burkhard *et al.,* 2012). Since the publication of the MEA (2005), numerous researchers have discouraged the use of the term 'supporting services' and instead suggested that they considered as *ecological processes* (Carpenter *et al*., 2009; Hein *et al*., 2006).

The classification proposed in TEEB (the second international initiative between 2007 and 2010) used the familiar MEA (2005) categories including provisioning, regulating and cultural but dropped the use of supporting services on the basis that:

> *"If we accept there are layers of different ecological structures and processes that underpin all 'final service' outputs, then the category of 'supporting services' proposed by the MEA is probably unnecessary or best used as a synonym for ecological functions and processes (Haines-Young and Potschin, 2009)".*

TEEB (2010) introduced a new category of *habitat services* to replace supporting services which are recognised as underpinning almost all other services, although the motivation for this approach is unclear. Habitat services in TEEB have been interpreted as them having a supporting role, thus ambiguity remains (Haines-Young and Potschin, 2009).

CICES (the third international initiative published in 2013) aimed to provide a new standard classification of ecosystem services proposing the use of three main categories: *provisioning*, *regulating and maintenance* and *cultural*. The main distinction between the TEEB and CICES classifications is the treatment of *habitat services*. TEEB identifies *habitat services* as "a distinct grouping at the highest level whereas CICES regards them as part of a broader *regulating and maintenance* theme" (Haines-Young and Potschin, 2011).

In the UK, the most detailed and comprehensive assessment of the natural environment emerged in 2011 as the UKNEA (Brouwer *et al.,* 2013). The UKNEA (2011) was the "first analysis of the UK's natural environment in terms of the benefits it provides to society" and follows methods outlined in the MEA (2005) categorising ecosystems services as *provisioning*, *regulating*, *supporting* and *cultural* services.

One thing is clear, there are many contrasting ideas around how ecosystem services should be classified. Many researchers suggest that no single classification is appropriate for use in all cases and multiple classification systems are required for different purposes (Costanza, 2008; Fisher *et al.,* 2009; Burkhard *et al.,* 2012). In contrast to this, Nahlik *et al (*2012) argue that "developing a classification system that facilitates the identification of ecosystem services and a strategy to help guide research development in a way that is meaningful to natural and social scientists, and the public is imperative to moving ecosystem services from a concept to a practice". The real key is to understand the complexity of applying the concept across diverse services and environments and understanding how the services are of value to society. More important than classification is having an over-arching framework or model on which to *hang* approaches and studies. Little analysis, to date, has been undertaken in terms of examining these differing classifications in the context of rivers with their unique characteristics.

2.2.2 The Cascade model

The distinction between ecosystem processes, ecosystem functions, (intermediate and final) ecosystem services, goods and benefits has been a hot topic of discussion by researchers (Daily, 1997; Boyd and Banzhaf, 2005; Costanza *et al.,* 1997; de Groot *et al.,* 2002; MEA, 2005; Brown *et al.,* 2006). Haines-Young and Potschin (2010) proposed "a way of representing the logic that underlies the ecosystem service paradigm and the debates that have developed around it" through the idea of an ecosystem service cascade model. Potschin and Haines-Young (2011b) present this as "a production chain linking ecological and biophysical structures and processes on the one hand and elements of well-being on the other with potentially a series of intermediate stages between them" (Figure 1-2). The model suggests that "to understand these relationships we need to identify both the functional characteristics of ecosystems that give rise to services and the benefits and values that they support". Users are encouraged to scrutinise the difference between *services* and *benefits*, and "to examine the particular functional characteristics of ecosystems that yield services, as opposed to the broad ecological structures and processes that support them" (Potschin-Young *et al*., 2017). Understanding the differences between *ecosystem functions, services* and *benefits* are needed for many practical applications of the ecosystem service concept (de Groot *et al.,* 2010; Haines-Young and Potschin, 2010; Burkhard *et al.,* 2010; Burkhard *et al.,* 2012). The five elements of the cascade are described further below.

The first element of the cascade, *biophysical structure or process* are simplistically described by Scott *et al.* (1998) as the "interactions among elements of the ecosystem". The second element, *ecosystem function* describes "the capacity or capability of the ecosystem to do something that is potentially useful to people e.g. slowing the passage of water" (Haines-Young and Potschin, 2010; Costanza *et al.,* 1997; Daily, 1997; Brown *et al.,* 2007) which produce the third element of the cascade, the *final ecosystem* service, e.g. flood mitigation. However, many ecosystem processes have functions that appear to matter only to the organisms themselves and appear to provide almost no services to people. The first two elements of the cascade are not considered final ecosystem services but are collectively considered *intermediate services* (Fisher and Turner, 2008), within the cascade model, which ultimately generate *final services* (Haines-Young and Potschin, 2013).

'Final ecosystem services' are the outputs of ecosystems that contribute to human well-being, whether natural, semi-natural or highly modified. Fundamentally, they "retain a connection to the underlying ecosystem structure, processes and functions that generate them" (Haines-Young and Potschin, 2013).

Haines-Young and Potschin (2013) argue that the fourth and fifth elements, collectively termed *ecosystem goods and benefits* are defined as "the things that people create or derive from final ecosystem services, recognising that term good is synonymous with benefit". *Goods and benefits* are "no longer functionally connected to the systems from which they were derived" (Haines-Young and Potschin, 2013).

The cascade model undoubtedly provides a useful way of conceptualising the ecosystem service concept, despite being a simplification of the *real world* (Haines-Young and Potschin, 2009). Often simple linear relationships do not exist in ecosystems. Often a single ecosystem service can be a product of multiple processes and similarly a single process can contribute to more than one service (de Groot *et al.,* 2002; Fisher and Turner, 2008). Another complexity is that ecosystem services are not always constant but may vary with season or the weather (e.g. skiing). Some recent work has been undertaken on this in relation to intermittent rivers (Jorda-Capdevila *et al*., 2021) looking at how ecosystem services vary between dry and wet episodes. The ecosystem cascade underpinned the work of Large and Gilvear (2015) in relation to riverine ecosystem service assessment.

2.2.3 Biodiversity-ecosystem services relationships

Biodiversity seems to have a unique association with ecosystem services. There is an assumption that high biodiversity should be associated with high ecosystem service provision however, the relationship is a complex one and even in simple ecosystems, the relationship between biodiversity and the elements of the cascade model are complex and poorly understood (Mace *et al.,* 2012; Adams, 2014; Harrison *et al.,* 2014; Schröter *et al.,* 2014; Balvanera *et al.,* 2014; 2016; De Groot *et al.,* 2016). Mace *et al* (2012) provides valuable theoretical information on the role that biodiversity plays in ecosystem service delivery.

Biodiversity is included in ecosystem service assessments in very different ways, has many definitions, encompasses different biodiversity metrics and components for different purposes and plays multiple roles in ecosystem processes and services (Mace *et al.,* 2012). In the literature, two main approaches are apparent with regards to how biodiversity fits into the ecosystem service concept. The first approach suggests that biodiversity and ecosystem services are synonymous (whereby biodiversity underpins ES) implying that managing one will automatically enhance the other (Bullock *et al.,* 2011; Mace *et al.,* 2012). Sufficient evidence suggests that biodiversity does directly influence or strongly relate to certain provisioning and regulating services, (noted by some that this relationship is not always a positive one -Tallis *et al.,* 2008; Carpenter *et al.,* 2009; Reyers *et al.,* 2012; Harrison *et al.,* 2014) but for other ecosystem services there is insufficient data (Cardinale *et al.,* 2012). The second approach suggests biodiversity *is* an ecosystem service (Bullock *et al.,* 2011; Mace *et al.,* 2012).

The research adopts the proposal of Mace *et al* (2012) recognising that:

> *"Different relations exist at different levels whereby biodiversity can be a regulator of fundamental ecosystem processes, an ecosystem service itself, or a good. Biodiversity provides the support to key processes; it directly affects the delivery of some ecosystem services and it may itself be the good that is valued."*

2.3 **Riverine Ecosystem Services**

Rivers are recognised as highly valued freshwater ecosystems (UKNEA, 2011; Raymond *et al*., 2009; Morris *et al*., 2009; Naiman *et al*., 2005; Tockner and Stanford, 2002) providing essential ecosystem services to society. Riverine ecosystem services can be defined as "the quantifiable or qualitative benefits of ecosystem functioning to the overall environment, including the products, services, and other benefits humans receive from natural, regulated, or otherwise perturbed river ecosystems" (after Thorp *et al*., 2010 and Large and Gilvear, 2015) or more simply as "as those provided by rivers and the broader landscapes that are hydrologically connected to rivers" (after Thorp *et al*., 2006; Hanna *et al*., 2018). River systems are naturally dynamic and face intermittent changes however, anthropogenic activity is accelerating both the rate and intensity of change to unprecedented levels across space and time (Ekka *et al*., 2020; Bock, 2018; Steffen *et al.,* 2015; Krausmann *et al.,* 2013; Simberloff *et al.,* 2013). This has major implications for managing river ecosystem services and presents a major challenge for river mangers and researchers alike (Oliver *et al.,* 2015; Arthington *et al.,* 2010; Pahl-Wostl, 2006).

The biophysical structure of rivers and their floodplains provide the template upon which ecosystem services are generated (Tomscha *et al*., 2017). They largely depend upon the effective functioning of biophysical processes, which are linked to geomorphological, ecological and hydrological characteristics of the river landscape (Ekka *et al*., 2020; Thorp *et al*., 2006, 2008). Ultimately, water, sediment and biogenic matter drive the relationship between biophysical processes and physical habitat characteristics, resulting in the provision of ecosystem services (Thorp *et al*., 2006, 2008; Large and Gilvear, 2015).

The ecological protection of riverine ecosystems and the exploitation of them to meet societal demands (such as water resources, flood mitigation etc) has developed overtime into an environmental issue (Pahl-Wostl, 2006), threatening the ecological health of riverine ecosystems and thus their ability to provide services which humans depend upon (Vörösmarty *et al.,* 2010; Arthrington, 2012; Yeakley *et al.,* 2016). That said, there is a need to acknowledge that ecologically degraded rivers may be valued by society for a variety of reasons (e.g., Adams, 1997; Junker *et al*., 2007). With that in mind, the ecosystem service concept is advantageous for evaluating the diverse ways river ecosystems contribute to human well-being (Dufour *et al*., 2011; Schindler *et al*., 2014; Schröter *et al*., 2017; Hanna *et al*., 2018) recognising social and ecological interactions in a way that is meaningful for river managers and scientists alike.

2.3.1 Riverine ecosystem service categories

The three main categories of ecosystem services are described, in Table 2-1 (source: Feeley *et al*., 2016), with examples given for freshwater ecosystems. These categories and descriptions reflect how riverine ecosystem services are considered throughout the remainder of the thesis. Provisioning ES provide direct and measurable contributions to human wellbeing (Sutherland *et al*., 2018; Schaefer *et al*., 2015) and thus have received a lot of attention. On the other hand, regulating ES mainly provide indirect benefits to human wellbeing through maintaining environmental quality. Despite their critical value to society (Sutherland *et al*., 2018), the fact that regulating ES are not directly consumed or experienced by people has been argued to make them prone to be overlooked and undervalued (Villamagna *et al*., 2013) in ecosystem service assessments. Cultural ecosystem services have the most variable definition (Feeley *et al*., 2016) and thus remain the subject of on-going debate (Fish *et al*., 2016).

Table 2-1: "Descriptions of the three main ecosystem service categories, with examples in the context of freshwater ecosystems" (Source: Feeley et al., 2016, p 7)

Service	Description
Final services	
Provisioning	Readily understandable as the material or energy outputs from ecosystems, and include the supply of fish, food, fibre or other renewable materials (TEEB, 2010a; Bullock and O'Shea, 2013). For example, the supply of water for consumption, agriculture and industry are among the key provisioning services of freshwater ecosystems (Haines-Young and Potschin, 2013)
Regulating and maintenance	Sometimes referred to as maintenance services, these incorporate the various ways in which living organisms can mediate or moderate the ambient environment that affects humankind (Haines-Young and Potschin, 2013). For example, they ensure water quality by removing excess nutrients and degrading waste and toxic substances through living processes. Other examples include the regulation of local climates, water flow moderation and the regulation of human health (Haines-Young and Potschin, 2013)
Cultural[b]	These perhaps have the most variable definitions of all. They have been proposed to include the non-material benefits that people obtain from contact with ecosystems, such as direct or indirect benefits in the form of amenity and recreation and also certain non-use goods that are valued for their pure existence or which are perceived to contribute to quality of life (TEEB, 2010a; Bullock and O'Shea, 2013). CICES (Haines-Young and Potschin, 2013) categorised cultural services as the physical setting for recreational activity and for cultural values.
Intermediate services	
Supporting processes[c]	These underpin almost all other services. In freshwaters, they relate to all levels of aquatic biodiversity from genetic to community diversity, primary production and other ecosystem processes and functions that underpin well-functioning ecosystems and their resilience to internal and external pressures (Mace *et al*., 2012)

A recent study, undertaken by Hanna *et al* (2018), has compiled information on the global distribution, types and quantities of ecosystem services evaluated across eighty-nine publications (Figure 2-2; source: Hanna *et al*., 2018, p 4). The methods used to quantify ecosystem services are also evaluated using definitions and categories from the MEA (2005). The results demonstrate the huge variety of ecosystem services and a diversity in methods used to quantify them in the literature (Hanna *et al*., 2018). Despite it being suggested previously that regulating services are prone to be over-looked and under-valued (Villamagna *et al*., 2013), this study identified an emphasis in the literature on both provisioning and regulating services, which is also documented in other reviews for different types of ecosystems (e.g. Martínez-Harms & Balvanera, 2012; Seppelt *et al*., 2011). The reason for this is thought to be because provisioning and regulating services "produce, or sustain the production of, material goods, which can increase their perceived importance in society" (Martín-López *et al*., 2012) thus facilitating their quantification and monetary valuation (Hanna *et al*., 2018). The review emphasises the need to more clearly define" indicators, data sources and methods for quantifying riverine ecosystem services" and that assessments should include multiple services across diverse spatial extents and better integrate stakeholders to inform effective river management (Hanna *et al*., 2018).

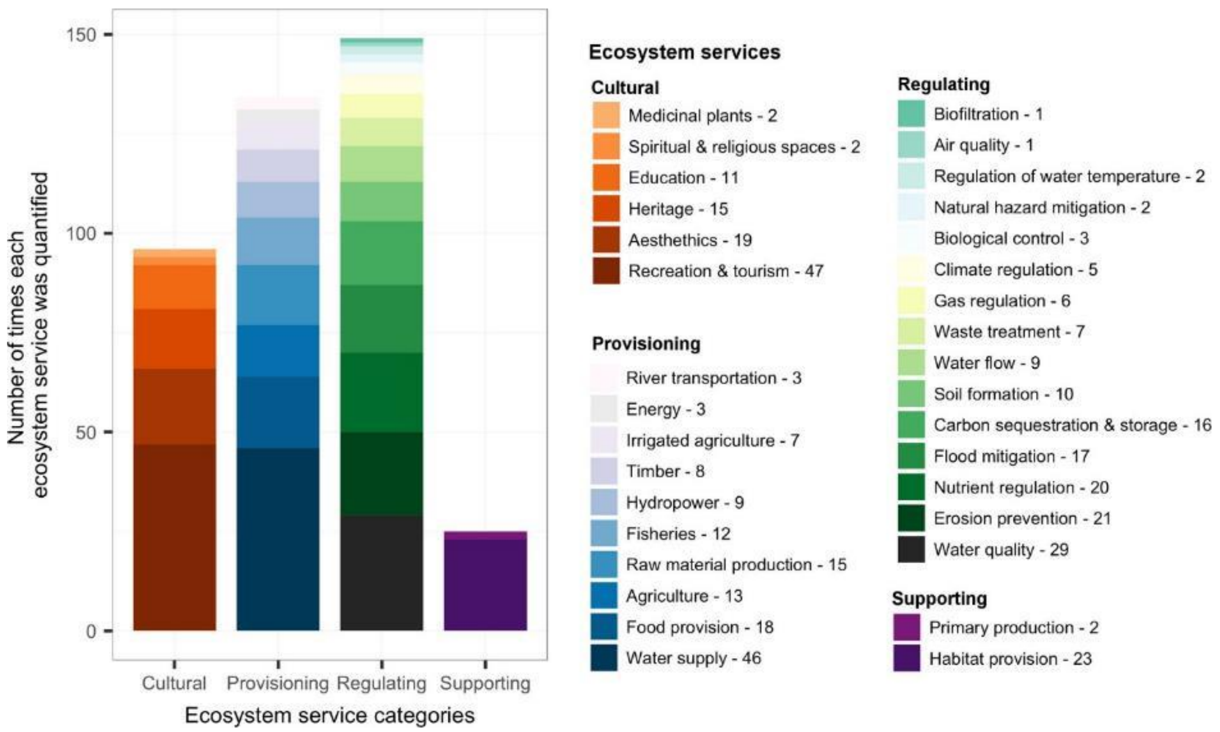


Figure 2-2 "Ecosystem services evaluated among 89 reviewed studies conducted in riverine habitats. The 33 types of ecosystem services quantified are listed in the legend and followed by the number of times each of them was quantified (total of 404 unique ecosystem service quantifications across all studies). Ecosystem services are separated by over-arching ecosystem service categories, as defined in the MEA, 2005". (Source: Hanna et al., 2018)

2.3.2 Riverine ecosystem cascade model

The principle of an ecosystem service *cascade model* linking ecological and biophysical structures and processes of the ecosystems to functions, to ecosystem services and ultimately elements of well-being (Potschin and Haines-Young, 2011) has been applied to riverine ecosystems (Large and Gilvear, 2015). The Large and Gilvear (2015) methodology for reach-based river ecosystem service assessment used the GE™ platform which can be applied from source to mouth. The methodology relies on principles from the RES– (Thorp *et al*., 2006), recognising that "attributes of rivers that positively enhance heterogeneity, connectivity and fluvial dynamics within river corridors positively enhance ecosystem service provisioning". Large and Gilvear (2015) identify linkages between "(i) fluvial features, morphological measures and land cover types, (ii) ecosystem processes, (iii) ecosystem functions and (iv) ecosystem services delivered in riverine ecosystems", as outlined in Table 2-2) and "place these linkages within the wider cascade framework of Potschin and Haines-Young (2011)" as shown in Figure 2-3 (source: Large and Gilvear, 2015, p 4). In the methodology eighteen fluvial features, attributes or land classes are defined, that govern the type and level of ecosystem service, of which eight have been considered. The methodology goes onto define a system for extracting the fluvial features/attributes from remotely sensed data using the GE™ platform and then scoring them to generate a range of indices representing ecosystem service provision.

Table 2-2 "Linkages between riverscape feature/attributes or land cover type, fluvial processes and characteristics, natural ecosystem functions and ecosystem services delivered" (Source: Large and Gilvear,2015)

Riverscape feature/attribute or land cover type	Inferred fluvial processes and characteristics	Natural ecosystem functions	Ecosystem services
Sinuosity	Bar development. Outer bank erosion; pool formation; riffle formation; longer path length and reduced slope	Flow attenuation; hydraulic diversity; channel dynamism	Fisheries; flood mitigation; biodiversity
Secondary channels or braiding	Channels with variable hydraulic and substrate characteristics; usually dynamic	Refugia; hydraulic diversity; channel dynamism	Fisheries; flood mitigation; biodiversity
Tributaries	Sediment and water supply; biotic and nutrient transfer	Hydraulic diversity; channel dynamism; habitat creation	Water supply; biodiversity
Active channel complexity	Sediment erosion, transport and deposition; channel cut-off	Sediment storage; habitat heterogeneity; increased wetted perimeter	Biodiversity; fisheries
Slope	Low slopes reduce energy gradient for transfer of water, sediment and nutrients, promoting storage and biogeochemical processing; reworking of sediment in active reaches	Hydraulic diversity; channel dynamism; habitat creation; sediment storage; habitat heterogeneity; increased wetted perimeter	Flood mitigation; water quality
Valley side connectivity with river	Sediment input to the sector	Hydraulic diversity; channel dynamism; habitat creation	Biodiversity
River/river corridor width ratio	With higher ratios, increased residence time of floodwaters and associated deposition of sediment from suspension	Flood attenuation; sediment storage; hydraulic diversity; channel dynamism; habitat creation	Flood mitigation; biodiversity
Riparian/river bank woodland	Shading, allochthonous leaf litter and woody debris input	Habitat creation and hydraulic diversity; cooling of water; food source	Biodiversity; fisheries
Floodplain physical habitat mosaic	Hydromorphological heterogeneity and channel dynamism; varied land use patterns	Range of freshwater-terrestrial habitats; ecotone creation	Biodiversity; fisheries
Palaeochannels	Semi-aquatic habitats; plant and animal succession processes; sites for nutrient storage and transformation	Carbon sequestration, phosphorous uptake and denitrification; habitat heterogeneity, flow attenuation, refugia, channel dynamism	Water quality; biodiversity
Wetlands	Semi-aquatic habitats; plant and animal succession processes; enhanced nutrient cycling and storage	Carbon sequestration, phosphorous uptake and denitrification; habitat heterogeneity; flow attenuation; refugia	Water supply; water quality; biodiversity
Floodplain forest	Substrate stabilization; enhanced hydraulic roughness	Flow attenuation, enhanced nutrient cycling and storage; habitat heterogeneity	Carbon sequestration; flood mitigation; biodiversity; water quality
Floodplain lakes	Water storage; nutrient cycling	Refugia, nursery areas for fish and amphibians; habitat heterogeneity	Water supply; carbon sequestration; water quality; biodiversity; fisheries
Agriculture	Potential for increased runoff response; enhanced fine sediment input; water quality deterioration	Loss of natural land cover; hydrological alteration	Natural ecosystem services reduced with increased crop production
Woodland plantation	Substrate stabilization; enhanced hydraulic roughness	Flow attenuation; biomass increase	Timber production; flood mitigation
Urban areas	Potential for increased runoff response and water quality deterioration	Loss of natural land cover; hydrological alteration	None
Embankments	Elimination of flood inundation	Loss of natural land cover; hydrological alteration	None
Channel dynamism/ 'naturalness'	Retention of natural system dynamics	All of the above	Whole range of natural ecosystem services

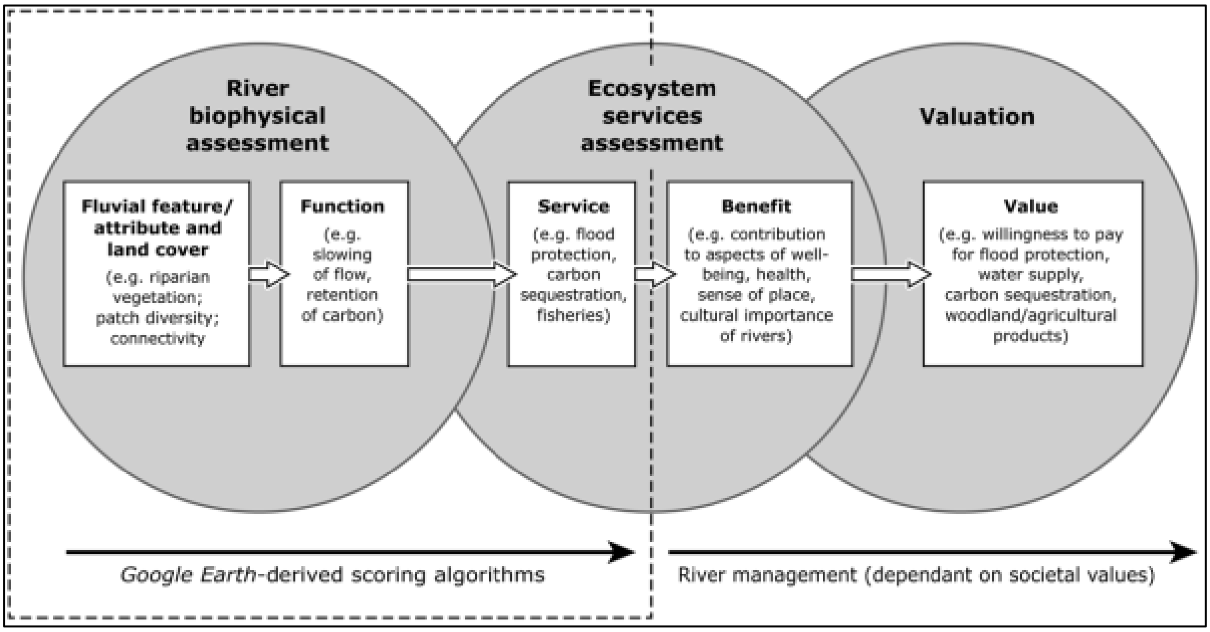


Figure 2-3 "Adaption of Potschin and Haines-Young (2011) ecosystem service cascade model illustrating its applicability to riverscapes" (Source: Large and Gilvear, 2015).

The linkages outlined in Table 2-2 are predominantly based on river science knowledge which recognises that "hydrological, geomorphological and ecological linkages and pathways of water, sediment and biogenic matter drive the relationship between river processes and physical habitat character and ecosystem services" (Thorp *et al*., 2006, 2008). For example, the fluvial attribute *active channel complexity* is a measure of the presence of bars and backwaters, which form primarily as a result of the interactions between sediment (erosion, transport, deposition) and flow resulting in greater habitat complexity to support ecological processes. Large and Gilvear (2015) recognise that human modifications, which typically simplify or reduce habitat heterogeneity, connectivity and dynamism, still offer services for example, agricultural land provides food and woodland plantations provide timber. It is also recognised that several assumptions were made about the linkages based on knowledge of river science and it is suggested that further refinement of the approach set out in Large and Gilvear (2015) should be a focus for the river science community moving forwards. Clearly then, interdisciplinary integration of ecological, hydrological and geomorphological principles, whereby the interactions amongst these form the biophysical template upon which ecosystem services are generated, is crucial for better informing the linkages set out in the form of the cascade model. This is the primary focus underpinning the research within this thesis.

2.4 Eco-hydromorphology as a basis for river ecosystem service evaluation

2.4.1 Eco-hydromorphology

As recognised in the previous section, ecology, geomorphology and hydrology are the three key scientific disciplines which support understanding of the biophysical structure and ecological condition of riverine ecosystems. Vaughan *et al* (2009) defines eco-hydromorphology as "the interactions of the biological entities and ecological processes of a river with the hydrological and geomorphological form and dynamics". The physical character of river networks provides the template upon which ecological processes operate (Fuller *et al*., 2019; DeBoer *et al*., 2020; Garcia *et al*., 2021) and thus provides a suitable basis for assessing the ecological health of a river (Maddock, 1999; Garcia *et al.*, 2021). This is of particular interest to river ecologists who wish to understand the ecological structure and function of both *natural* and *modified* riverine ecosystems (Thorp *et al*., 2006).

Durance *et al*. (2006) describes 'Eco-' as encompassing "riverine biota at all levels of organization, taxonomy and functional groupings including, ecological processes manifested in individuals through to entire ecosystems, acting over a wide range of time and spatial scales". 'Hydromorphology' encompasses the hydrological and geomorphological characteristics of a river ecosystem including flow and sediment regimes, channel and floodplain morphology, continuity and connectivity across longitudinal, lateral, vertical and temporal dimensions, (European Commission, 2000; Gilvear *et al*., 2004) as well as physical modifications imposed by humans such as weirs and bank reinforcement, to name but a couple (Vaughan *et al*., 2009).

Over the years, conceptual views of the structure and functioning of riverine ecosystem have developed from viewing the stream in its valley (Hynes, 1970), nutrient spiralling (Webster and Patten, 1979), the river continuum concept (Vannote *et al*., 1980), the flood pulse concept (Junk *et al*., 1989; Tockner *et al*., 2000) and hierarchical patch dynamics (Pringle *et al*., 1988, Townsend, 1989; Poole, 2002, 2010; Thorp *et al*., 2006, 2008; Thoms, 2006; Winemiller *et al*., 2010; Sponseller *et al*., 2013) to cite just a few. Increasing in popularity by river scientists is the concept of hierarchical patch mosaic dynamics (e.g. Poole, 2002, 2010; Thorp *et al*., 2006, 2008) which Large and Gilvear (2015) describe as "providing a useful landscape-scale framework for understanding both the broad, often discontinuous patterns along river networks and local ecological patterns across various temporal but typically smaller spatial scales".

Fluvial geomorphologists have typically focused research on the physical template of riverine ecosystems, researching their flow and sediment transport regimes and resulting channel and floodplain morphologies (Thoms, 2006). Geomorphologically, variable flows have been demonstrated to maintain the in-stream complexity of rivers. More recently, geomorphic concepts such as stream order (Horton, 1945; Strahler, 1957) which relate stream size, power and other hydrologic and geomorphic characteristics to stream position within the network, have been adapted by stream ecologist (Poole, 2010). Ecologists, on the other hand, have typically concentrated on interactions between biological communities and their physical environment as well as within community interactions. In determining biological communities and ecosystem processes, stream ecologists, focused research on the role of more local-scale patch dynamics, habitat heterogeneity and temporal variability (Junk *et al*., 1989; Ward, 1989; Thorp and Delong, 1994; Montgomery, 1999; Benda *et al*., 2004; Thorp *et al*., 2006; Winemiller *et al*., 2010), largely ignoring a network perspective of rivers and streams. However, the transportation of organisms, nutrients, organic carbon and other materials within rivers and on their floodplains is underpinned by flow variability (Thoms, 2006) across space and through time.

Effective river management in the future needs to be informed by increased understanding of eco-hydromorphological interactions within riverscapes and wider anthropogenic pressures such as climate change, altered flow regimes and increased water consumption (Vaughan *et al*., 2009), all of which will alter the movement of water and sediment and possibly biota in impacted riverine ecosystems.

2.4.2 Conceptual spatially-hierarchical frameworks

Rivers are recognised as being strongly hierarchical (Poole, 2002; Parsons & Thoms, 2007) and, as such, developing spatially hierarchical frameworks has been a focus of research to help describe the functioning of riverscapes (Gurnell *et al*., 2016). This topic has been reviewed by various authors including Naiman *et al* (1992), Kondolf *et al* (2003) and more recently Gurnell *et al* (2016). Kondolf *et al* (2003) describes hierarchical classifications as "interlocking spatial units whereby the variability of each smaller hierarchical unit is restricted by that of the higher hierarchical level".

Typically, most frameworks consider that spatio-temporal heterogeneity of riverine ecosystems is manifested as interactive pathways along four dimensions (Figure 2-4; Ward, 1989), although the temporal dimension is not included in all frameworks (Gurnell *et al*., 2016). The longitudinal dimension recognises interactions that occur in an upstream-downstream (and vice versa) direction; the lateral dimension recognises interactions that occur between the channel and the riparian / floodplain system; the vertical dimension incorporates interactions between the channel and continuous groundwaters (Hyporheic zone) and the temporal dimension recognises that rivers are continually changing in response to all the other spatial dimensions throughout time. Wohl (2017) conceptualises longitudinal, lateral and vertical dimensions as "a continuum of *river connectivity* from fully connected to disconnected over diverse temporal and spatial scales."

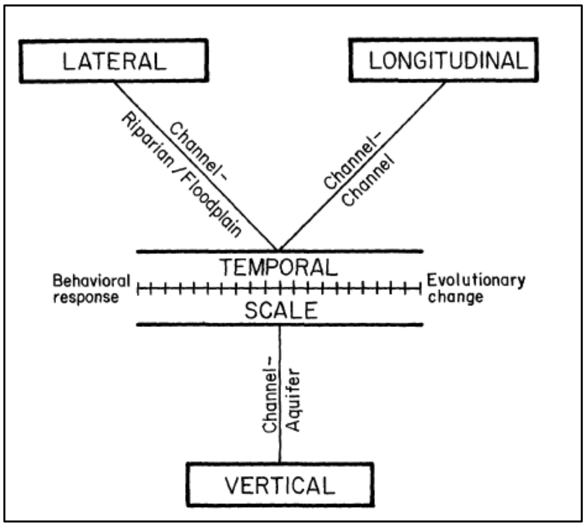


Figure 2-4 "A conceptualization of the four-dimensional nature of lotic ecosystems" (Source: Ward, 1989)

An attempt to provide conceptual cohesiveness in the field of river science, by specifically bringing together concepts and paradigms from the disciplines of landscape ecology, lotic ecology and fluvial geomorphology (Figure 2-5) was first published in 2006 in the journal of *River Research and Applications*, set out by RES (Thorp *et al*., 2006).

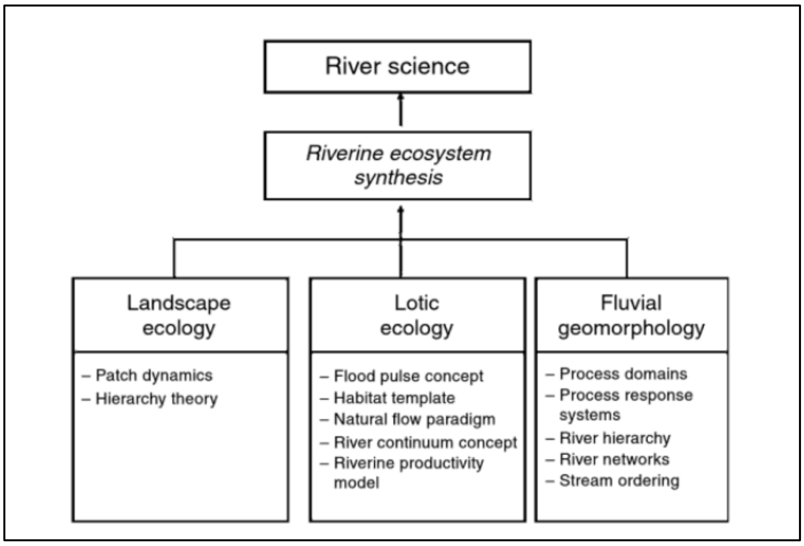


Figure 2-5 "Contribution of the Riverine Ecosystem Synthesis towards conceptual cohesiveness in the field of river science" (Source: Hughes, 2012)

Thorp *et al* (2006) describe the RES as "providing a framework for understanding both broad, often discontinuous patterns along longitudinal and lateral dimensions of river networks and local ecological patterns across various temporal and smaller spatial scales".

As described in Hughes (2012), the RES has three broad components:

> *"A fundamental, physical model describing the hierarchical patchy arrangement of riverine landscapes within longitudinal and lateral dimensions based primarily on hydrogeomorphology and emphasising a new geomorphic division (a Functional Process Zone or FPZ) between the reach and the valley scale.*
>
> *Ecological implications of the physical model in terms of an expandable set of 17 general to specific (testable) hypotheses, or model tenets, on biocomplexity which is applicable in some form to both pristine and altered riverine landscapes.*
>
> *A framework for studying, managing and rehabilitating riverine landscapes through the use of hierarchical physical model and*

aquatic applications of the terrestrially derived hierarchical patch dynamics (HPD) model (Wu and Loucks, 1975). (Hughes., 2012, p.2)"

The hierarchical physical-based organisation of the river landscape is depicted in Figure 2-6 (source: Meitzen *et al.,* 2013) demonstrating the nested elements that represent progressively finer resolution units.

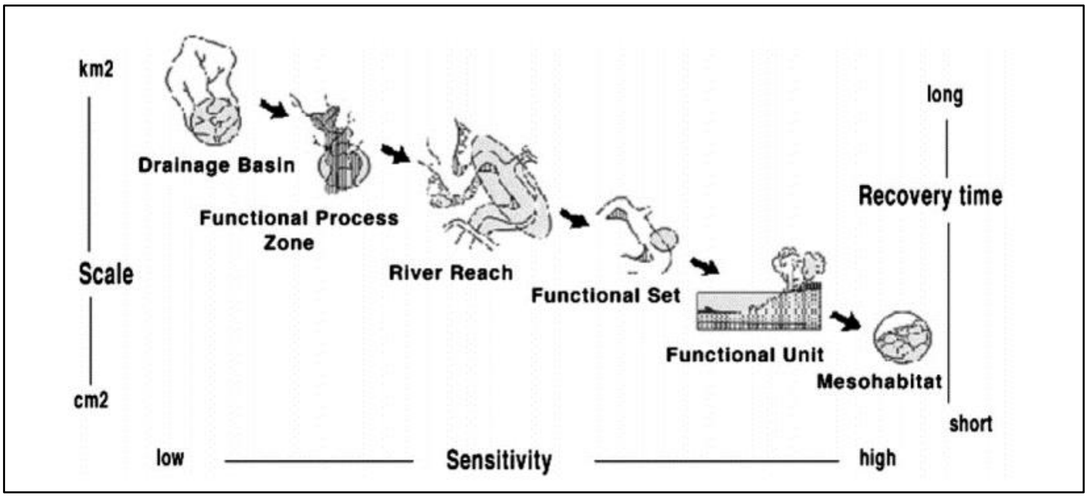


Figure 2-6 "Hierarchical physical-based organisation of a river system" (Source: Meitzen et al., 2013) ;

At the valley-to-reach scale, which is typically considered the most appropriate scale for riverine management (Thorp *et al*., 2006; Gurnell *et al*., 2016), the RES predicts that "biodiversity, system metabolism, and many other functional ecosystem processes are enhanced by habitat complexity" (Thorp *et al*., 2010). Furthermore, ecosystem service provisioning is enhanced by attributes of rivers that positively enhance heterogeneity, connectivity and fluvial dynamics (Large and Gilvear, 2015).

Despite progression in the field, the work of Frissell *et al* (1986) continues to present "one of the most comprehensive conceptual multi-scale frameworks incorporating hydromorpholgoical processes and forms and vegetation across spatial scales in relation to their influence on habitat" (Gurnell *et al*., 2016). Like those that have succeeded it, spatial units are organised hierarchically, with smaller habitat subsystems nested within larger spatial boundaries (Frissell *et al*., 1986). Within the hierarchy, spatiotemporal scales are associated with each of the tiered systems. (Figure 2-7).

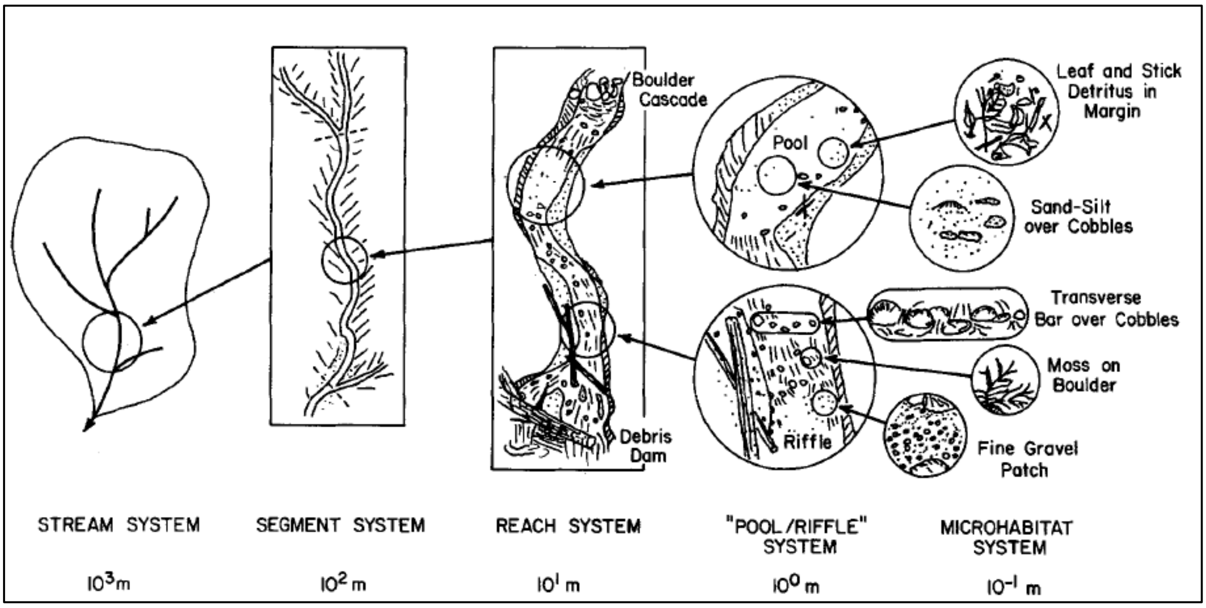


Figure 2-7 Nested hierarchy of stream habitats (Source: Frissell et al., 1986)

Another widely cited hierarchical model is that conceptualised by Montgomery and Buffington (1997, 1998) which provides a "process-based, channel typology developed for use in mountain drainage basins in the Pacific Northwest of the USA". This conceptualises a rivers morphology, defining specific channel types, in relation to the ratio of sediment supply and transport capacity (Figure 2-8). Morphological characteristics are associated with each channel type, as outlined in Figure 2-9. The concept of process domains underpins this typology whereby "spatial variability in geomorphic processes governs temporal patterns of disturbances that influence ecosystem structure and dynamics" which are ultimately linked to ecological communities (Montgomery, 1999).

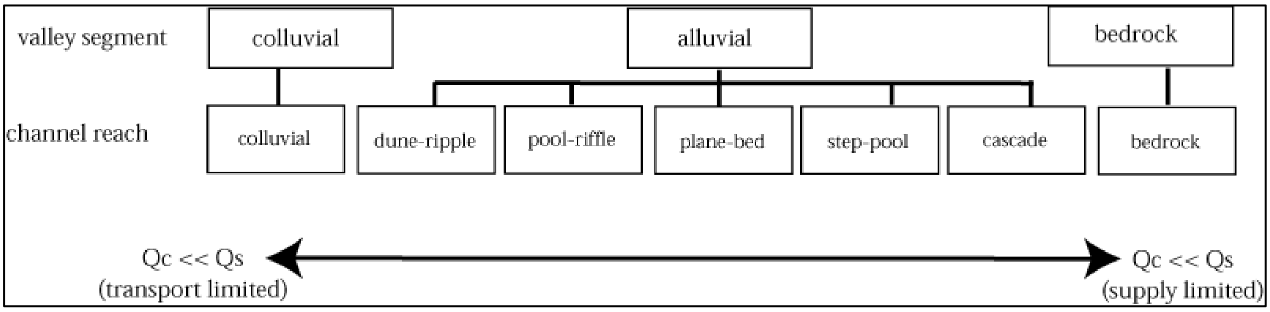


Figure 2-8 "Channel types of Montgomery and Buffington shown as a function of transport capacity to relative sediment supply" (Source: Montgomery and Buffington, 1997).

	Dune ripple	Pool riffle	Plane bed	Step pool	Cascade	Bedrock	Colluvial
Typical bed material	Sand	Gravel	Gravel-cobble	Cobble-boulder	Boulder	Rock	Variable
Bedform pattern	Multilayered	Laterally oscillatory	Featureless	Vertically oscillatory	Random	Irregular	Variable
Dominant roughness elements	Sinuosity, bedforms (dunes, ripples, bars) grains, banks	Bedforms (bars, pools), grains, sinuosity, banks	Grains, banks	Bedforms (steps, pools), grains, banks	Grains, banks	Boundaries (bed and banks)	Grains
Dominant sediment sources	Fluvial, bank failure	Fluvial, bank failure	Fluvial, bank failure, debris flows	Fluvial, hillslope, debris flows	Fluvial, hillslope, debris flows	Fluvial, hillslope, debris flows	Hillslope, debris flows
Sediment storage elements	Overbank, bedforms	Overbank, bedforms	Overbank	Bedforms	Lee and stoss sides of flow obstructions	Pockets	Bed
Typical confinement	Unconfined	Unconfined	Variable	Confined	Confined	Confined	Confined
Typical pool spacing (channel widths)	5 to 7	5 to 7	None	1 to 4	<1	Variable	Unknown

Figure 2-9 Diagnostic features of each channel type (Source: Montgomery and Buffington, 1997)

Fundamentally, spatially hierarchical frameworks based on hydromorphological principles provide a physically and ecologically meaningful basis for classifying riverine ecosystems. It has been recommended by Thorp *et al* (2010) that riverine ecosystem services should be evaluated in this way.

2.4.3 Classifications used in river management

A range of classifications have been developed for management purposes, some key examples from across the globe include the *River Habitat Survey*, UK (Newson *et al*., 1998), the *morphodynamic typology*, France (Schmitt *et al*., 2007), the *Rosgen classif*ication, US (Rosgen, 1994, 1996), the *River Environment Classification*, New Zealand (Snelder and Biggs, 2002), *The River Styles* approach, Australia (Brierley and Fryirs, 2005) and the REstoring river FOR effective catchment Management framework (REFORM), Europe (Gurnell *et al*., 2016). Furthermore, classifying channel types based on geomorphic typology has been used to link reach-scale physical habitat and invertebrate assemblages in upland streams in Scotland (Milner *et al*., 2015).

An operational approach to assess the physical condition of rivers across England has recently been developed by Gurnell *et al* (2020). The approach is said to be an attempt to "bridge the gap between a *physical habitat assessment* (as defined by Belletti *et al*., 2015) and a *geomorphic condition assessment*" (as defined by Fryirs, 2015). It formed part of *Biodiversity Metric 2.0* (which has recently been superseded with an updated version, Biodiversity Metric 3.0) which provides "a habitat-based methodology for measuring and accounting for biodiversity losses and gains resulting from development or land management change at individual project sites across England".

Thirteen geomorphic river types, which can be found in England are defined within the approach (Figure 2-10), although the three multithread river types are rarely observed in England (Gurnell *et al*., 2020). Reaches are the key spatial units within the approach and assigning an *indicative river type* to each reach assessed is central to its implementation. Understanding the broad geomorphic river type has been described as providing a useful basis for understanding a rivers physical habitat and vegetation structural assemblage when functioning naturally (England and Gurnell, 2016).

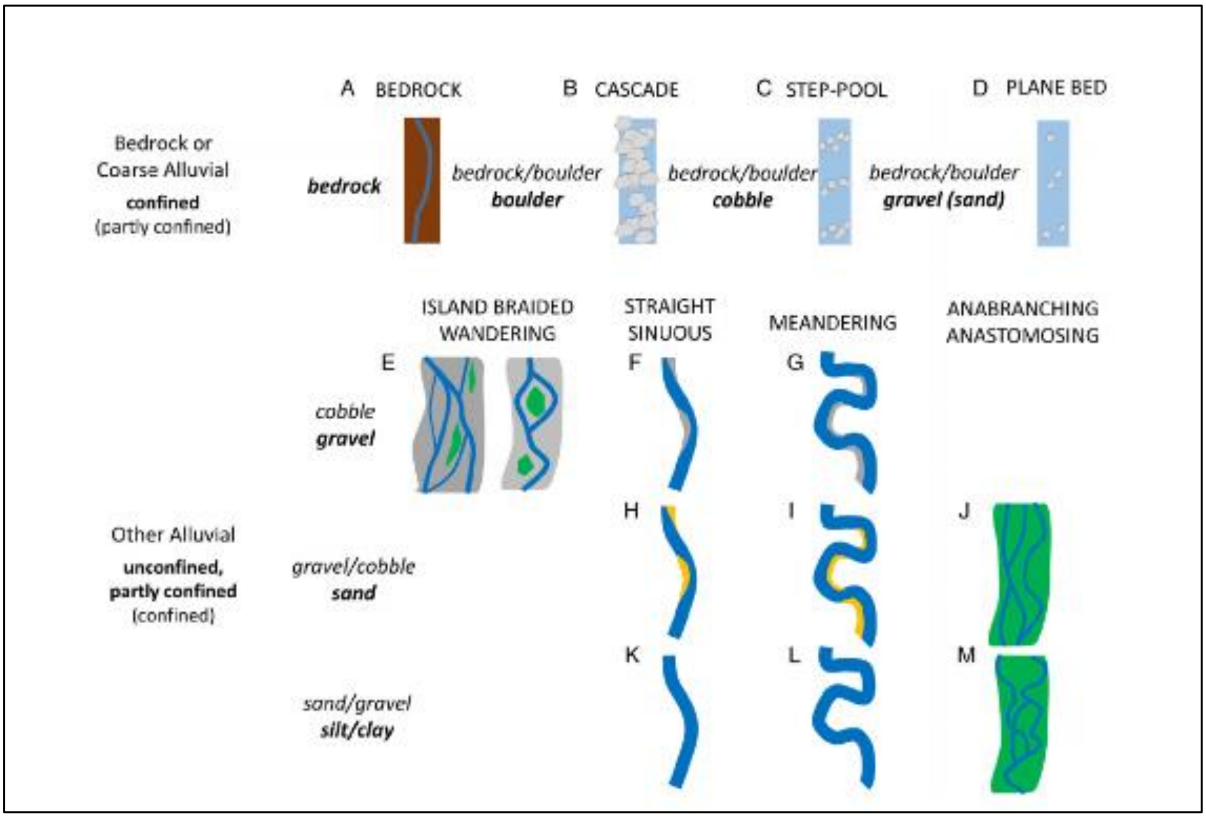


Figure 2-10 "Thirteen indicative river types (A to M) that may be found in England, reflecting their bed material, planform, and valley confinement. (Bed material size is indicated in an italic font with the most likely dominant type emboldened. The most likely level of valley confinement is emboldened)" (Source: Gurnell et al., 2020)

Gurnell *et al.* (2020) provide a *decision tree* (Figure 2-11) which is used to define an *indicative river type* to each river reach. Within the decision tree, values for a suite of indicators (A1 to A3 and A5 to A8) are used to define the indicative river type. The indicators are estimated from maps and aerial imagery (A1 – A5) or from field observations (A6 - A8) and include: A1 Braiding Index (BI); A2 Sinuosity Index (SI); B3 Anabranching Index (AI); A4 Level of confinement; A5 Valley gradient; A6 Bedrock reaches; A7 Coarsest bed material size class and A8 Average alluvial bed material size class. More information on the indicators used for identifying the indicative river type is provided as supporting information to (Gurnell *et al*., 2020). The aim of the assessment is to test whether, in its current planform, the river is showing appropriate physical characteristics and thus human interventions that may have influenced indicators A1 – A5 are not considered. This classification system is of direct relevance to the research presented in this thesis and will be adopted for classifying geomorphic river types commonly found in England.

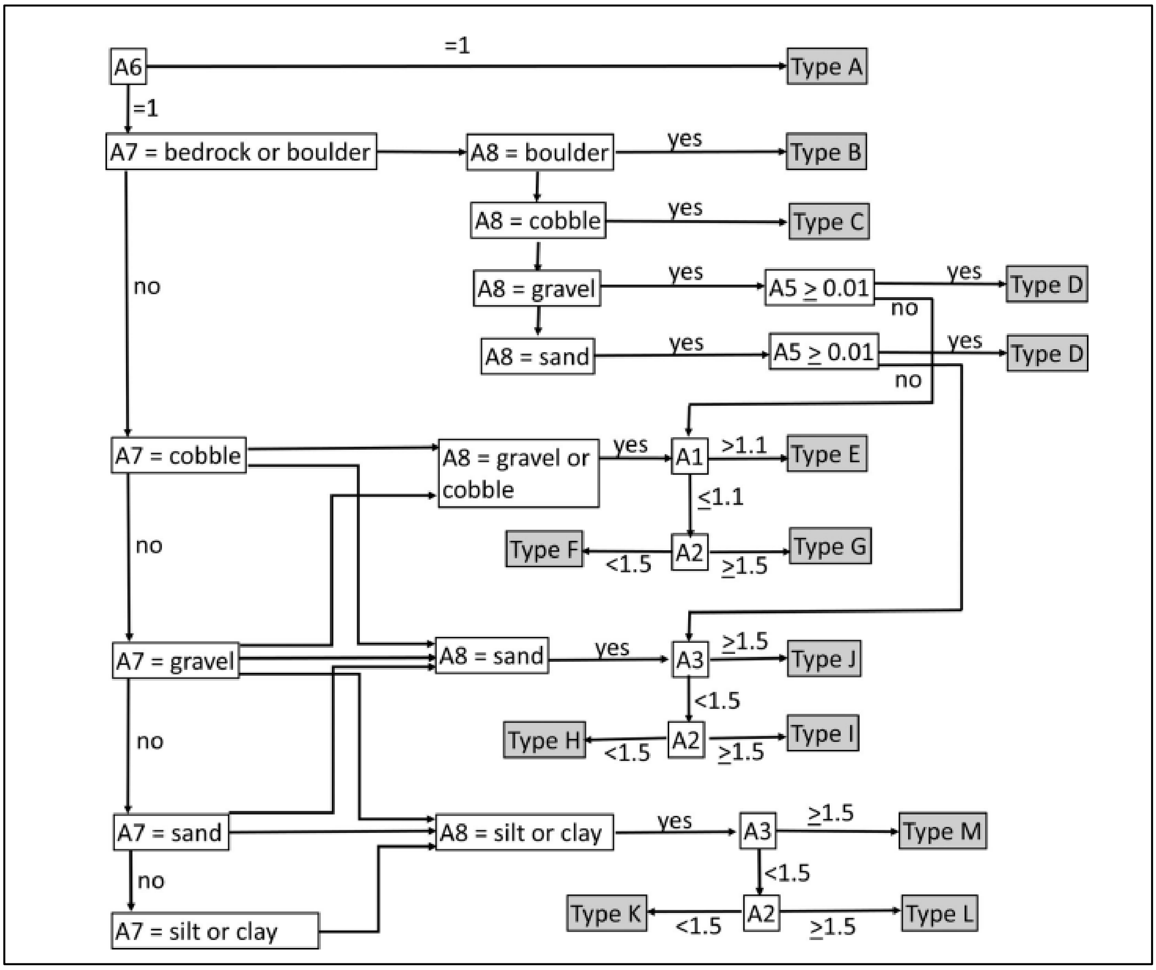


Figure 2-11 "Decision tree used to assign a reach of an English river to an indicative river type using values of indicators A1 to A3 and A5 to A8" (Source: Gurnell et al., 2020)

2.5 Summary in context of the thesis

In summary, this literature review highlights the complexity of river ecosystems and the importance of understanding both eco-hydromorphological interactions and social interactions for effective management of river ecosystem services. It highlights the need to incorporate existing frameworks and classifications of river systems within the ecosystem service concept to support sustainable river management in the Anthropocene. It highlights significant knowledge gaps including: (1) classifying and delineating attributes of river ecosystems which give rise to ecosystem services, (2) developing an evidence base upon which to link attributes of river ecosystems to ecosystem service provision, (3) evaluation of ecosystem services using geomorphic river type classifications which can provide a useful template for understanding the structure and functioning of river ecosystems and the capacity of ecosystem services under natural or modified condition, (4) developing a methodology for assessing ecosystem services across whole river networks.

3 A critical review of Large and Gilvear’s (2015) reach-based riverine ecosystem service assessment methodology

3.1 Introduction

The previous chapter reviewed the ecosystem service concept with a focus on riverine ecosystems. It stressed that riverine ecosystem services are the result of complex interactions between the geomorphic, hydrologic and ecologic processes operating across a range of spatiotemporal scales.

This chapter firstly synthesises then critiques the Large and Gilvear (2015) methodology (referred to here after as L&G2015) for riverine ecosystem service assessment. The intention of L&G2015 is to provide a robust universal reach-based ecosystem service assessment using remote sensing via GE™. It was designed to "be applicable to any ecoregion globally and to rivers of any size, degree of human modification and character" and based on a simple scoring system. L&G2015 is broadly based on concepts discussed in the RES (Thorp *et al*., 2010) whereby the "attributes of rivers that positively enhance heterogeneity, connectivity and fluvial dynamics within river corridors positively enhance ecosystem service provisioning". The methodology requires the GE™ global imaging platform, to assess riverscape features, attributes and land cover classes, linking them to the provision of individual ecosystem services. The methodology shows clear potential for such an assessment; however, the authors acknowledge there are limitations to its application and thus there is a need for testing, improvement and refinement by the river science community.

3.1.1 Aims and Objectives

The L&G2015 approach emerged at a time when ecosystem service research in the field of river science was really in its infancy. The subject is still evolving as an important field of river research and doesn't yet have an established standard. The initial development of L&G2015 was based on theoretical understanding and has only been piloted on three rivers world-wide (two in the UK and one internationally), despite it being intended to have global application and relevance. This chapter aims to critically evaluate the methodology the context of English rivers.

The specific objectives are:

1. To apply the existing desk-based methodology, using GE™, to two contrasting rivers in England
2. To critically evaluate the strengths and limitations of the methodology and review the results generated from application to the two rivers
3. To identify further research needs and opportunities for developing a bespoke riverine ecosystem service assessment methodology for application across English river networks

3.2 **Methodology**

This section synthesises the L&G2015 methodology, describing assumptions that have been made for the deployment of the methodology in this study. It then describes the two study sites and the methods for applying the approach to them.

3.2.1 Overview of L&G15

The specific objectives outlined by L&G2015 were as follows:

> *"(i) To use the Thorp et al (2006) synthesis to define the theoretical link between specified riverscape fluvial features, attributes and land cover types, natural ecosystem functions and river ecosystem service delivery.*
>
> *(ii) To place these linkages in (i) within the wider framework of Potschin and Haines-Young (2011) cascade model to assess river ecosystem service delivery from source to mouth.*
>
> *(iii) In the context of rivers, to advance the Potschin and Haines-Young (2011) model by developing a rules-based scoring approach and applying it at the reach scale from source to mouth.*
>
> *(iv) With regard to (i) to (iii), to devise a robust ecosystem service assessment tool applicable to any ecoregion and to rivers of any size.*
>
> *(v) To illustrate the robust nature of the tool by applying it to three rivers of differing character."*

3.2.1.1 Objective (i)

L&G2015 recognise that there is "a direct relationship between (i) fluvial features, morphological measures and land cover types and (ii) ecosystem processes and ecosystem services delivered". L&G2015 have theoretically linked each of their eighteen chosen riverscape features / attributes or land cover classes to a suite of eight ecosystem services (Table 3-1; source: Large and Gilvear, 2015), based on professional judgement and themes discussed in the RES (Thorp *et al*., 2006). A striking omission was the exclusion of cultural ecosystem services. It is not the aim of this research to address this however it is recognised that an attempt to rectify this has been proposed in Keele *et al* (2019).

Table 3-1 "Ecosystem services determined from river feature/attributes and land cover classes visible on Google Earth, and their division into Provisioning, Regulating and Supporting ecosystem services". (Source: Large and Gilvear, 2015)

Ecosystem Service	Fluvial features/ attributes and land cover classes																		
	Sinuosity	Secondary channels or braiding	No of tribs / confluences	Active channel complexity (bars and backwaters)	Slope	Valley side connectivity	River/river corridor ratio or floodplain / channel confinement	Riparian/river bank woodland	Floodplain physical habitat mosaic	Palaeochannels	Wetlands	Floodplain forest	Floodplain lakes	Agriculture	Woodland plantation	Urban	Embankments	Instability/ naturalness	No. of features contributing to ecosystem service
Provisioning																			
Fisheries	■	■	■	■				■				■	■					■	8
Agricultural crops														■					1
Timber															■				1
Water Supply			■								■		■					■	4
Regulating																			
Flood mitigation	■	■		■	■		■					■			■			■	8
Carbon sequestration										■	■	■	■		■			■	6
Water quality / purification					■		■			■	■	■	■					■	7
Supporting																			
Biodiversity	■	■	■	■		■	■	■	■	■	■	■	■					■	13
Number of benefiting ecosystem services	3	3	3	3	2	1	3	2	1	3	4	5	5	1	3	0	0	6	

3.2.1.2 Objective (ii)

L&G2015 place these linkages within the wider framework of Potschin and Haines-Young's (2011) *cascade model* to assess river ecosystem service delivery as outlined in Section 2.3.2; Figure 2-3 & Table 2-2.

3.2.1.3 Objective (iii)

With this as a basis for the methodology, L&G2015 address Objective (iii) by developing a rules-based scoring approach which can be applied at the reach scale from source to mouth. Methods have been developed to delineate and measure riverscape features / attributes or land cover types observable from GE^{TM}, utilising the in-built path, line and ruler functions alongside visual interpretation. Finally, they developed rules relating to assigning potential ecosystem service scores to each theoretical linkage. A summary of the delineation and scoring of each riverscape features/attributes or land cover type is given in Table 3-2 (source: Large and Gilvear, 2015). Two key metrics, the *Individual Ecosystem Service Score* (reach IESS) and the *Total Ecosystems Service Score* (reach TESS), are derived at the river reach scale from source to mouth. Scoring is on a 0–3 scale with 0 representing an absent or virtually no ecosystem service value and 3 an optimal or maximum value. These values do not have intrinsic numerical meaning (i.e. a value of 2 is not twice as much ecosystem service delivery as a value of 1) but indicate ranking which allow for areas of higher or lower ecosystem service provision to be identified. Outputs are best expressed using a score derived per kilometre of river length.

Table 3-2 "Method of delineation and measurement of riverscape features/attributes or land cover types and rules relating to attributing riverscape features/attributes or land cover types to potential ecosystem service scores" (Source: Large and Gilvear, 2015)

Riverscape features/attributes or land cover types	Observable evidence	Delineation and measurement of riverscape features/attributes or land cover types	Score			
			0	1	2	3
Sinuosity	River with bends	Use Path and Line tool to calculate Valley	Straight (1:1)	Sinuous (<1.5)	Highly sinuous (1.5–2.5) Tortuous	Tortuous (>2.5)
Secondary channels/braiding	Anabranching channels from the main channel; separated by vegetated islands and/or unvegetated bars	Delineate path length, and for top, mid and bottom of reach, sum number of active thalwegs across corridor and average to gain a value for sector	None	<2	2-3	>3
No of tributaries	River channels originating from the valley sides	Count number of rivers that actively flow onto the valley floor	None	1	2-3	>3
Active channel/hydraulic complexity	Presence of exposed bars and backwaters connected to the main channel at their downstream end	Delineate path length. For three cross-sections (top, mid and bottom of reach), sum number of bars and backwaters and average for whole reach	>3	2:1–3:1	1:1–2:1	<1:1
Slope	GE georeferenced elevation data	Use cursor elevation indicator to obtain top minus bottom altitude and divide by sector length	>2%	0.5–2%	0.1–0.5%	<0.1%
Valley side connectivity with river	River directly abuts valley side; bluffs observable	Determine extent of steep-sided slopes in proximity to channel. Use elevation cursor to define valley side	Absent–trace (<5%)	Low (6–25%)	Medium (25–50%)	High (>50%)
River/river corridor width ratio	Edges of water and exposed sediment define channel; valley side edge or steep rise in elevation above river level	Use ruler tool. Where floodplain delineation complex use elevation of cursor point as indicator	1:1	1:11–1:5	1:51–1:10	>1:10
Riparian/river bank woodland	Narrow, linear strip of textured vegetation bordering channel edges, including on islands and bars	Estimate length bordering channel	Absent–trace (<5%)	Low (6–25%)	Medium (25–50%)	High (>50%)
Floodplain physical habitat mosaic	Frequency of separately coloured patches and/or tone variability	Estimate number of separately coloured patches	Simple/uniform (mosaic absent)	Low patch variability	Moderate patch variability	Highly heterogeneous

Palaeochannels	Presence of scroll bars and linear depressions	Estimate percentage area of linear channel-like features often not containing water	Absent–trace (<5%)	Low (6–25%)	Medium (25–50%)	High (>50%)
Wetlands	Discrete usually darker tones (imagery specific)	vegetation with diffuse edges, often bordering water bodies	Absent–trace (<5%)	Low (6–25%)	Medium (25–50%)	High (>50%)
Floodplain forest	Mottled, usually darker patches of non-uniform vegetation often in proximity to water	Estimate percentage area. At high magnification, individual trees or canopy details can sometimes be seen	Absent–trace (<5%)	Low (6–25%)	Medium (25–50%)	High (>50%)
Floodplain lakes	Uniform: dark, near-black-open/clear water; turquoise-white (if ice/algae-covered); silver-white (sun-glint)	Count number of discrete open water bodies within sector	None	1-2	3-10	>10
Agriculture	Uniform vegetation/soil colour, presence of field patterns, straight drainage channels etc.	Estimate percentage area	Absent–trace (<5%)	Low (6–25%)	Medium (25–50%)	High (>50%)
Woodland plantation	Uniform textured vegetation often with straight edges	Estimate percentage area. At high magnification, individual trees or canopy details can sometimes be seen	Absent–trace (<5%)	Low (6–25%)	Medium (25–50%)	High (>50%)
Urban areas	Uniform areas of settlement, straightened boundaries, regulated reaches	Estimate percentage area	Absent–trace (<5%)	Low (6–25%)	Medium (25–50%)	High (>50%)
Embankments / clearly incised	Narrow linear, clearly artificial features paralleling channel	Estimate length	Absent	Locally present	Discontinuous but extensive	Fully embanked on both sides
Channel instability/ naturalness	Absence of human influence on land cover and channel form	Presence of exposed bars, scroll meanders, multiple thalwegs, backwaters and palaeochannels	Man-made/ artificial Channel/ impounded	Highly modified/ regulated with weirs and bank protection	Channel appears natural but human modification of corridor	No human influence/ wilderness channel

3.2.1.4 Objective (iv)

Based on the (i) and (iii), L&G2015 then developed an ecosystem assessment tool, which consists of three basic steps which (a) identify, (b) extract and (c) score the eighteen riverscape features visible from GE^{TM}, to determine the type and level of ecosystem service provided on a reach-by-reach basis for a river catchment from source to mouth. The minimum reach scale recommended is 500 m, with a 10 km sector length used on the longest of the three rivers L&G2015 assess.

Data extracted for each reach is recorded in a matrix, listing the eighteen riverscape features / attributes and their corresponding reach scores derived, for each feature. Calculations of a variety of river indices are then calculated from the matrix using the summing feature in Excel. These include a *feature/attribute score*, a *sector IESS* and a *sector TESS*. Two further indices are calculated at the whole river scale, a *total individual ecosystem services score* (River TIESS) and *total ecosystem service score* (River TESS), as summarised in Table 3-3. The ecosystem service score is derived by summing individual feature/attribute scores. Each ecosystem service score is a sum of a variable number of features/attributes which are deemed to contribute to the provision of individual ecosystem services, as derived from Table 3-1 (source: Large and Gilvear, 2015). Finally, sector IESS and river IESS can be grouped into *Provisioning*, *Regulating* and *Supporting* and statistics are produced. L&G2015 did not consider cultural services within their methodology and their inclusion of *supporting services,* namely *biodiversity* is theoretically weak.

Table 3-3 Description of the various scores which are derived for the L&G2015 methodology (adapted from Large and Gilvear, 2015)

Statistic derived	*Calculation*
Feature/attribute score	Sum of scores for each feature / attribute for each sector. i.e. sum of all 18 individual feature scores for each sector. Min, max, total for river and average per km of river are calculated.
Number of benefiting ecosystem services score	Sum of the benefiting ecosystem services (max 8)
Individual ecosystem service score (**sector IESS**)	Sum of each individual feature score contributing to each ecosystem service (as devised from Table 3-1), per river sector. Scores can also be summed to provide sector category ecosystem service scores for each- Provisioning, Regulating and Supporting service type.
River total individual ecosystem services score (**River TIESS**)	Sum of each sector IESS for length of river surveyed. Also given as a %. Scores can also be summed to provide river total category ecosystem service scores for each-Provisioning, Regulating and Supporting service types.
Total ecosystem service score (**sector TESS**)	Sum of individual ecosystem service scores for surveyed length of river. This is also given per km of river
River total ecosystem service score (**river TESS**)	Sum of individual ecosystem service scores for surveyed length of river. This is also given per km of river

3.2.1.5 Objective (v)

Finally, L&G2015 address objective (v) by applying their assessment tool to three rivers of differing land use, ecoregion and scale. These are: "the Yana River in northern Russia, selected as a large pristine river; the River Tyne in Northeast England, selected as a river impacted by industrial and urban development; and the River Allan in Scotland, selected as a river impacted by floodplain agriculture".

L&G2015 recognise that two rivers were selected from the same ecoregion (UK) but deem it appropriate given their different land uses. It is questionable whether the methodology has been appropriately tested to ensure robust results are derived, at either a local or global-level.

3.2.2 Study areas

To critically review the L&G2015 methodology, it has applied and tested on a further two contrasting river systems in England (from source to mouth), the River Lyd in

Devon and the River Wharfe, North Yorkshire (Figure 3-1). These rivers were chosen due to them encompassing differing scales, physical habitat characteristics, degrees of human modification and land use types, similar to those of the River Tyne and River Allan, as assessed by Large and Gilvear (2015). The quality and coverage of aerial GE™ imagery also differs between these two rivers. The River Lyd is an example of a small upland (low order) river (around 30 km^2 catchment area) predominantly controlled by a boulder/cobble bed morphology over a much shorter length and with a much smaller catchment area than that of the River Wharfe. The River Wharfe has a catchment area over four times greater than that of the River Lyd. The River Wharfe is a good example of a gravel-bed river displaying both upland and lowland riverine features in close juxtaposition as well as a glacial legacy, in the North of England. It has a high environmental and amenity value flowing through the Yorkshire Dales National Park.

The River Lyd rises at Lyd Head by Corn Ridge, to the north of Woodcock Hill within Dartmoor National Park, at 483 m elevation. The River Lyd is a tributary of the River Tamar and extends for a length of ~25 km from headwaters to the confluence with the Tamar. In the high moor there are remains of extensive peat works to the Southeast of Lyd Head including the evocatively named Bleak House. From here, it flows in a predominantly NE to SW direction towards Lydford, where it has cut Lydford Gorge, a dramatic feature of the river Lyd designated as a Site of Special Scientific Interest (SSSI[2]). This gorge extends ~2.4 km and is the deepest gorge in South West England. Here it leaves the National Park and flows predominantly E to W through Lydford Forest to the Lifton area where it joins the River Tamar. It has a predominantly rural landscape which comprises of farmed land including, land used

[2] SSSI: https://jncc.gov.uk/our-work/guidelines-for-selection-of-sssis/ (accessed 09.12.2021)

for crops, temporary and permanent grassland, a variety of different semi-natural and natural habitats including woodland, blanket bog, heathland and mires.

The River Wharfe rises in the region of Pen Y Ghent in the Yorkshire Dales National Park as a series of steep narrow tributary channels, the principal ones of which are Oughtershaw Beck and Greenfield Beck in Langstrothdale. The headlands of the River Wharfe are at the confluence of these two Becks at 310 m elevation. The river winds its way through several towns for a length of ~120 km before joining the River Ouse near Cawood. The Wharfe has a catchment area of just over 100 km^2. Many reaches have environmentally sensitive designations including SSSI status, for the channel between Hubberholme and the River Skirfare confluence, and *Special Area of Conservation*[3] (SAC) / *Special Protection Area*[4] (SPA) designations across the North Pennine Moors. In addition, the river is important for several migratory fish species including Atlantic salmon (*Salmo salar*). The Upper Wharfedale river channel and floodplain are heavily influenced by both historic and contemporary management, predominantly for the purposes of flood risk and agriculture. Valencia-Avellan *et al (*2017) has reported on significant water management issues which have been identified in this catchment and include: "diffuse pollution from rural areas, flow problems associated with reservoir releases, physical modifications and natural conditions as well as the effects of historical metal mining at Hebden Beck". The study extent in which the L&G2015 methodology has been applied encompasses the Upper Wharfe and part of the Mid Wharfe to Addingham, a total extent of 50 km.

[3] SAC: https://jncc.gov.uk/our-work/special-areas-of-conservation-overview/ (accessed 09.12.2021)
[4] SPA: https://jncc.gov.uk/our-work/special-protection-areas-overview/ (accessed 09.12.2021)

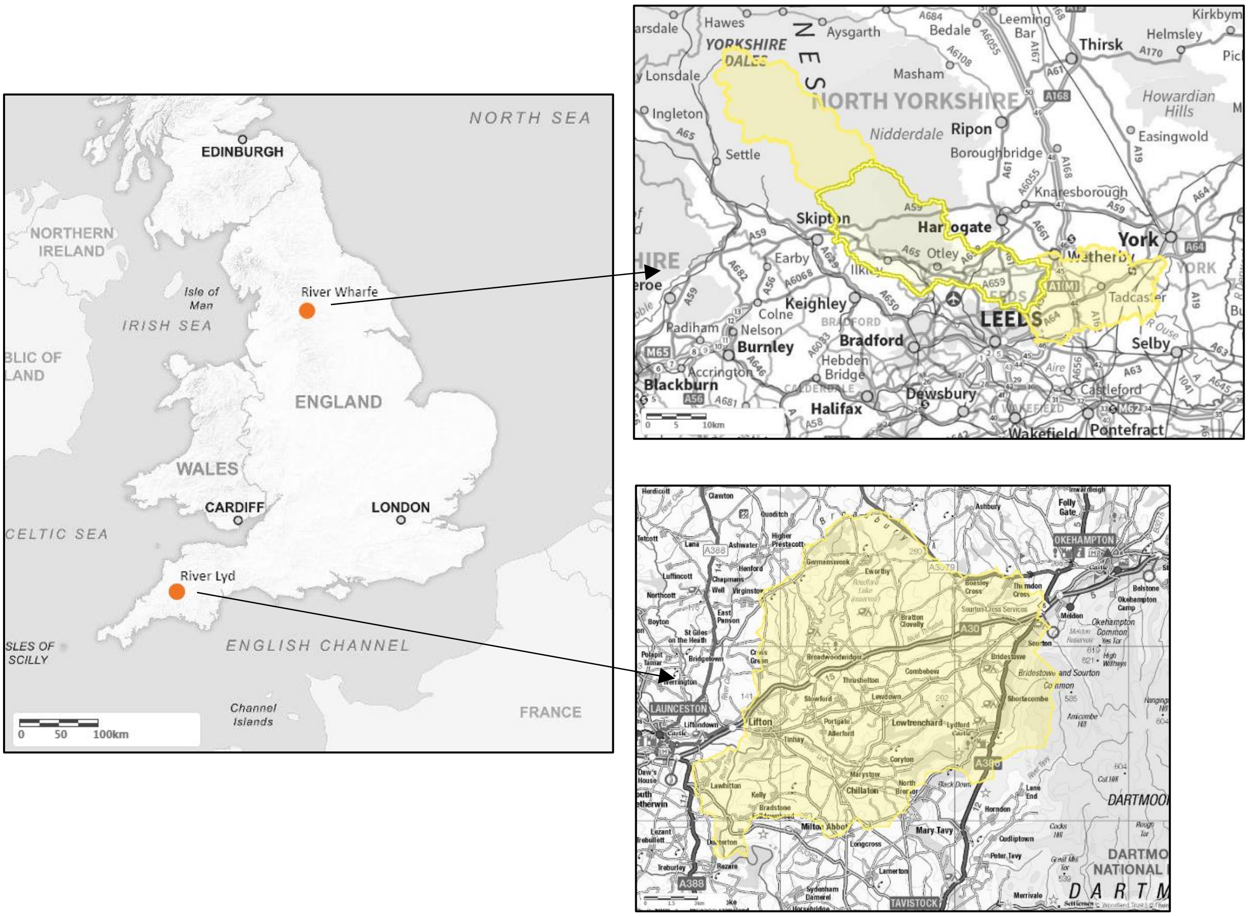


Figure 3-1 Overview map showing location of study sites in England and catchment area

3.2.3 Application of L&G15 to the two study areas

Firstly, a semi-automated approach to deriving the template needed from which to extract data was developed using the river centreline and catchment boundary[5]. These datasets were imported into ArcGIS for the chosen study sites. Statistical analysis tools were used to divide each of the river centrelines into 500m reaches. Each of these reaches (sectors) was further divided into thirds to provide an upper, middle and lower segment providing the template from which to extract data (Figure 3-2). The shapefile was converted to '.kmz' format and imported into GE^{TM}. This automated part of the approach was developed to provide a consistent and accurate

[5] Data obtained from DEFRA data services platform: https://environment.data.gov.uk/ (accessed 10.03.2018)

way of deriving a template, which could be applied to the entire dataset covering all English rivers, in a matter of minutes.

Figure 3-2: Screengrab showing centreline (yellow) and sub divisions perpendicular to the centreline (red) of reach 15 on the River Lyd, extracted from GE™. White dots delineate the start and finish of the reach (Source: Google Earth™).

The River Wharfe was divided into one hundred, 500m reaches (sectors) and the River Lyd was divided into forty-four, 500m reaches (sectors) to test the L&G2015 approach in detail. For each riverscape feature / attribute or land cover class, raw data was collected for each river reach and recorded using a Microsoft Excel spreadsheet, containing the formulae to generate scores based on the scoring criteria outlined in Table 3-2. A variety of river indices were then determined from the spreadsheet using the summing feature. These include a *feature / attribute score*, a sector IESS and a sector TESS. Two further indices were then calculated at the whole river scale, a River TIESS and River TESS (based on the methods described in Table 3-3).

3.3 **Results**

The results herein follow the presentation of results as given in L&G2015. Results are presented both in tables and Figures. Summary statistics are given in Table 3-4. As per the L&G2015 methodology, these essentially "quantify the ecosystem service value for individual ecosystem services and in totality for the whole river length surveyed. Because reach/sector length varies on rivers of differing size, for true cross river comparison, total river scores need to be calculated per river kilometre". Table 3-5 expresses the sector IESS data as a percentage contribution for each river, based on the equal weighting assumption of the methodology. It similarly shows the percentage contribution of the river lengths of the three rivers in terms of *Provisioning*, *Regulating* and *Supporting* services.

Table 3-4 "Summary statistics for reach/sector survey output, riverscape feature/attributes and total ecosystem services scores (TESS) for the two rivers surveyed using the ecosystem service assessment tool developed by L&G15 [1] Values not directly comparable between rivers because of differing sector lengths".

Summary statistics		River Wharfe	River Lyd
Surveyed length of river (km)		49.5	22
Number of reaches / sectors		100	44
Reach / sector length (km)		.5	.5
Feature score (range over surveyed length	Min	15	15
	Max	23	23
Total feature score per river length (and per km)		1891 (37.8)	830 (33)
ES score (range over surveyed length	Min	22	25
	Max	51	46
Total ecosystem score (for surveyed length of river)[1]		3724	1797
Total ES score (TESS) per river km		75.2	81.6

Table 3-5 "Summary statistics for individual ecosystem service scores and Provisioning, Regulating and Supporting services at the river scale (river IESS - individual ecosystem service score.). Values are expressed as percentage contributions for the two rivers surveyed using the ecosystem service assessment tool".

Ecosystem service	River Lyd	River Wharfe
Fisheries (P)	13.2	15.5
Water Supply [P]	1.1	1.3
Flood mitigation [R]	21.3	24.0
Carbon Sequestration [R]	4.1	2.0
Biodiversity [C]	31.0	29.6
Water quality [R]	23.0	19.9
Timber [P]	0.5	0.1
Agricultural crops [P]	5.8	7.6
Total	100.0	100.0
Categories		
Provisioning services	21	24
Regulating services	48	46
Supporting services	31	30

Downstream patterns and sector IESS for each of the two rivers are also presented graphically in Figure 3-3. Sector IESS and sector TESS are plotted against distance downstream. Alternatively, the data can be grouped into each ecosystem service category, *Provisioning*, *Regulating* and *Supporting*, as shown in Figure 3-4.

Individual feature scores, sector IESS and sector TESS for both the River Lyd and River Wharfe, are given in Appendix 1.

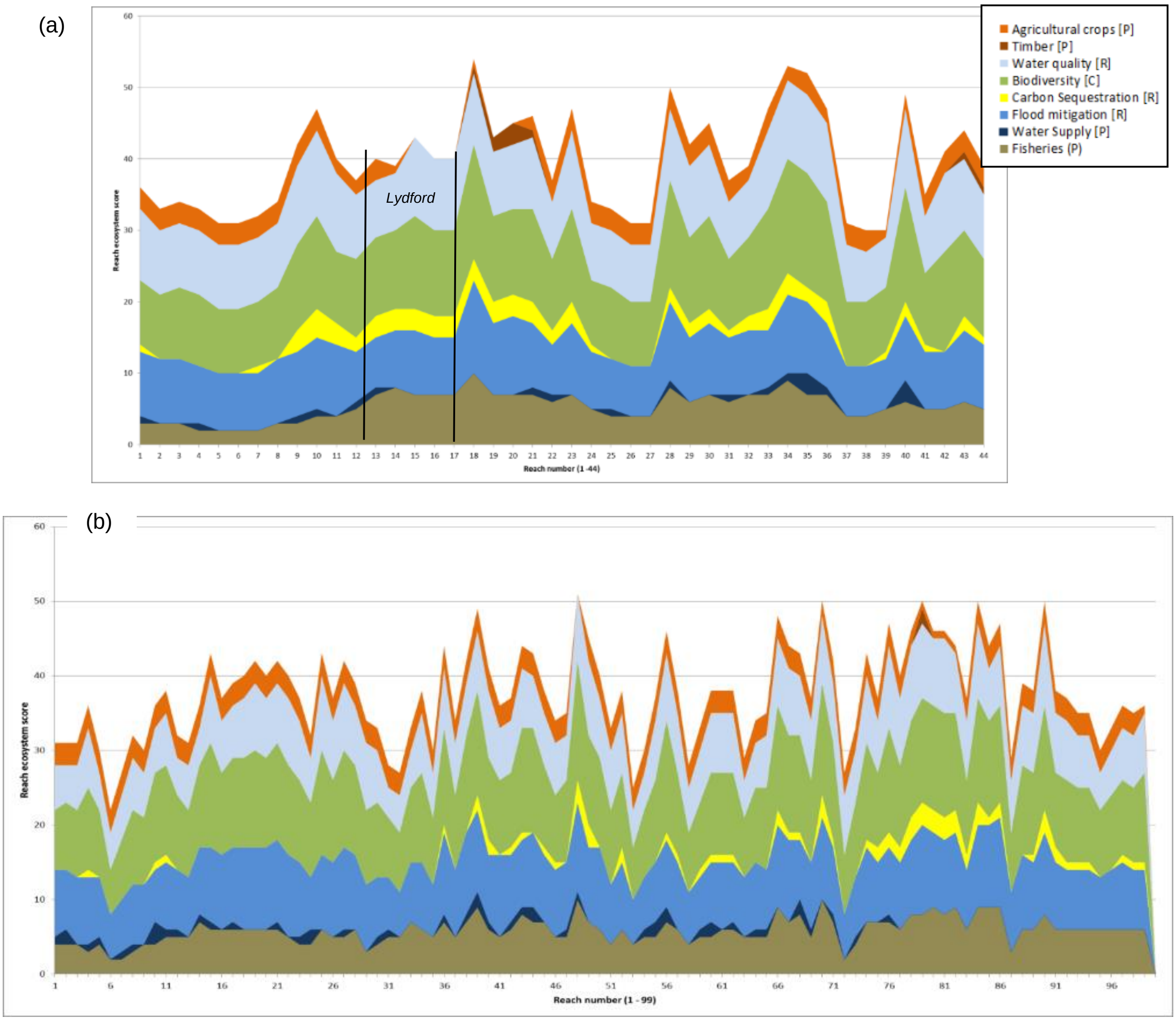


Figure 3-3. Downstream patterns in individual ecosystem service scores and total ecosystem service scores. (a) River Lyd and (b) River Wharfe

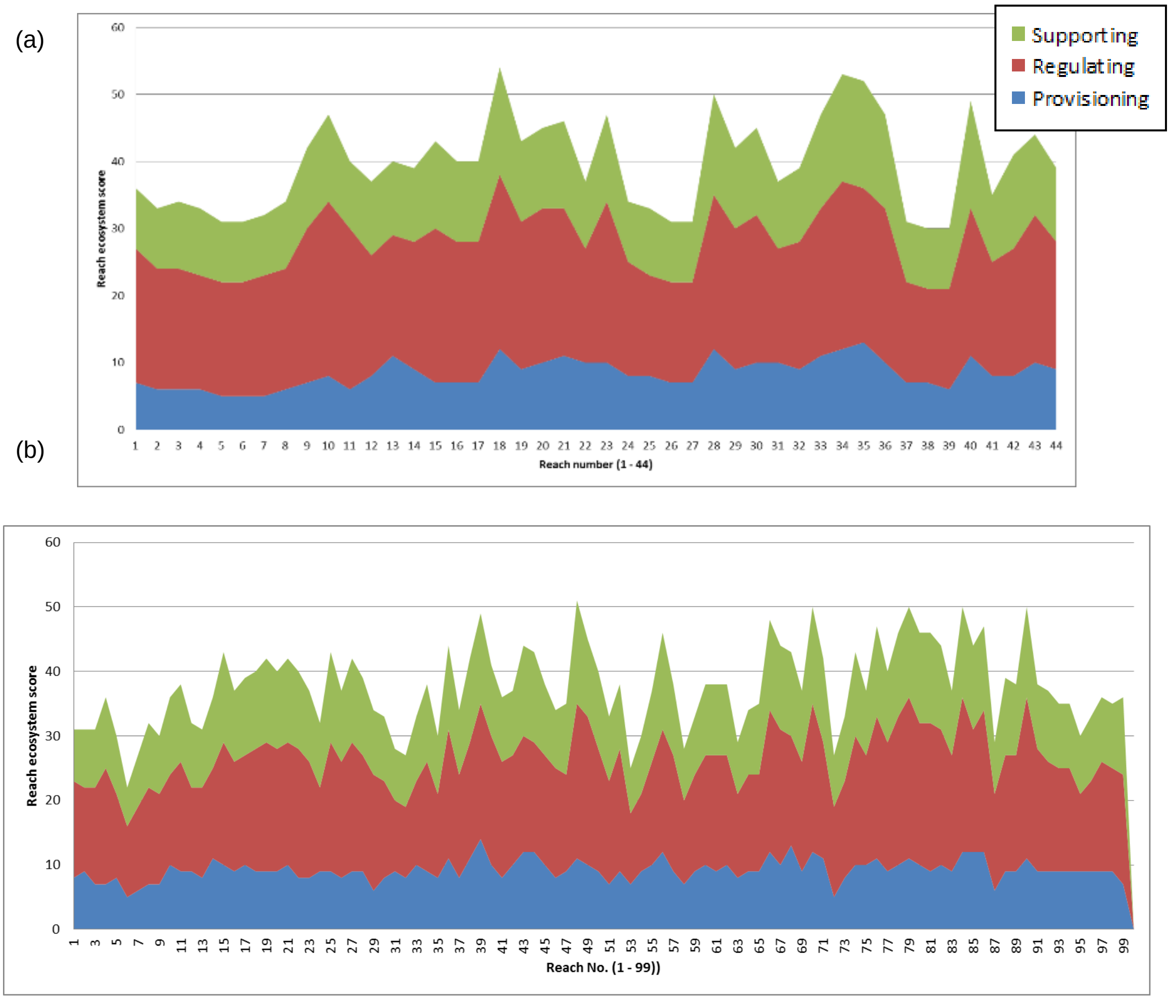


Figure 3-4. Downstream patterns in ecosystem services (ES) displayed in terms of their Provisioning, Regulating or Supporting attributes for the two rivers assessed in this study. (a) River Lyd and (b) River Wharfe.

3.3.1 River Lyd

The River Lyd is defined by TESS values of around 81 per kilometre. The TESS value ranges from 25 – 46. Figure 3-3a show the downstream patterns in sector IESS and river TESS for the River Lyd, Devon. The plot shows the individual contributions of individual ecosystem services to the total score sector by sector. It demonstrates a limited sector-to-sector scale variability but with a general pattern of higher reach IESS throughout the mid-reaches.

Lydford Gorge is a dramatic feature of the River Lyd and has been marked on Figure 3-3a to depict its location. The results obtained from applying the methodology, however, do not show the gorge to be particularly distinctive. When assessed further, it was found that the gorge features lack of prominence in the results was due to the channel being obscured for much of the gorge's length, by extensive tree cover and shading. Firstly, this highlights the fundamental uncertainty concerning the methodologies dependence upon aerial imagery using GE^{TM}, particularly with application to English rivers where tree cover is typical, and obscurity of the river is common. Throughout the River Lyd's length, 30 reaches of the 44 reaches assessed were subject to obscured in-channel visibility predominantly resulting from the presence of an extensive wooded riparian corridor and / or floodplain. This is detrimental to providing an accurate assessment of the associated reaches and is very difficult to overcome with a desk-based approach centred on remote sensing via GE^{TM}.

As a result of the channel being obscured, the observer in this case then falsely identified the presence of 'floodplain forest' along sectors of the gorge and scored it accordingly. This highlights a second issue around observer introduced error. The observer was aware that there cannot be functional floodplain within a gorge, however, due to the obscurity within aerial imagery from tree cover and limited accuracy of elevation data, this was misidentified during data collection.

3.3.2 River Wharfe

The River Wharfe is defined by TESS values of around 75 per kilometre, slightly lower than the River Lyd. TESS ranges from 22 – 51, which is slightly greater than those assessed for the River Lyd. Figure 3-3b shows the downstream patterns in sector IESS and sector TESS for the River Wharfe. The plot shows the individual contributions of individual ecosystem services to the total score sector by sector. It demonstrates a similar pattern as with the River Lyd, showing limited sector-to-sector scale variability but with generally higher ecosystem service scores throughout the mid-reaches. Summary statistics for *Provisioning*, *Regulating* and *Supporting* services at the river scale exhibit the same trend for both rivers. Regulating services score the highest, followed by supporting then provisioning services, for both rivers assessed (Table 3-5).

The ecosystem service scores along the River Wharfe fluctuate throughout the rivers length without any particularly noteworthy patterns or ‘hotspots’ in ecosystem service provision. This suggests that despite variability in reach-scale characteristics, whereby the morphology fluctuates between single thread and wandering river types, the scoring range for assigning individual features scores is too broad to reflect subtleties on rivers in England, which are relatively small on a global scale and the array of fluvial features, attributes and land cover types may be inappropriate. In contrast to the River Lyd, most of the channel is clearly visible from GE^{TM} for the length of the River Wharfe, meaning obscurity was less of an issue.

3.3.3 Comparisons

In general, the summary statistics presented in Table 3-5 for the two rivers assessed are very similar, despite the two rivers being chosen to represent differing scales, characteristics and land use cover. In order to make observations on the reasons for this, the individual feature scores, provided in Appendix 1, have been scrutinised in more detail.

The individual feature scores reveal consistently low scores for several of the individual features assessed, for both rivers . For example, the individual feature scores extracted for the *average number of secondary channels* reveals that 25 reaches out of 44 score ‘0’ (it should be noted that reaches where visibility obscures views also score a ‘0’) and 19 reaches out of the 44 score ‘1’ for the River Lyd. None of the reaches assessed score a ‘2’ or ‘3’. For the River Wharfe, the individual feature scores for *secondary channels / braiding* reveal a score of ‘1’ for every reach assessed. L&G2015 was designed to be applicable to any ecoregion, river of any scale and character and thus the rules for scoring reflect the broad variety of rivers globally. The application to these two rivers, however, indicates that the scoring of some of the features therefore may not be reflective or appropriate for rivers in England as demonstrated by consistently low scores. This supports the idea that the scoring range for some individual features is too broad and needs refinement for application to rivers in England.

Other individual features assessed, for example *active channel complexity*, show a wider distribution of scores and reveal subtle differences in the two rivers, as to be expected. The individual feature scores for the River Lyd reveal that 36 reaches out of 44 score ‘0’, 7 reaches out of the 44 score ‘1’ and 1 reach out of the 44 scored a ‘2’ for *active channel complexity*. None of the reaches assessed score a ‘3’. This is as expected given the River Lyd is a confined / partly confined river valley with limited diversity in bedforms such as bars. For the River Wharfe, a much broader range of scores were recorded with 27 out of 100 reaches scoring a 0, 28 out of 100 reaches scoring a 1, 30 out of 100 reaches scoring a 2 and 14 out of 100 reaches scoring a 3. The River Wharfe is a gravel bed river exhibiting an actively meandering and sometimes wandering planform which is thus reflected in these scores. Despite these differences being picked up in the individual feature scores, they do not translate into great differences in the ecosystem service scores (Table 3-5). It is proposed that the methodology needs to be tested on a greater range of rivers in England representing a range of characteristics and scales. Given rivers in England are typically small on a global scale and exhibit relatively low geomorphic diversity, a revised scoring system criterion may be needed to ensure the results provide meaningful information.

3.4 Evaluation of the application of L&G2015 to the Wharfe and Lyd river networks

The application of the methodology to the River Lyd and River Wharfe has highlighted strengths as well as limitations and gaps in the methodology, with a particular focus on assessing the robustness and the suitability of the methodology to English river corridors. This section is structured to evaluate each section of L&G2015 paper – Methods, Results, Discussion – highlighting the strengths and weaknesses of each section.

3.4.1 Critique of methods

3.4.1.1 Identification of linkages

L&G2015 make clear that there are three basic steps in their methodology. The initial stage is the ability to "*identify relevant riverscape-scale features or attributes and land cover classes that in turn determine the type and level of ecosystem service*." Three flaws are noted at this stage in the methodology, which challenge the validity of the approach and support the need for further refinement. These are links between fluvial features / attributes and ultimately ecosystem services are based on theoretical linkages determined though *professional judgement*; the number of ecosystem services assessed is limited to eight; and biodiversity is classified as a supporting service in its own right.

Firstly, the linkages described in Table 3-1 (reproduced from L&G2015) use the RES (Thorp et al. 2006) and the *cascade model* (Potschin and Haines- Young, 2011) as a basis to define linkages between fluvial features, attributes and land cover classes, which is itself based upon the principles that "hydrological, geomorphological and ecological linkages and pathways of water, sediment and biogenic matter drive the relationship between river processes and physical habitat character and ecosystem services" (Thorp et al., 2006, 2008). The linkages described are theoretical linkages, determined through professional judgement, and thus a research gap is identified whereby the linkages could be underpinned with a scientific evidence basis to improve the confidence and robustness of the approach.

Secondly, L&G2015 assess eight ecosystem services only, which they deemed to be appropriate to encompass the three main ecosystem service categories- *Provisioning*, *Regulating* and *Supporting.* Despite this, L&G2015 recognises that "a wide range of other services can be derived from rivers depending upon biogeographical region and river type". The recent review by Hannah *et al* (2018), quantified a total of thirty-three unique types of ecosystem services across eighty-nine studies conducted in riverine habitats (Hanna *et al.,* 2018; see Chapter 2; Section 2.3.3). A matching exercise between the thirty-three ecosystem services quantified in Hanna *et al* (2018) and the eight ecosystem services assessed in L&G2015 has been carried out (Table 3-6). The number of times each of the ecosystem services were quantified across the eighty-nine studies reviewed is also provided in brackets. Six of the eight ecosystem services from L&G2015 are directly comparable with those quantified in Hanna *et al* (2018). *Agricultural crop* (defined by L&G2015) has been assumed to be synonymous to *agriculture* and/or *irrigated agriculture* (defined in Hanna *et al.* 2018) and *biodiversity* (defined by L&G2015) has been assumed to be comparable to *habitat provision* and/or *primary production* (defined by Hanna *et al.,* 2018). As highlighted by the comparison, the ecosystem services which L&G2015 have chosen to include have been quantified most often in the review. For example, L&G2015 include *water quality*, which has been quantified twenty-nine times; *water supply*, which has been quantified forty-six times and habitat provision which has been quantified twenty-three times across the reviewed studies. Table 3-6 demonstrates that many additional ecosystem services to those assessed in L&G2015, have been quantified in the literature. With the methodology relying on GE^{TM} to identify features/attributes which contribute to ecosystem service provision in mind, additional services which are thought to be easily visible / measurable are highlighted in bold and it is recommended that they are considered further in this research.

Table 3-6 Comparison showing the thirty-three types of ecosystem services quantified from eighty-nine studies reviewed in Hanna et al (2018) and the eight ESs assessed in L&G2015. Ecosystem services are separated into categories, as defined by the MEA (2005) and ordered most to least frequently quantified.

Ecosystem services quantified in Hanna *et al* (2018). Number of times each of them was uniquely quantified is given in brackets.	Ecosystem services L&G2015
Provisioning	
Water Supply (46)	Water supply
Food provision (18)	
Agriculture (13)	Agricultural crop
Irrigated agriculture (7)	
Raw material production (15)	
Fisheries (12)	Fisheries
Hydropower (9)	
Timber (8)	Timber
Energy (3)	
River transportation (3)	
Regulating	
Water quality (29)	Water quality
Erosion prevention (21)	
Nutrient regulation (20)	
Flood mitigation (17)	Flood mitigation
Carbon sequestration & storage (16)	Carbon sequestration
Soil formation (10)	
Water flow (9)	
Waste treatment (7)	
Gas regulation (6)	
Climate regulation (5)	
Biological control (3)	
Natural hazard mitigation (2)	
Regulation of water temperature (2)	
Air quality (1)	
Biofiltration (1)	
Supporting	
Habitat provision (23)	Biodiversity
Primary production (2)	

Cultural	
Recreation & tourism (47)	
Aesthetics (19)	
Heritage (15)	
Education (11)	
Spiritual & religious spaces (2)	
Medicinal plants (2)	

Finally, despite the lack of a generally agreed upon meaning or definition for *biodiversit*y in relation to ecosystem service research (Jax and Heink, 2015), L&G2015 classifies *biodiversity* as a supporting ecosystem service and derives scores for it. The way in which the L&G2015 methodology generates an ecosystem service score for the provision of *biodiversity* is based upon scores derived from thirteen out of the eighteen fluvial features, attributes and land cover classes, observed from GE™, which in turn are based on professional judgement alone (Table 3-1). As can be seen in the summary statistics results derived for *biodiversity*, through applying the L&G2015 methodology to the River Lyd and River Wharfe (Table 3-5), the results for the two rivers are very similar, despite them being chosen to encompass differing characteristics. Based on the results derived herein and the review of *biodiversity* in other ecosystem service assessments (Section 2.3.1), it is argued that the assessment of *biodiversity* in L&G2015 is too simplistic. The research on the subject recognises that "the relationship between biodiversity, biophysical processes and the provision of ecosystem services is intricate and poorly understood" (Mace *et al.,* 2012; Adams, 2014; Harrison *et al.,* 2014; Schröter *et al.,* 2014; Balvanera *et al.,* 2014, 2016; De Groot *et al.,* 2016). Henceforth, this thesis will screen out *biodiversity* as an ecosystem service in its own right and instead will recognise that different relationships exist at different levels whereby biodiversity will be considered a nested service which can be "a regulator of fundamental ecosystem processes, a final ecosystem service itself, or a good", after Mace *et al* (2012).

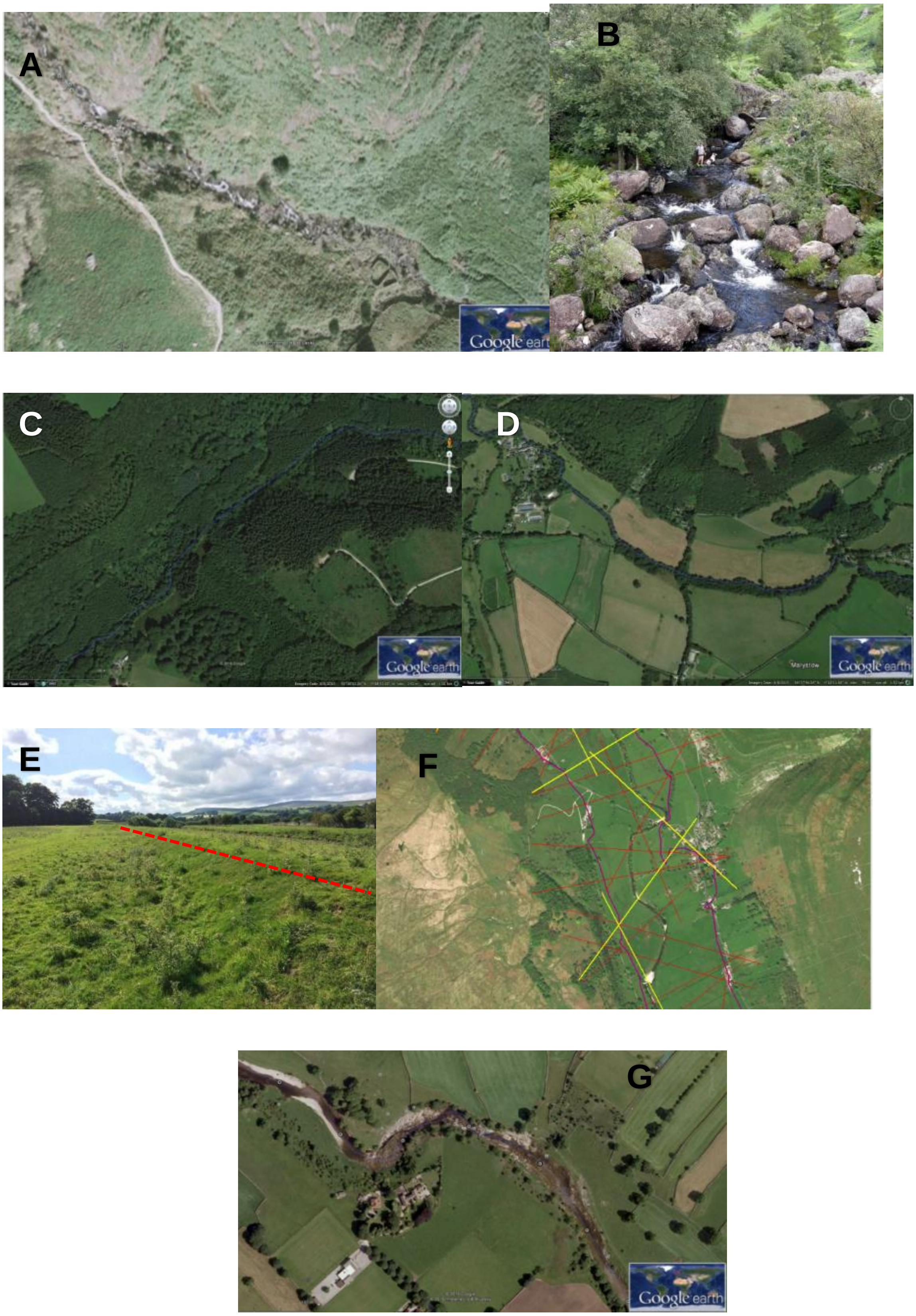
Despite this, *biodiversity*, however it is defined, is an important component of any ecosystem and should be recognised as an important driver in conservation planning and management (Jax and Heink, 2015). A similar approach has been adopted in other applications of the L&G2015 methodology whereby Keele *et al* (2019) also choose to exclude *biodiversity* as an ecosystem service, accepting that "biodiversity is a fundamentally essential component of natural systems that underpins and makes possible the provision of many of the services in all categories" (Balvanera *et al*., 2014).

3.4.1.2 Extraction of data from GE™

The second step in the L&G2015 methodology is "*to develop a method and system for extracting the riverscape features/attributes from the remotely sensed data at appropriate scales"*. Several limitations were highlighted at this stage in the methodology when applied to the two study sites. These are: visibility of key features being measured from GE™ imagery (tree canopy in particular obscuring views- Figure 3-5, C); quantification of key attributes, particularly slope (poor accuracy/low resolution vertical accuracy in GE™), double counting of key features (problematic on meandering rivers where data extraction template divisions overlap- Figure 3-5, F), the scale of the study (size of the river) and lack of validation of the extracted data through field-based survey assessment. These are discussed in more detail below.

Satellite imagery is now widely accessible to the general public through virtual globes, allowing us to explore the earth’s surface like never before (e.g. Pringle, 2010). GE™ was released in 2005 and remains the most influential virtual globe (Yu and Gong, 2012). Universally, however, satellite imagery and data quality varies, both spatially and temporally (Tooth *et al.,* 2015; Mather *et al.,* 2015). Some studies have confirmed its accuracy both spatially and in proportions and distances when compared to field data (Potere, 2008; Fisher *et al.,* 2012; Tewksbury *et al.,* 2012; Boardman, 2016). Other studies have described limitations or error relating to a variety of factors including poor spatial resolution, shadowing, warping, sensor look angle, orthorectification, obscured channel margins (due to riparian vegetation, anthropogenic augmentation, seasonal variability in leaf cover, crop patterns and cloud cover, recent flooding, etc) and user error (Marcus and Fonstad, 2008; Fisher *et al.,* 2012, 2013; Mather *et al.,* 2015; Yu and Gong, 2012; Luo et al., 2018). Figure 3-5 shows some of the issues encountered when extracting data from GE™ using the L&G2015 methodology.

Figure 3-5 Screengrabs showing some of the limitations outlined in Section 3.4. A Narrow upland channel on Stickle Ghyll, Lake District; B Georeferenced photo uploaded at the same locality as A; C Heavily wooded sector of the River Lyd (note: channel and floodplain features are not visible); D Thin riparian zone that obstructs in-channel views on the River Lyd; E Embankment visible in the field but not detectable from Google Earth, River Ure, Yorkshire Dales; F Extracting measurements in sinuous reaches (Yellow lines are derived at 500m intervals, red lines represent top, middle and bottom cross sections within each 500m reach, purple line represents 'floodplain'); G Exposed bedrock outcrop (reach 49), River Wharfe, Yorkshire



As discussed, the application of the methodology on the River Lyd highlighted issues along reaches characterised by heavily wooded tree cover, proving detrimental to providing an accurate assessment of those reaches. Marcus and Fonstad, (2008) record the most obvious optical constraint: "the stream must be visible from above". Optical remote sensing of rivers and streams cannot be done where obstacles such as trees or bridges, overhang the stream. This is described as the *no-obstruction criterion* which is particularly limiting in headwater streams, or along densely vegetated river banks, as realised on the River Lyd, Devon. This limitation is particularly difficult to overcome with a desk-based approach centred on remote sensing. Although L&G2015 promote the methodology as universally applicable, appropriate testing on small, wooded rivers and headwater streams which make up a large part of the English river network has not been undertaken. Instead, L&G2015 focused on main stem rivers and so proportionately did not include detailed analysis on smaller streams. It is therefore suggested that further testing and refinement is required to encompass a wide range of English river types (e.g. see Figure 3-5a and Figure 3-5b), in particular low order streams and rivers with confined and partially confined valleys exhibiting bedrock, cascade, step-pool and plane bed morphologies. The L&G2015 methodology has not been tested on these river types and it is anticipated that it will be unable to generate robust and reliable results for such, in its current format.

Furthermore, *embankments* are considered an important (anthropogenic) feature in the methodology, due to their impact on river – floodplain hydrological interactions and thus the provision of associated ecosystem services. However, their often-subtle nature and small scale rendered them difficult to identify and in most cases, they were undetectable from GE™ aerial imagery due to low resolution of the imagery or where they are 'camouflaged' by the surrounding land use (as noted on the River Ure, Figure 3-5e). Obscured channel margins, riparian tree cover and the scale of embankments being too small to identify using elevation data further contributed to this difficulty. This provides an opportunity to explore the utility of incorporating additional datasets which are readily available for England, such as asset datasets[6], to enhance the reliability of the methodology.

Channel slope, a key attribute in the L&G2015 assessment of riverine ecosystem services, is notoriously difficult to determine from GE™ (Thorndycraft *et al*., 2009) and is recorded as the greatest difficulty in Large and Gilvear (2015). In particular, studies have caveated that the accuracy of GE™ is not sufficiently high to enable precise quantitative measurements of geometric and topographic parameters (e.g. areas, volumes, slopes, peaks, contours, aspects, curvatures etc) (Thorndycraft *et al.,* 2009; Luo *et al.,* 2018) deeming precise measurements impossible without additional software and digital data sets (e.g. DEMs) (Tooth, 2015; Luo *et al.,* 2018). Slope measurements, extracted for the River Lyd and River Wharfe, using GE™ elevation data resulted in the slope value increasing in a downstream direction in 5 reaches out of 44 reaches and 22 reaches out of 100 reaches, respectively. Many of these reaches were in the lower parts of the catchment dominated by low relief alluvial floodplains supporting the findings of Thorndycraft *et al* (2009). L&G2015 suggests "the potential to use a free online tool for the extraction of elevation data from GE™ imagery (Zonum Solutions, 2010)" to address this issue however, chose not to apply it in their study. Similar difficulties arise when determining breaks in

[6] Available at https://environment.data.gov.uk/dataset/019a8eaa-b27f-4ae6-a9fd-e8e27cdd101a (accessed 13.12.21)

slope from a 2D to delineate the floodplain margins. To address this L&G2015 suggests the use of elevation data and oblique angle views to aid interpretation however, this was found to provide limited support in many cases in this study or proved ambiguous. This issue is amplified when combined with wooded or obscured riparian/floodplain zones. Slope information contributes to the delivery of flood mitigation and water quality in the methodology; therefore, the results for these ecosystem services have a much greater degree of uncertainty.

Another issue arose around double counting of several fluvial attributes, particularly in sinuous reaches. *River / river corridor ratio* requires measurements to be taken on the upper, middle and lower cross sections of each river reach. Measurements are taken perpendicular to the channel which, in sinuous reaches, led to overlap of the cross sections (as shown in Figure 3-5f). Therefore, there is an inherent risk of either over-estimating or under-estimating the potential for ecosystem service provision in a reach. In contrary, recording features as absent in a reach, where in fact the feature is present but is located between the upper, middle or lower cross sections, occurred on occasion for both *active channel complexity* and *secondary channels or braiding*, undervaluing the benefits from these features.

The size (length) of the river is the final challenge posed by the second step in the L&G2015 methodology. The methodology is "intended to be international in scope, equally applicable to rivers and streams of varying order of magnitude and size, and to allow whole river-length comparative assessment of differing zones or extended reaches". Large and Gilvear (2015) specify a minimum reach length of 500m to allow correlation with other indices (e.g. RHS, UK) but on large rivers broke the length down to longer reaches to make the assessment practical (up to 1500m). They acknowledge that "too coarse a scale (extent) runs a risk of missing ‘hotspots’ of dynamism or ecosystem provisioning, while too fine a scale (grain) would make any assessment cumbersome and potentially inappropriate in terms of either spatial or time scales". Rivers in England are small on a universal level, with some of the river reaches assessed here in, measuring <5m in width. In these cases, a 500m reach is too coarse a scale and inevitably misses ‘hotspots’. It is then not representative to compare this to a 500m reach of a 40m wide channel, for example. L&G2015 propose calculating a score per km to allow for comparison between rivers of differing scales. We argue that using a scale which is relative to the river being studied, for example twenty times the average channel width (Milner and Gilvear, 2012), may provide a more useful and representative measure.

3.4.1.3 Scoring system

The final stage in the L&G2015 methodology is "*to produce a matrix scoring system for assigning riverscape features/attributes to individual river ecosystem services".* They adopted an integer-based scoring system whereby 0 meant *absent* or of virtually no value to ecosystem service provision and 3 implied the *optimal* or near maximum possible potential for ecosystem service provisioning (shown in Table 3-2). L&G2015 "deliberately apply equal weighting across all eight ecosystem services assessed; but acknowledge that in reality, this becomes a societal decision depending on where elsewhere in the world the method might be applied".

The rules relating to scoring are not clearly defined for accurate replication of the methodology, which has led to several assumptions being made during this application. These assumptions are outlined in Table 3-7 and were adopted to ensure consistency in its implementation in this study. It is not clear whether the authors also encountered these issues and if so, how they overcame them when applying the methodology to their three study rivers.

Table 3-7 Summary of flaws when scoring the fluvial features/attributes and land cover classes in the methodology and assumptions made in the application of the methodology to the River Lyd and River Wharfe

Limitation / flaw	Description	Assumptions adopted in this study
Defining and scoring active channel complexity	*Active channel complexity* is defined as "the average number of bars and backwaters, which are summed from measurements taken across three cross sections". The rule for scoring specifies "a ratio of bend apices to exposed bars and backwaters". These descriptions are ambiguous.	Ratio of bend apices was ignored, instead the average number of bars / backwaters was scored based on the following: If average number of bars and backwaters is 0 score =0; if <=2 score = 1; if <=3 score =2; if >3 score = 3.
Defining and scoring *riparian woodland*	The delineation method requires the applicant to "estimate the length bordering channel", which was assumed to be in metres. The rule relating to scoring is recorded as a %.	The riparian woodland is measured using the path and line tool. Both banks summed = 100%. Scoring categories remain the same.
Defining and scoring floodplain physical habitat mosaic	*Floodplain physical habitat mosaic* is measured by "estimating the number of separately coloured patches" in a reach, assigning an integer score of 0 – 3. . The rule relating to scoring provides a descriptive score classification whereby '0 = simple/uniform (mosaic absent), 1 = low patch variability, 2 = moderate patch variability and 3 = high patch variability. There is no indication of how many (number) separately coloured patches equate to low, moderate or high.	This application adopted a scoring criterion whereby simple/uniform (mosaic absent) = 0 patches, low = 1-2 patches, moderate =3-5patches and high = >5patches.
Delineation of floodplain extent for scoring *river / river corridor ratio*	*River / river corridor ratio* delineation method states "Use ruler tool. Where floodplain delineation complex use elevation of cursor point as indicator", meaning this is reliant on elevation data. The floodplain extent generally varies throughout the length of a river reach however, the method does not state where along the reach or how many measurements should be taken and then averaged.	Three measurements of river width and three measurements for the floodplain width on each bank were recorded. These were measured at the top, middle and bottom cross sections and averaged for the reach. This was then converted into a ratio. Where river corridor / floodplain extent was difficult to distinguish, the elevation cursor was used as a guide whereby up to 1m in elevation change from the bank was used as a rule to delineate the floodplain extent.
Delineating and scoring embankments and their contribution to ecosystems service provision	The lengths of embankments are estimated numerically however, rules relating to scoring embankments are descriptive assigning 0 where embankments are 'absent', 1 where they are 'locally present', 2 where they are 'discontinuous but extensive' and 3 where they are 'fully embanked on both sides'. This demonstrates the flood mitigation service to be seen as the beneficiary as, in theory, the greater the presence of embankments means higher ecosystem service scores. However, when calculating IESS and TESS's, embankments do not contribute to their delivery so is a pointless thing to record. The reason for their inclusion is not understood.	Embankments were recorded according to the descriptive classification scores. This did not have any significance when it came to deriving ecosystem service scores as they do not contribute towards them. Using a descriptive classification can introduce subjectivity from the user's observations.
Scoring of Urban areas	'Urban areas' are assessed in the methodology but are not incorporated into deriving any ecosystem service scores. The authors do not state the reasoning for this.	While the presence of 'urban areas' is not incorporated into directly deriving ecosystem service scores, their presence means other land use classes cannot occupy the floodplain.

3.4.2 Critique of results

L&G2015 present the results in tabulated and graphical format. Summary statistics for individual ecosystem service scores and Provisioning, Regulating and Supporting services at the river scale (river IESS) are provided in a table. In addition, L&G2015 provide summary statistics for reach/sector survey output, riverscape feature/attributes and total ecosystem services scores (TESS) for the three rivers tested (as reproduced in the application to the River Lyd and River Wharfe, Table 3-5). Downstream patterns in individual ecosystem service scores and total ecosystem services scores are shown in Figure 3-3. Downstream patterns in ecosystem services (ES) displayed in terms of their Provisioning, Regulating or Supporting attributes for the three rivers assessed are shown in Figure 3-4. While the benefit of graphically representing the data provides a simplistic way to look at downstream patterns of change in ecosystems service provision, the detriment of this is the loss of finer reach by reach detail limiting the ability to interrogate the results. L&G2015 have not provided raw data for the fluvial features/attributes and land cover classes for each river reach, as extracted from GE™, to supplement the graphical data which has prevented further individual reach scale analysis to be undertaken. L&G2015 suggests that total ES score (TESS) needs to be calculated per river kilometre for true cross river comparison, as the reach/sector length can vary widely on rivers of differing scales.

3.4.2.1 Calculation of sector IESS and river TESS

Calculating sector IESS requires summing each individual feature score which contributes to the provision of each ecosystem service (as devised from the theoretical linkages shown in Table 3-1), per river sector and river TESS requires summing each individual ecosystem service scores for entire surveyed length of river (also given per km). To replicate the methodology when applying it to the River Lyd and River Wharfe, the authors of L&G2015 provided an excel spreadsheet containing the necessary formulas to derive the statistics shown in Table 3-3. A discrepancy was noted between the linkages outlined in Table 3-1 and the excel spreadsheet provided by the authors whereby different combinations of features/attributes and land cover classes were summed to generate the results provided. Table 3-8 shows a comparison between the two methods described to derive scores, whereby the individual features and attributes which are summed to derive the scores differ. Method 1 has been used to derive the scores presented in the L&G2015 paper and has been adopted to derive scores in this experimental chapter. Method 2 represents the theoretical linkages between the features/attributes and ecosystem service provision reproduced from L&G2015, shown here in Table 3-1. This discrepancy has meant that some theoretical linkages are defined in L&G2015 but are subsequently not used to calculate the results presented. The features which have been dismissed from the final step of devising the ecosystem service scores are given in red.

Table 3-8 Contribution of feature/attributes to deriving each individual ecosystem service score

		Method 1- Actual contributing features used to derive the statistics which are presented in L&G15		Method 2- Theoretical contributing features as shown in Table 3-1, reproduced from L&G15	
		Features/attributes which contribute to the score of each of the 8 ecosystem services assessed	Number of contributing features	Features/attributes which contribute to the score of each of the 8 ecosystem services assessed	Number of contributing features
Ecosystem service	Fisheries (P)	Sinuosity, secondary channels/braiding, active channel complexity, riparian/river bank woodland, floodplain forest, floodplain lakes	6	Sinuosity, secondary channels/braiding, active channel complexity, riparian/river bank woodland, floodplain forest, floodplain lakes, naturalness, no of tributaries	8
	Agricultural crops [P]	Agriculture	1	Agriculture	1
	Water Supply [P]	No of tribs, wetlands, floodplain lakes	3	No of tribs, wetlands, floodplain lakes, naturalness	4
	Timber [P]	Woodland plantation	1	Woodland plantation	1
	Flood mitigation [R]	Sinuosity, secondary channels/braiding, active channel complexity, slope, river/river corridor ratio, floodplain forest, woodland plantation	7	Sinuosity, secondary channels/braiding, active channel complexity, slope, river/river corridor ratio, floodplain forest, woodland plantation, naturalness	8
	Carbon Sequestration [R]	Palaeochannels, wetlands, floodplain forest, floodplain lakes	4	Palaeochannels, wetlands, floodplain forest, floodplain lakes, woodland plantation, naturalness	6
	Water quality [R]	Active channel complexity, river/river corridor ratio, palaeochannels, wetlands, floodplain forest, floodplain lakes, naturalness	7	Active channel complexity, river/river corridor ratio, palaeochannels, wetlands, floodplain forest, floodplain lakes, naturalness	7
	Biodiversity [S]	Sinuosity, secondary channels/braiding, no of tribs, active channel complexity, valleyside connectivity, river/river corridor ratio, riparian/bank woodland, floodplain habitat mosaic, Palaeochannels, wetlands, floodplain forest, floodplain lakes	12	Sinuosity, secondary channels/braiding, no of tribs, active channel complexity, valleyside connectivity, river/river corridor ratio, riparian/bank woodland, floodplain habitat mosaic, Palaeochannels, wetlands, floodplain forest, floodplain lakes, naturalness	13

3.4.2.2 L&G2015 case study results

L&G2015 does not specify hypotheses in regard to the application of the methodology to the three case studies, stating that the main objective of their research is to provide "a robust ecosystem service assessment tool applicable to any ecoregion and to rivers of any size, degree of human modification and character". Therefore, the application of the methodology in this chapter is not able to assess whether an individual case study provided the results the researchers expected. Rather, the focus is on implementing the methodology to the three case studies and then theoretically reviewing whether the results identify patterns in ecosystem service provision which would be expected based on the theory behind the methodology. For example, results from the assessment of the Yana River produced TESS values in the mid-catchment (sectors 47 to 65 in L&G2015 results) that are approximately three times greater than the values derived in the headwater reaches (sectors 1 to 26). L&G2015 associates this "with additional river features being associated with floodplain development (e.g. floodplain forest) in the mid-reaches and increased channel dynamism in the lateral dimension (e.g. palaeochannels and secondary channels)". They point out "a notable drop in TESS value at sector 44 which equates to a gorge section of the river. Elsewhere on the long profile, lower values are typically associated with the valley floor being constrained in width, although they acknowledge these sectors as potentially significant in terms of sediment delivery because of the presence of valley side bluffs". The results presented for the River Allan provide low scores through reaches 50 to 53 which also relate to a gorge section, as on the Yana River. L&G2015 describe low IESS's and TESS's for the most part as being "a result of human modifications to the river and floodplain. Specifically, the low TESS's centred on reach 60 (Figure 3-5c) equate with a straightened and engineered river channel with flood embankments to help provide flood protection to the town of Bridge of Allan". The results derived from applying the methodology to the River Lyd are less distinctive, despite having some similar features. For example, the River Lyd also has a distinctive gorge section between sectors 12-17, known as Lydford Gorge (Figure 3-3). Although these reaches do exhibit a small dip in TESS, it is not one which is distinct from other sectors where the channel is not confined by a bedrock gorge.

3.4.2.3 Applications to river management

Figure 3-6c and Figure 3-6d, taken from Large & Gilvear (2015) demonstrates the present-day situation for the River Allan through applying the methodology to the current baseline and a hypothetical restoration scenario, respectively. Under the current baseline, sectors 18–30 flow through an area where the floodplain is under agricultural land use with earthen flood embankments close to the river edge. This has resulted in the natural tendency of the river to meander and create cut-offs being restricted by the presence of embankments and bank reinforcement over the last two centuries. A restoration proposal for sectors 18 – 30 represents an ambition to re-meander the river Allan along this sector. This is expected to lead to a reduction in channel slope and subsequent improvement in physical habitat diversity through actions to remove or set back the flood embankments which will allow inundation of the floodplain and lateral exchanges of water and sediment. The authors stipulate that these interventions were visualized by means of photo montages of the proposed reaches, simulating reengineered sinuosity and re-introduction of riverscape features/ attributes, although these were not provided. The authors incorporate these scenarios into the excel-based matrix and the assessment tool.

The scores generated demonstrate a significant increase in TESS values, whereby baseline scores are between 2 and 15 and post-restoration scores are between 27–34, across the restored reaches. The greatest increase in IESS scores are observed for flood mitigation and water quality. Generating results by simulating a hypothetical restoration scenario are particularly useful for demonstrating and quantifying potential benefits to stakeholders e.g. landowners, river managers and planners in a way which is easily accessible and simple to visualise. .

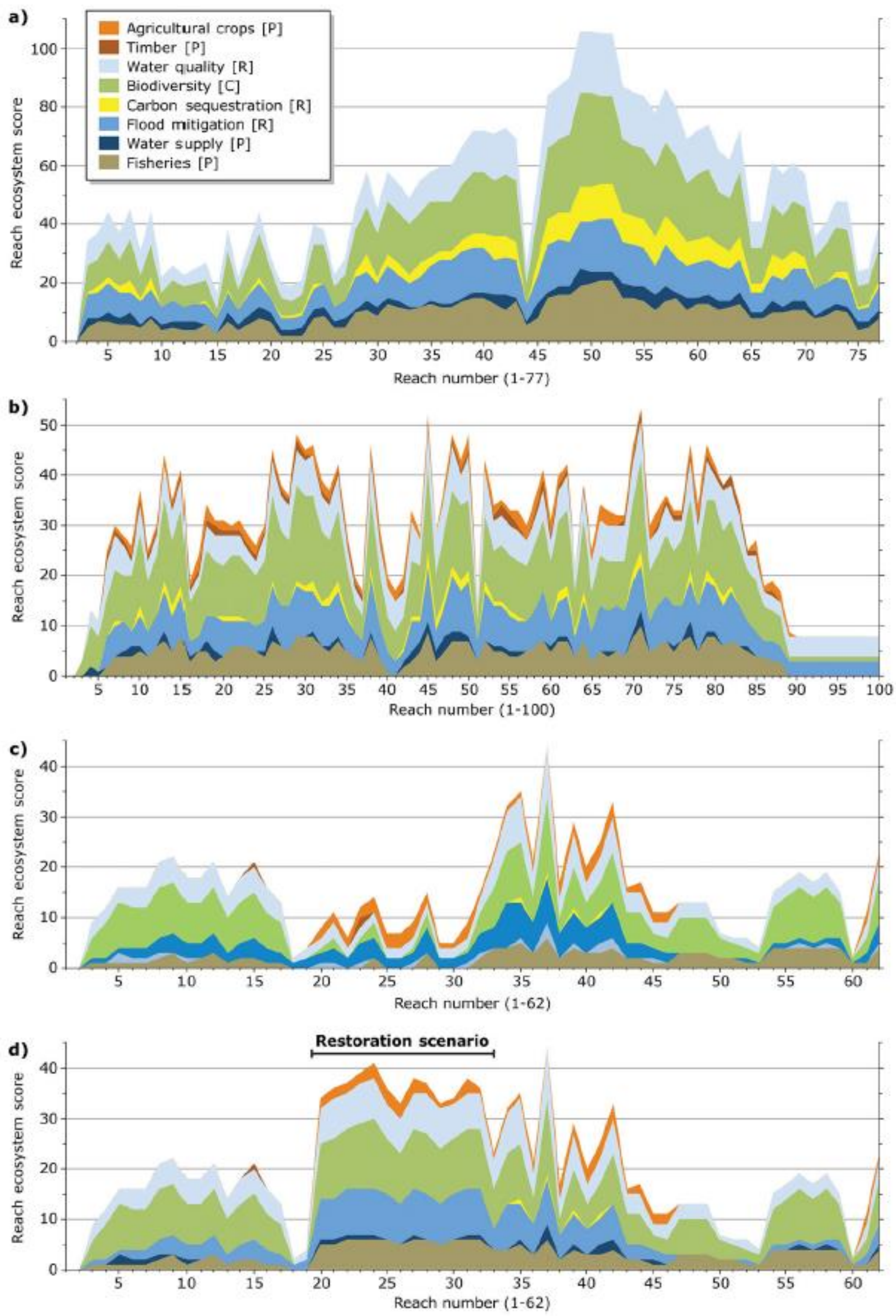


Figure 3-6 "Downstream patterns in individual ecosystem service scores and total ecosystem services scores. (a) Yana River, (b) South Tyne, (c) river Allan and (d) river Allan under a restoration scenario".

3.4.3 Critique of discussion

The discussion in L&G2015 explores the utility and appraisal of the methodology, outlines some of the limitations and challenges encountered and proposes some opportunities for further refinement. The approach is regarded as "providing a foundation upon which heuristic improvement and refinement should be a focus of the river science community" (Large and Gilvear, 2015). Further limitations have been identified through the application of the methodology and when considering its applicability to English rivers.

Some of the limitations and challenges which have been identified through the application of the methodology to the River Lyd and River Wharfe (outlined in Section 3.4.1), are acknowledged in the discussion section of the L&G2015 article. The limitations acknowledged include the acceptance that the linkages between riverscape features, attributes and land cover classes (Table 3-1) are theoretical, whereby L&G2015 propose that, "going forward, the river science community needs to strive to reduce uncertainties in the linkages". Also acknowledged is the difficulty relating to image interpretation and feature detection through the use of GE^{TM}. L&G2015 provide suggestions to aid image interpretation which include the use of elevation data and oblique angle views nevertheless; this remained a challenge when applying the methodology to the River Wharfe and the River Lyd. Channel slope was said to have caused the greatest difficulty for L&G2015, on the three original case study rivers, which was also a difficulty encountered through the application to the River Lyd and River Wharfe.

Despite acknowledging channel obscurity as an issue, L&G2015 do not discuss how they overcame it to derive ES scores. Furthermore, the authors recognise issues with slope and propose a method to facilitate the measurement of this attribute, but again, do not state how they overcame it in their study. Finally, they do not discuss the limitations around validation of the methodology.

Whilst the limitations of using GE^{TM} are acknowledged, there are also many strengths associated with visualisation tools. For example, Guralnick *et al.* (2007) and Guralnick and Hill (2009) recognise that tools like GE^{TM} can "bridge the gap between researchers and those who need most to be reached with the results of research -in particular, policymakers and the public". In addition, GE^{TM} functionality can be used to

> *"(i) highlight unintended consequences of actions in river systems (Turner and Daily, 2008), (ii) evidence shifting baselines for conservation management and restoration purposes (Papworth et al. 2009) and (iii) demonstrate opportunities to seek win–win synergies between environmental management disciplines where optimisation rather than maximization of services is the desired objective (Everard and McInnes, 2013). (Large and Gilvear., 2015)"*

3.5 **Conclusions and research needs**

The overarching aim of this research is to test and improve an existing virtual globe based river ecosystem service assessment approach that is suitable for application across English river networks. The first step in achieving this has been to critically review the existing L&G2015 riverine ecosystem service assessment methodology and identify its strengths, limitations and opportunities for improvement. This critical review of the methodology and its application to the River Lyd and River Wharfe has confirmed a number of limitations and challenges which need to be addressed in order to refine the methodology and develop it into a framework suitable for application on English rivers. Developing a 'one size fits all' methodology for application to rivers in any ecoregion, and of any size, with varying degrees of human modification and character, as L&G2015 have attempted to do, is unrealistic. Valuation (monetary or otherwise) of ecosystem services has to be reflective of where in the world it is being implemented and it has been argued that ESs are too case-specific for applying a common classification system (Burkhard *et al.* 2012; Costanza, 2008). The key recommendations and research gaps based upon the discussion in Section 3.4 are provided below. These are addressed in subsequent chapters to allow the river ecosystem service assessment methodology to be refined for application to English river corridors.

- Firstly, it is recommended that further testing of the approach, specifically focusing on low order / headwater streams and wooded river corridors in England, is undertaken as L&G2015 focus solely on mainstem rivers (addressed in Chapter 4)
- Secondly, the methods for extracting information on riverscape attributes using remote sensed data via GE^{TM} required validation and it is recommended that this is undertaken through paired analysis of desk and field-based survey (addressed in Chapter 4)

4 Further testing and validation of the use of Google Earth™ as the platform for undertaking the L&G2015 riverine ecosystem service assessment methodology on English rivers.

4.1 Introduction

Cumulatively, headwater streams constitute the great majority of channel length within a river network (Downing *et al*., 2012) and their importance in research is widely documented (Wohl, 2017). In Great Britain, headwaters are estimated to make up 70% of total stream length[7]. To develop a robust riverine ecosystem service assessment methodology that is applicable to entire river networks across England, accounting for the provision of ecosystem services in headwaters streams is vital.

The L&G2015 methodology has not yet been tested on headwater streams in England where the practical limitations associated with using the GE™ platform to undertake the assessment are anticipated to be more prevalent e.g. obscurity of riverscape attributes and image resolution. To test the utility of the methodology on headwater streams in particular and validate the use of GE™ for extracting data on riverscape attributes, the L&G2015 methodology has been applied to twenty-four river reaches, two thirds of which are headwater streams. A field data collection methodology was devised to replicate the L&G2015 desk-based methodology (see section 5.2.20) and applied to the twenty-four river reaches through field survey. The L&G2015 methods for scoring fluvial features, attributes and land cover classes and subsequently deriving a variety of river indices and ecosystem service scores has

[7] Catchment based approach Biodiversity pack: Headwaters available at: https://catchmentbasedapproach.org/learn/caba-biodiversity-pack/ Accessed: 02.02.2022

been applied to the field survey and GE™ extracted datasets. Statistical methods have then been calculated to compare the two datasets allowing for the accuracy and reliability of using remote sensing data collection via GE™, for assessing river ecosystem service provision of English rivers, to be evaluated.

Specifically, the objectives of this chapter are;

- To test the suitability of the methodology on headwater streams in England
- To specifically assess the impacts of feature obscurity where heavily wooded riparian cover is present and the issues with image resolution where stream width is small
- To validate the methods described in L&G2015 for delineating and extracting measurements of 18 fluvial features, attributes and land cover classes by comparing field datasets with GE™ datasets

4.2 **Methods**

4.2.1 Study site selection

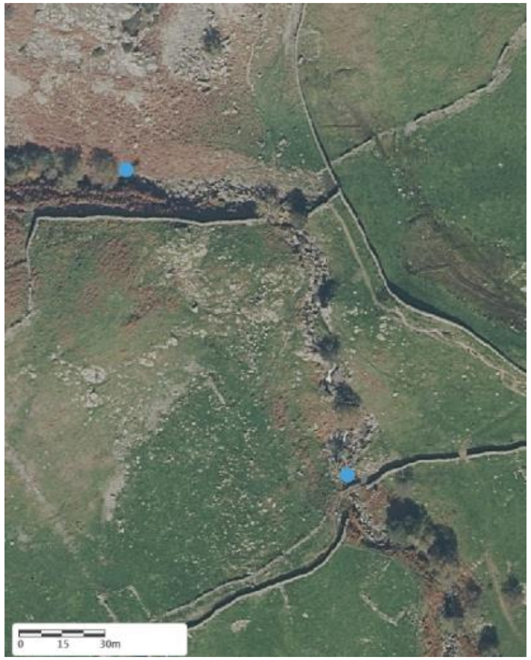
To fulfil the objectives, twenty-four study sites across England, representing a single ‘river reach’ have been selected and the field and desk-based methodology applied (see section 4.2.2.). Study sites where selected by ‘virtually navigating’ across England from an aerial perspective using the GE™ platform, which provides a quick and easy way to observe the earth’s surface. Twenty-four study sites were chosen to represent a range of scales (stream order; channel width) and a range of tree cover densities to test the boundaries of the methodology. Study sites with heavily/moderately wooded river corridors and representing small (low order[8])

[8] Strahler stream order classification

streams, typical of a large proportion of the English river network, form two-thirds of the total study sites tested. Large, main stem river reaches without heavily wooded river corridors form one-third of the total study sites selected.

To assess the impacts of feature obscurity where heavily wooded riparian cover is present and the issues with image resolution where stream width is small a Google Earth Screening Score (GESS) system has been developed and a score assigned to each study site. The GESS provides an integer-based traffic light scoring system ranging from 1 to 3, 1 representing reaches were <50% of attributes were visible; 2 representing reaches were >50%- <99% of attributes are visible and 3 representing 100%, full visibility of attributes (Table 4-1). Nine river reaches scored a GESS of 1; ten river reaches scored a GESS of 2; five river reaches scored a GESS of 3. It is predicted that the study sites assessed by L&G2015 reflected rivers scoring a GESS of ‘3’ for the majority of their length. Therefore, a greater number of study sites scoring a GESSs of ‘1’ and ‘2’ have been chosen to further test the limits and reliability of the L&G2015 methodology for application to English rivers. These predominantly represent headwater streams with a varying degree of riparian tree cover. Fewer study sites scoring a GESS score or ‘3’ and representing main stem higher order rivers were chosen for comparative purposes.

Table 4-1 Description of GESS system with example study sites representing each of the GESS's

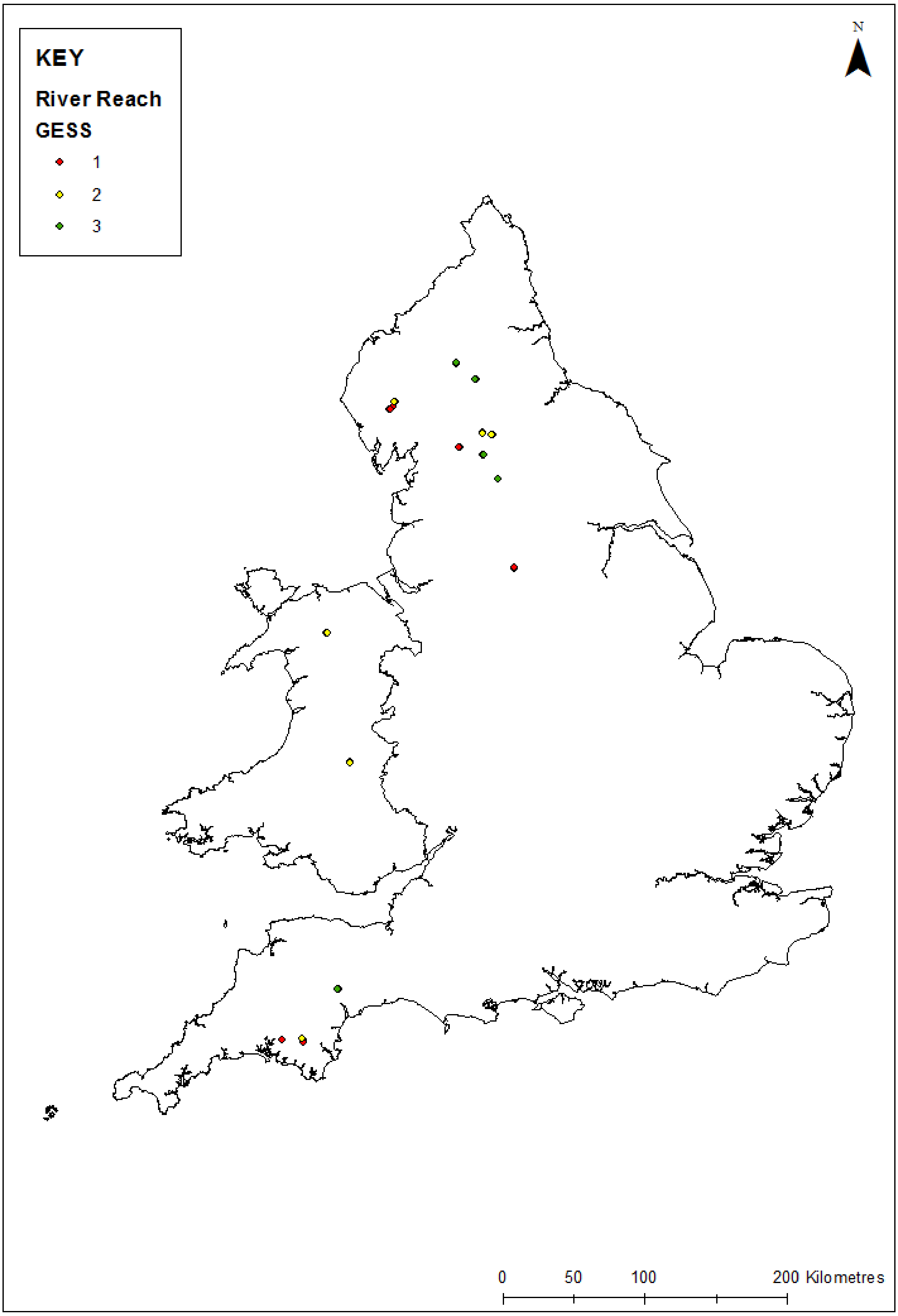
GESS	1	2	3
Description	In-channel features or floodplain features are obscured for >50% of the reach length (either due to tree cover or poor-resolution imagery)	In-channel features or floodplain features are obscured for <50% but more than 10% of the reach length (either due to tree cover, shadowing or poor-resolution imagery)	In-channel features and floodplain features are visible for the entire reach length.
Example	Reach C007, River Avon, Dartmoor Reach displays extensive tree cover, ~100% of riverscape attributes obscured by tree canopy. Average river width 11m. 	Reach C010, Dungeon Ghyll, Cumbria C010 Reach represents a 1st order stream with an average channel width of 4m. The scale of the river means image resolution is typically poor. Despite being able to see some attributes, many are difficult to measure with confidence 	Reach PR002, River Wharfe, Yorkshire Dales Reach represents a main stem river with good resolution imagery and clear visibility of riverscape attributes. Average river width 36m. 

For each of the study sites, the reach length was calculated as 20 times the average channel width (as per Milner, 2010). This has been modified from the original L&G2015 methodology which sets the reach length to a minimum of 500m. For the purpose of testing, the methodology on English rivers, a minimum reach length of 500m was considered too coarse for application to lower order streams (as supported by the findings in Chapter 3). Calculating reach length as 20 times average channel width is deemed to provide a useful scale over which to relate stream morphology to channel processes, response potential, and habitat characteristics in multiple studies (Montgomery and Buffington, 1997; Milner, 2010; Gurnell *et al*., 2016). A national grid reference (northing, easting) has been extracted from GE™ representing the start and end of each reach. Information on the twenty-four study sites, to which the L&G2015 desk-based methodology and field-based methodology has been applied, are given in Table 4-2. A map displaying the distribution of study sites throughout England is given in Figure 4-1.

Table 4-2 Study sites and associated Google Earth screening score (GESS) for all 85 sites; field data has been gathered on 24 study sites, as highlighted in bold.

Reach ID	River Name	Start x	Start y	End x	End y	Reach length	Average river width	GESS
Be001	River Tees	390148	528113	390538	527735	580	24	2
Be002	River Tees	389102	528323	389649	528255	580	34	3
Be003	River Derwent	416887	395311	416897	395171	140	5	2
Be004	River Avon	268398	63423	268223	63245	250	15	2
Be006	River South Tyne	375909	539108	375860	539265	170	6	3
Be007	River Ure	401540	488764	401914	488876	400	26	2
Be010	River Ribble / Thorn Gill	378513	480204	378423	480095	140	6	1
C004	River Plym	253835	63607	253650	63642	193	13	1
C007	River Avon	268398	62053	268507	61887	200	11	1
C009	Sourmilk Gill	331664	508905	331746	508818	120	7	1
C010	Dungeon Ghyll	329082	506579	329160	506472	160	4	1
SP002	River Plym	253544	63655	253373	63668	200	14	1
SP003	River Ribble / Thorn Gill	378158	479804	378047	479733	140	5	1
SP005	River Derwent	417013	396173	416956	396071	120	8	1
SP006	Stickle Ghyll	329215	506768	329340	506616	200	9	1
SP009	River Avon	267976	64820	268042	64701	160	9	2
SP010	Tongue Gill	333002	511843	332850	511799	160	6	2
PB003	River Wharfe	394882	474702	395107	474501	320	15	3
PR002	River Wharfe	405226	458061	405252	457512	600	36	3
PR004	Afon Conwy	284882	349548	285050	349761	300	19	2
PR006	River Ure	394368	490414	394741	490272	410	21	2
PR007	River Ure	400645	488750	401205	488696	800	37	2
PR009	River Wye	301379	258782	301328	258433	570	36	2
AM010	River Exe	292994	98948	292714	98928	490	32	3

Figure 4-1 Distribution of river reaches throughout England, displaying their GESS



4.2.2 Data collection

4.2.2.1 Desk-based L&G15 method

The L&G2015 methodology has been applied to the twenty-four study sites, with the revised river reach length calculation applied. A comprehensive summary of the L&G2015 assessment methodology is given in Section 3.2.1. Riverscape attributes which were not visible where recorded as 'NV' and subsequently given a default score of '0'.

4.2.2.2 Field-based method

For each of the fluvial features, attributes and land cover classes observed in the desk-based L&G2015 methodology, a field data collection method has been devised (Table 4-3). A field data assessment form has been developed to allow the measurements to be recorded in the field (Appendix 2).

During field data collection, the national grid reference extracted from GE™ for each of the study sites was used to locate the start and end limit of each reach. A measuring tape was then laid out along the river bank to define the exact reach length. A marker flag was inserted into the ground at the upper, middle and lower quartile, as required for measuring some of the riverscape features. Measurements for fluvial features, attributes and land cover classes were then recorded on the field data collection assessment form, according to the methods described in Table 4-3. The data is later input into an Excel spreadsheet where scores for each of the features, attributes and land cover classes, linking to ecosystem service provision are derived. A variety of river indices have been calculated as outlined in Chapter 3 Section 3.2.1. Both the desk-based data collected from GE™ and the field collected data are scored using the same methods, allowing for direct comparison of the reach scores.

Table 4-3 Field data collection methods

Riverscape feature	Field data measurements
Tributaries	Count the number of tributaries flowing into the study site along the river length
Palaeochannels	Measure the length of palaeochannels present within the study site and calculate as a % of channel length
Wetlands	Estimate % area of wetland present within floodplain
Floodplain lakes	Count the number of lakes and ponds present within the study site
Floodplain physical habitat mosaic	Estimate number of separately coloured patches (Heterogeneity?) for both banks combined otherwise risk of double counting
Sinuosity	Measure river length and valley length in the field. SI is calculated when measurements are input to excel
Slope	Using a Trupulse angle and distance measurer and two ranging poles, measure the channel slope of the river reach. For this, a ranging pole should be placed on top of the river bed at the top and bottom extent of a representative section of channel, as indicated based on the river type. For example, a pool-riffle reach should measure from riffle crest to the next riffle crest, repeating up to 3 times to get an average.
Riparian / river bank woodland	As a % of total bank length vegetated, estimate the length bordering channel (sum of both banks).
Embankments	Estimate, as a %, the approximate length of embankment present along reach length (sum of both banks)
Floodplain forest	Estimate % area of forest covering the floodplain
Woodland plantation	Estimate total % area of woodland plantation across the floodplain (right and left bank combined).
Agriculture	Estimate % area of floodplain covered by agricultural land (This includes pasture, arable etc)
Urban areas	Estimate % area of floodplain which is urban (buildings, roads etc)
River / river corridor ratio	Across the defined top middle and bottom cross sections, measure channel width (using aTrupulse or tape measure), and measure floodplain width (using a Trupulse or tape measure). This data will later be summed in excel and averaged for the reach
Secondary channels or braiding	Across the top middle and bottom cross sections, count the number of active thalwegs across the valley floor (channels separated by islands of vegetation or gravel).). This data will later be summed in excel and averaged for the reach
Active channel complexity	Across the top middle and bottom channel cross section, count the number of bars and backwaters present. This data will later be summed in excel and averaged for the reach
Channel dynamism / 'naturalness'	Observe the 'naturalness of the reach by considering degree of human influence, presence of natural features vs man-made features Circle relevant category of naturalness plus comments
Valley side connectivity	Determine extent of steep-sided slopes in proximity to channel (Visually / walking along river bank). L+G measures this a % of connectivity based on professional judgement.

4.2.3 Data processing methods / Statistical analysis

4.2.3.1 River indices

The data collected using each of the two methods, for all twenty-four study reaches is input into an Excel spreadsheet. Using the summing feature in Excel, a variety of indices was determined from the data (Table 4-4), as per the L&G2015 methodology (See section 3.2.1.4).

Table 4-4 Summary of river indices calculated for each datasets

Summary statistic	Calculation
Individual feature score **(IFS)**	Individual score for each feature derived using L&G15 rules relating to scoring (Table 3-2).
Total feature score per reach (**Reach TFS**)	Sum of scores for each feature / attribute for each reach i.e. sum of all 18 individual feature scores for each reach
Individual ecosystem service score (**Reach IESS**)	Sum of each individual feature score contributing to each ecosystem service, per river reach, based on L&G15 methods (Table 3-1).
Total ecosystem service score (**Reach TESS**)	(as per L&G15) Sum of Reach IESS per river reach.

4.2.3.2 Data comparison methods

To investigate the accuracy of the GE^{TM} dataset, the field dataset and GE^{TM} dataset have been statistically compared for the twenty-four study sites. In addition to the river indices calculated by L&G15, a simple calculation for absolute accuracy error[9] has been applied to the datasets to produce a suite of error comparison scores (methods are given in Table 4-5). Absolute Error is used to derive a value representing the difference between the *experimental value* and *true value*. The *True value* (in this case the field dataset) is compared with the *experimental value* (in this case the GE^{TM} dataset) to highlight the difference or error as follows:

[9] https://www.statisticshowto.datasciencecentral.com/absolute-error/ (accessed 27/01/2020)

Absolute accuracy error is:

$$E = x_{\text{experimental}} - X_{\text{true}}.$$

Where:

$x_{\text{experimental}}$ is the measured value (GE dataset)

X_{true} is the true value (field dataset)

Table 4-5 Statistical methods for deriving error comparison scores

Summary statistic	Calculation
Individual Feature Absolute Error score (**IFAE**)	For each of the eighteen riverscape features across the 24 river reaches validated, an absolute error has been calculated; $$\text{IFAE} = \text{Individual feature score}_{\text{GE dataset}} - \text{Individual feature score}_{\text{field dataset}}$$ IFAE score can be positive or negative. '+' scores are derived where individual feature score from field dataset is < total feature score from GE dataset '-' scores are derived where individual feature score from field dataset is > total feature score from GE dataset.
Reach total "+"feature absolute error scores (Reach **T"+" FAE**)	Sum of the positive (+) individual feature absolute error scores for all 24 river reaches. Positive scores are resultant of features being observed in GE but not in the field or to a lesser extent in the field, thus GE has over-estimated their presence. $$\text{T} + \text{FAE} = \sum ' + ' IFAE$$
Reach total "-"feature absolute error scores (Reach **T"-" FAE**)	Sum of the negative (-) individual feature absolute error scores for all 24 river reaches. Negative scores are resultant of features being observed in the field but not in GE or to a lesser extent in GE, thus GE has under-estimated their presence. $$\text{T} - \text{FAE} = \sum ' - ' IFAE$$
Individual Ecosystem Service Absolute Error (**Reach IESAE**)	For each of the Ecosystem Service categories, an individual ecosystem service absolute error score has been calculated for each of the 24 river reaches. $$\text{Reach IESAE} = \text{Reach IESS}_{\text{GE dataset}} - \text{Reach IESS}_{\text{field dataset}}$$ Reach IESAE scores can be positive or negative. '+' scores are derived where Reach IESS from field dataset is < Reach IESS from GE dataset '-' scores are derived where Reach IESS from field dataset is > Reach IESS from GE dataset.
Total Ecosystem Service Absolute Error (**Reach TESAE**)	Reach TESAE is derived from subtracting the field derived Reach TESS from the GE derived Reach TESS, for all 24 river reaches. TESAE = (GE Reach TESS – Field Reach TESS) Reach TESAE score can be positive or negative. '+' scores are derived where Reach TESS from field dataset is < Reach TESS from GE dataset

	'-' scores are derived where Reach TESS from field dataset is > Reach TESS from GE dataset.
Total '+' Individual ecosystem Service Absolute Error (Total "+" IESAE)	Sum of the positive ('+') individual ecosystem service absolute error scores for all 24 river reaches. $$\text{T"} + \text{"IESAE} = \sum +Reach\ IESAE$$
Total '-' Individual ecosystem Service Absolute Error (**Total "-" IESAE**)	Sum of the '-' individual ecosystem service absolute error scores for all 24 river reaches $$\text{T"-"ESAE} = \sum -Reach\ IESAE$$

4.3 **Results**

This section presents a summary of the key results derived from the analysis of both the field and desk-based datasets and calculation of river indices and absolute error analysis. The raw field and desk-based extracted measurements are provided in an excel spreadsheet, Appendix 2.2.

4.3.1 Individual riverscape attributes indices

Table 4-6 provides the individual feature scores derived from each of the two datasets. Riverscape attributes which were not visible (nv) when applying the desk-based methodology (due to feature obscurity/tree cover or poor resolution imagery) have been assigned a default score of ‘0’.

Individual feature absolute error scores have been calculated to highlight which riverscape attributes resulted in discrepancies between individual feature scores through applying the two data collection methods, allowing further interrogation into the underlying reasons. Individual feature absolute error scores (+/- IFAE) are presented in Table 4-7. The range of IFAE scores are between -3 and 3, for each feature.

Positive absolute error values are resultant of the features being observed and measured from GE^{TM} imagery but were not found to be present or were present to a lesser extent in the field collected dataset. This results in the GE^{TM} dataset over-estimating the individual feature scores which subsequently leads to an over-estimation of overall ES scores, compared to the field dataset. Negative absolute error values are resultant of features being observed in the field that were not observed from GE^{TM}. This results in the GE^{TM} dataset under-estimating the individual feature score and thus under-estimating overall ES scores compared to the field dataset. Table 4-8 shows the sum of +IFAE scores and sum of –IFAE scores for each of eighteen riverscape attributes to highlight which of the riverscape attributes where most frequently discrepant.

A summary table describing the reliability of the L&G15 methods for delineating individual riverscape attributes and scores for application of the assessment to English rivers, based on the results herein is provided in Table 4-9.

Table 4-6 Individual feature scores for each of the 24 river reaches showing both field measured and GE observed datasets. Features 'Not Visible' (NV) are given a default score of 0 for calculation of ecosystem service scores.

	Field(F) / Desk (D)	Study reach ID (GESS)																							
		Be001 **(2)**	Be002 **(3)**	Be003 **(2)**	Be004 **(2)**	Be006 **(3)**	Be007 **(2)**	Be010 **(1)**	C004 **(1)**	C007 **(1)**	C009 **(1)**	C010 **(1)**	SP002 **(1)**	SP003 **(1)**	SP005 **(1)**	SP006**(1)**	SP009 **(2)**	SP010 **(2)**	PB003 **(3)**	PR002 **(3)**	PR004 **(2)**	PR006 **(2)**	PR007 **(2)**	PR009 **(2)**	AM010 **(3)**
Sinuosity	F	1	1	0	1	1	1	0	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	2	2
	D	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	2	2
Secondary channels/braiding	F	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	D	1	1	1	1	1	1	1	NV	NV	NV	NV	NV	1	1	NV	1	1	1	1	1	1	1	1	1
*No of tributaries**	F	1	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	0	0	0
	D	1	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	2	1	0	0	0
Active channel/hydraulic complexity	F	1	1	0	1	1	1	0	1	1	1	1	1	0	0	1	1	0	0	1	1	1	1	1	1
	D	0	1	0	0	0	0	0	NV	NV	NV	NV	NV	0	0	NV	1	1	0	1	1	1	0	1	1
Slope	F	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	2	2	1	1	0	1	1
	D	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	2	1	2	0
Valley side connectivity with river	F	2	0	2	2	0	2	1	3	3	2	2	2	0	1	2	0	2	0	1	1	0	2	1	0
	D	0	0	0	1	0	0	0	NV	NV	0	1	NV	0	1	2	0	3	0	0	0	0	1	2	0
River/river corridor width ratio	F	1	3	3	1	3	1	3	0	0	1	1	1	0	2	1	2	1	3	3	2	3	1	1	0
	D	2	2	3	2	3	1	3	0	0	3	0	0	3	3	3	2	0	3	1	2	3	1	2	2
Riparian/river bank woodland	F	3	2	2	3	0	3	0	3	3	3	0	3	2	0	2	0	0	3	2	3	3	3	3	2
	D	3	3	1	3	0	3	2	3	3	0	1	3	2	0	2	0	0	3	2	3	1	3	3	3
Floodplain physical habitat mosaic	F	2	2	2	1	1	1	1	2	2	2	1	2	1	2	2	2	1	1	1	1	1	2	2	1
	D	2	2	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	2	1
Palaeochannels	F	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	2
	D	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wetlands	F	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	D	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
*Floodplain forest**	F	0	0	2	3	0	2	0	3	0	0	0	3	0	0	0	0	0	0	0	0	0	2	2	0
	D	1	0	0	0	0	0	0	3	2	0	0	3	0	1	0	0	0	0	1	0	0	2	2	0
Floodplain lakes	F	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	D	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Agriculture	F	0	3	0	0	3	2	3	0	0	0	0	0	3	0	0	0	0	3	3	3	3	1	3	3
	D	3	3	2	0	3	3	3	0	2	0	2	0	3	0	0	0	0	3	3	3	3	2	3	3
*Woodland plantation**	F	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	D	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
*Urban areas**	F	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	0	0	1	0	1
	D	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	1	1	0	1	1	1
*Embankments / clearly incised**	F	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	1	2	1	0	2	0	1	0
	D	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	2	0	0	1	0	2	0
Channel instability/ naturalness	F	2	2	2	2	2	2	1	3	2	2	1	2	2	2	1	0	2	1	0	1	1	1	2	1
	D	2	2	2	2	2	2	2	NV	NV	3	0	NV	2	2	NV	1	2	1	2	2	2	1	2	1
Total feature score per reach	F	14	18	18	15	14	16	11	18	17	13	8	16	10	10	11	7	8	19	18	15	15	16	20	15
	D	18	18	11	11	12	14	13	11	9	8	6	8	14	12	9	8	8	17	15	19	17	17	26	16

Table 4-7 Results showing +/-IFAE scores for each of the study sites assessed (Maximum value for each is +/- 3). (+/-IFAE score = GE dataset Individual feature score – field dataset individual feature score)

	Study reach ID **(GESS)**																							
Fluvial features / attributes	Be001 **(2)**	Be002 **(3)**	Be003 **(2)**	Be004 **(2)**	Be006 **(3)**	Be007 **(2)**	Be010 **(1)**	C004 **(1)**	C007 **(1)**	C009 **(1)**	C010 **(1)**	SP002 **(1)**	SP003 **(1)**	SP005 **(1)**	SP006**(1)**	SP009 **(2)**	SP010 **(2)**	PB003 **(3)**	PR002 **(3)**	PR004 **(2)**	PR006 **(2)**	PR007 **(2)**	PR009 **(2)**	AM010 **(3)**
Sinuosity	0	0	0	-1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Secondary channels/braiding	0	0	0	0	0	0	0	-2	-1	-1	-1	-1	0	0	-1	0	0	0	0	0	0	0	0	0
No of tributaries*	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0
Active channel/hydraulic complexity	-1	0	0	-1	-1	-1	0	-1	-1	-1	-1	-1	0	0	-1	0	1	0	0	0	0	-1	0	0
Slope	1	0	-1	0	1	0	-1	0	0	0	0	0	0	0	0	0	0	-1	-2	0	1	1	1	-1
Valley side connectivity with river	-2	0	-2	-1	0	-2	-1	-3	-2	-2	-1	-2	0	0	0	0	1	0	-1	-1	0	-1	1	0
River/river corridor width ratio	1	-1	0	1	0	0	0	0	-3	2	-1	-1	3	1	2	0	-1	0	-2	0	0	0	1	2
Riparian/river bank woodland	0	1	-1	0	0	0	2	0	0	-3	1	0	0	0	0	0	0	0	0	0	-2	0	0	1
Floodplain physical habitat mosaic	0	0	-1	0	0	0	0	-1	-1	-1	0	-1	0	0	-1	-1	0	0	0	0	0	-1	0	0
Palaeochannels	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	-2
Wetlands	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Floodplain forest*	1	0	-2	-3	0	-2	0	0	2	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0
Floodplain lakes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Agriculture	3	0	2	0	0	1	0	0	2	0	2	0	0	0	0	0	0	0	0	0	0	1	0	0
Woodland plantation*	0	0	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Urban areas*	0	-1	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	-1	0	1	0	0	1	0
Embankments / clearly incised*	0	0	0	0	-2	0	0	0	0	0	0	0	1	0	0	0	-1	0	-1	0	-1	0	1	0

Channel instability/naturalness	0	0	0	0	0	0	1	-3	-2	1	-1	-2	0	0	-1	1	0	0	2	1	1	0	0	0
Reach T+FAE	6	1	2	1	1	1	4	0	4	3	3	0	4	2	2	1	2	0	3	4	2	3	5	3
Reach T-FAE	-3	-2	-9	-6	-3	-5	-2	-10	-12	-8	-5	-8	0	0	-4	-1	-2	-2	-6	-1	-4	-3	0	-3

Table 4-8 Total positive and total negative absolute error scores for each riverscape attribute, summed for all 24 river reaches assessed.

Fluvial feature, attribute or land cover class	Sum of +IFAE score (features over-estimated from L&G15)	Sum of -IFAE score (features under-estimated from L&G15)	Total error range
Sinuosity	1	-1	2
Secondary channels/braiding	0	-7	7
No of tributaries*	2	-1	3
Active channel/hydraulic complexity	1	-11	12
Slope	5	-6	11
Valley side connectivity with river	2	-21	23
River/river corridor width ratio	11	-8	19
Riparian/river bank woodland	5	-6	11
Floodplain physical habitat mosaic	0	-8	8
Palaeochannels	0	-3	3
Wetlands	0	0	0
Floodplain forest*	5	-7	12
Floodplain lakes	1	0	1
Agriculture	11	0	11
Woodland plantation*	0	-2	2
Urban areas*	2	-3	5
Embankments / clearly incised*	2	-5	7
Channel instability/naturalness	7	-9	16

Table 4-9 Summary table describing the reliability of the L&G2015 methodology for each of the 18 fluvial features, attributes and land cover classes based on a review of the data provided in Appendix 2.2

Riverscape attribute	Description/comment on suitability of methodology (reasons) to English rivers based on datasets for the 24 study reaches	Limitation(s) resulting in error
Sinuosity	Excellent agreement between the two methods for data collection, regardless of GESS.	None
Secondary channels / braiding	Excellent agreement for reaches scoring a GESS of ‘3’ and ‘2’. Low agreement, solely due to lack of visibility on the channel, for reaches which scored a GESS of ‘1’. IFS for this riverscape attribute were consistently low (maximum of ‘1’) suggesting scoring criteria may need adjusting for application to English rivers Clarity needed in regards to scoring this attribute in upland rivers where large cluster of boulders are typical, splitting flow path	Tree cover obscuring view of riverscape attribute Clarity needed for upland rivers
No of tributaries	Excellent agreement between two datasets regardless of GESS. 23 out of 24 reaches scored the same individual feature score.	None
Active channel complexity	Low agreement for reaches scoring a GESS of ‘1’ and ‘2’, solely due to lack of visibility of the feature.IFS for this riverscape attribute were consistently low (maximum of	Tree cover obscuring view of riverscape attribute Adjustment of scoring criteria to needed for English rivers

	'1') suggesting scoring criteria may need adjusting for application to English rivers Clarity needed in regards to scoring this attribute in upland rivers where cobble 'berms' / side bars are commonly exposed under low flows.	Clarity needed for upland rivers
Slope	Low agreement regardless of GESS with some reaches resulting in negative slope values. Accuracy of GE is too coarse to enable precise measurements of geometric parameters. This issue however, wasn't always picked up in the score due to broad categories for scoring criteria	GE elevation data unsuitable for accurate slope delineation
Valleyside connectivity	Low agreement for reaches scoring a GESS of '1' and '2'. Moderate agreement for reaches scoring a GESS of '3'. Frequently under-estimated due to difficulty in observing bluffs (often obscured by tree canopy / pixelated data) in GETM and coarse resolution elevation data making it difficult to accurately define channel edge / valley edge.	Tree cover obscuring view of riverscape attribute Pixelated imagery in small, upland streams Coarse resolution elevation data
River / river corridor width	Low to moderate agreement across all GESS. Break in slope is often difficult to delineate, particularly in small low order streams and so GE elevation data is used to aid identification of floodplain width (Rule: 1m change in elevation from channel edge to valley edge). This approach often resulted in an over-estimation of floodplain width. Reaches with extensive tree cover generally resulted in an under-estimation of this attribute.	Tree cover obscuring channel and valley edge Poor resolution GE elevation data, particularly in small low order streams
Riparian / river bank woodland	Overall moderate agreement regardless of GESS. Accuracy of delineation can be subject to seasonal variability in leaf cover.	Seasonal variability
Floodplain physical habitat mosaic	Excellent agreement for reaches scoring a GESS of '3'. Moderate agreement for reaches with a GESS of '2' and '1' L&G15 scoring criteria is subjective	Seasonal variability Subjectivity of scoring criteria needs further consideration
Paleochannels	Not specific to GESS. Moderate agreement for laterally active river reaches where this feature is likely to be presentthought to be due to seasonal variability between the two datasets or anthropogenic augmentation of the land, making this feature difficult to depict.	Seasonal variability, anthropogenic augmentation of land
Wetlands	None of the reaches assessed recorded this feature.	further testing likely required
Floodplain forest	Moderate agreement regardless of GESS. Accurate delineation of feature was related to accurate delineation of floodplain extent, which in turn relies on a clear break in slope or GE elevation data being used to define break in slope (see river / river corridor width ratio). Clarity required regarding when the riparian corridor becomes a floodplain forest (numerical distance?)	Delineation of floodplain extent, poor resolution of GE elevation data
Floodplain lakes	Rare feature across study reaches	Further testing likely required? Or none

Agriculture	Excellent agreement for reaches scoring a GESS of ‘3’. Moderate agreement for reaches scoring a GESS of ‘2’ or ‘1’. Accurate delineation of feature was related to accurate delineation of floodplain extent, which in turn relies on a clear break in slope or GE elevation data being used to define break in slope.	Delineation of floodplain extent, poor resolution of GE elevation data
Woodland plantation	Excellent agreement regardless of GESS.	None
Urban areas	19 out of 24 scored the same Moderate agreement due to subjectivity in scoring criteria	Subjectivity of scoring criteria needs further consideration
Embankments / clearly incised	Moderate agreement regardless of GESS. Accurate delineation of feature was related to the prominence of the feature, whereby embankments can appear camouflaged within the surrounding landscape or the spatial resolution of the imagery is too coarse to delineate the feature using GE elevation data.	Often undetectable due to blending in with surrounding land use and coarse resolution of GE elevation data
Channel instability / ‘Naturalness’	Good agreement for reaches scoring a GESS of ‘3’ and ‘2’. Poor agreement for reaches scoring a GESS of ‘1’. Tree cover proved the main reason for poor delineation of this feature in reaches scoring a GESS of ‘1’ although it is recognised that bank modifications are often difficult to observe in GE due to the 1-d view of the river. L&G15 scoring criteria is subjective.	Tree cover obscuring channel Spatial resolution of GE imagery Subjectivity of scoring criteria needs further consideration

4.3.1.1 Over-estimation of riverscape features in GE™ (depicted by positive absolute error)

As outlined in Table 4-8, ‘river / river corridor width ratio’ was found to be the most frequently over-estimated (and 3rd most under-estimated) riverscape attribute when applying the L&G2015 desk-based methodology to the twenty-four study reaches, with eight of the twenty-four study reaches generating positive absolute error scores, totalling a score of 11 overall. This is due to desk-based GE™ floodplain width measurements being greater than the field-based measured floodplain widths.

The observable evidence for river/river corridor width ratio given in the L&G2015 method states that the "*edges of water and exposed sediment define channel; valley side edge or steep rise in elevation above river level*" define the river corridor. The method of delineation and measurement of the riverscape attribute given states "*use* *ruler tool. Where floodplain delineation complex use elevation of cursor point as indicator"*.

Despite attempting to use oblique views and elevation data available in the GE^{TM} platform to facilitate accurate desk-based data collection, error remained high. As shown in **Error! Reference source not found.**, the greatest error is associated with study reaches scoring a GESS of '3' and so it is concluded that the primary reasons for error in regards to 'river / river corridor width ratio' are associated with smaller, upland study reaches where the resolution of GE^{TM} is coarser (meaning it is difficult to accurately delineate break in slope) and the presence of heavily wooded river corridors, obscuring the valley edge/floodplain limit.

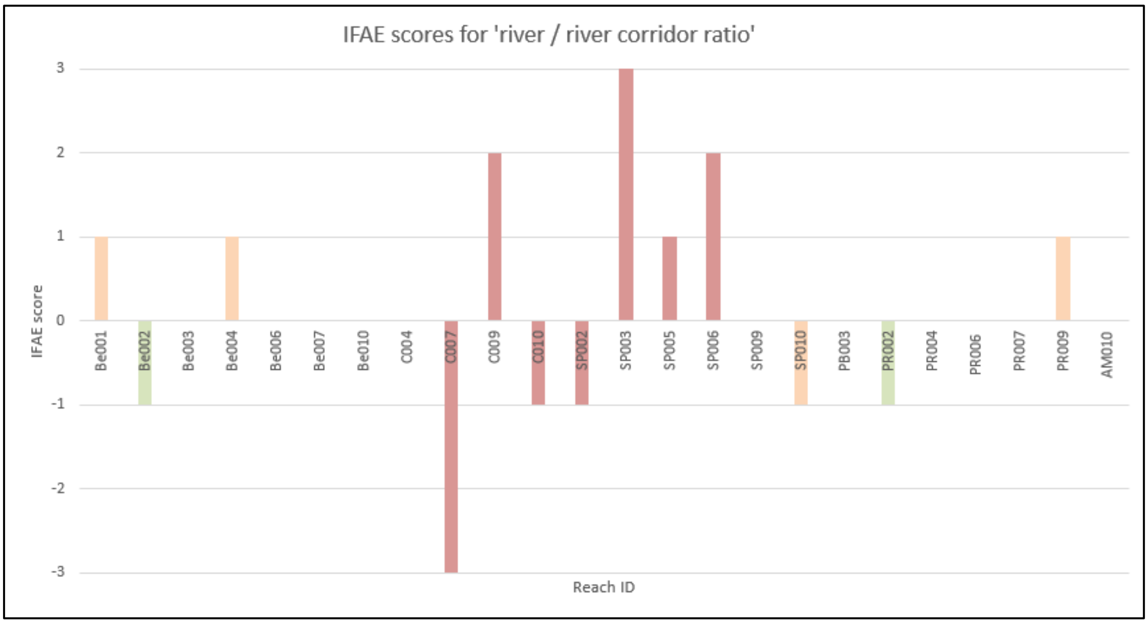


Figure 4-2 Graph showing IFAE for 'river / river corridor ratio' for all 24 study reaches (red bars = GESS 1; orange bars = GESS 2; green bars = GESS 3)

As an example, individual feature absolute error (IFAE) for ‘river / river corridor width ratio’ resulted in an individual feature score (IFS) of ‘3’ for study reach SP003. Reach SP003 is located on a small, upland river (low order stream with average river width of 5m) with a thin, discontinuous riparian corridor. Due to this, the reach was assigned a GESS of 3 based on the GESS criteria. Given delineation of the valley side edge was indistinct upon initial inspection from GE^{TM} imagery, (attributed in part due to tree cover), oblique angle views where inspected to no avail (Figure 4-3) and so, an elevation change of 1m was used to define the floodplain extent, as recommended where floodplain delineation was complex (Figure 4-4). This resulted in an average floodplain width of 60m on the left hand bank and 56m on the right hand bank However, when carrying out field data collection for SP003, a true floodplain was deemed to be absent (Figure 4-5), resulting in the discrepancy between individual feature scores.

Accurate delineation of this attribute is expected to be challenging across many upland areas of England where river channels are typically narrow (<10m width) and low-resolution imagery is inadequate for determining break in slope, making the floodplain extent difficult to distinguish. Very small rivers however are unlikely to have a floodplain and nestle within v-shape valleys.

Figure 4-3 Screen grab from GE^{TM} showing reach SP003 (oblique angle views)

Figure 4-4: Screen grab from GE^{TM} showing reach SP003. Red lines represent the horizontal limit to which a 1m change in elevation data, using the cursor point as an indicator, was recorded.

Figure 4-5 Photograph of reach SP003 showing high river banks with no true floodplain present, taken of reach during field data collection

‘Agriculture’ was equally an over-estimated riverscape attribute from the twenty-four study reaches assessed, resulting in positive absolute error scores for six of the twenty-four study reaches totalling a score of 11 overall. The method for measuring agriculture requires the percentage area of floodplain used for agricultural purposes to be estimated, which in turn requires accurate delineation of the floodplain extent initially. Over-estimation of this feature was therefore, generally caused by an over-estimation in floodplain extent, similar to that of ‘river / river corridor width ratio’. Therefore, accurate delineation of ‘agriculture’ firstly relies on accurate delineation of river corridor width.

4.3.1.2 Under-estimation of riverscape features from GE^{TM} (depicted by negative absolute error)

As outlined in Table 4-8, 'Valleyside connectivity with river' was found to be the riverscape attribute most under-estimated (greatest sum of –IFAE scores) when applying the L&G2015 methodology to the twenty-four study reaches, with thirteen of the twenty-four study reaches generating negative absolute error scores. This is predominantly due to the desk-based assessment assigning a score of '0' (often a default of 'nv') to this riverscape attribute and the field-based assessment assigning positive scores for this riverscape attribute.

The L&G2015 methodology requires observation of the '*river directly abutting the valley side; bluffs observable*' however, in the majority of study reaches where negative absolute error scores were derived for this riverscape attribute, extensive tree canopies obscured the view of the channel and valleyside edges meaning a score could not be derived (hence nv). GE^{TM} elevation data proved to be unreliable where extensive riparian corridors are present and thus did not aid identification of valley side edges further. In the study reaches tested, the greatest error was found to be predominantly associated with reaches scoring a GESS of '1' and 2' (Figure 4-6). Whilst the majority of study reaches scoring a '1' and '2' are representative of narrow, upland river channels, this is a factor of study reach selection rather than solely being the cause of the difficulty. Instead, this difficulty is expected to present widespread erroneous results, regardless of position within the catchment, if dense riparian corridors are characteristic of the study reach.

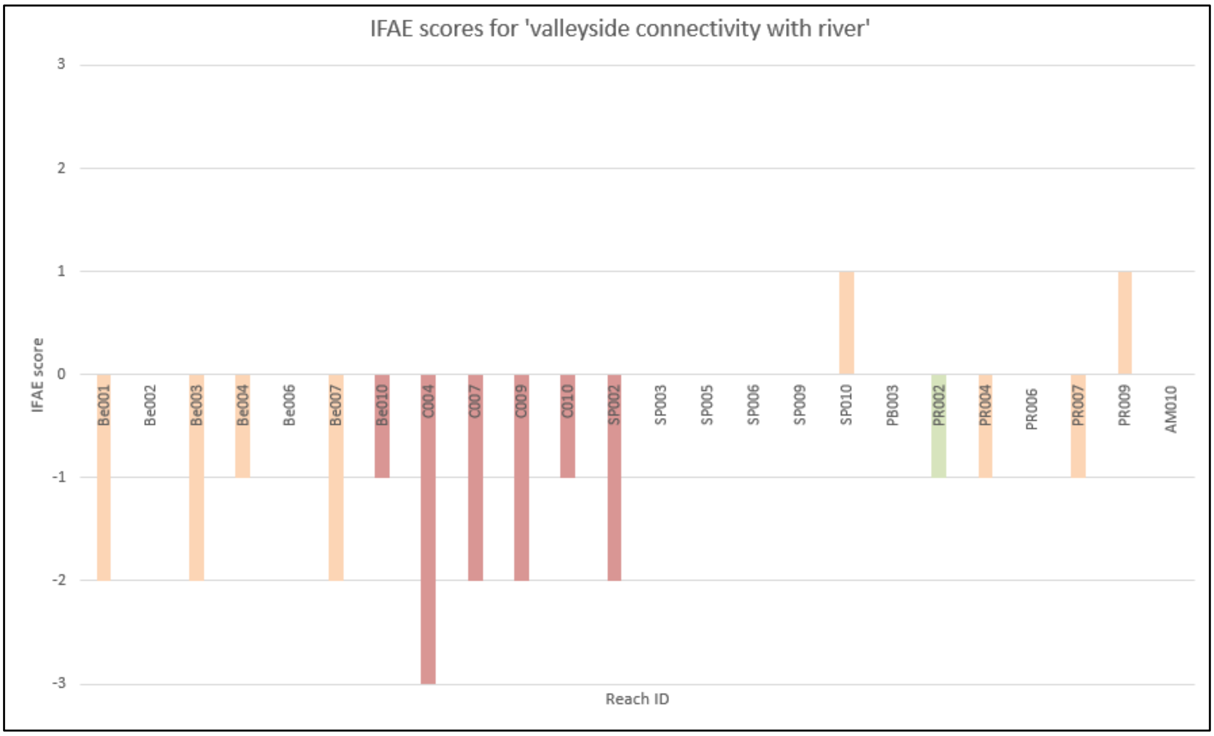


Figure 4-6 Graph showing IFAE for 'valley side connectivity with river' for all 24 study reaches (red bars = GESS 1; orange bars = GESS 2; green bars = GESS 3)

As an example, absolute error for 'valleyside connectivity with river' resulted in a score of '3' for reach C004. Reach C004 again, represents a low order stream (3^{rd}) with an average river width of 13m. The reach was assigned a GESS of '3' due to a complete lack of channel visibility (Figure 4-7). Given the channel and valley edge was not visible from GE^{TM}, it was assigned a score of '0' (default from nv). However, when carrying out field data collection, it was apparent the channel abutted bedrock on the valleyside (Figure 4-8) and thus was assigned an indivudal attribute score of '3' describing the high degree of valleyside connectivity. Under-estimation of this is therefore attributed to the extensive wooded river corridor obscuring views of bluffs when applying the desk-based L&G2015 methodology using the GE^{TM} virtual platform.

Figure 4-7 Screenshot of reach C004 showing the dense riparian corridor / wooded valley

Figure 4-8 Photograph of reach C004 taken from being stood on a 'bluff' looking across river to a further bluff/bedrock valley side) abutting the water's edge.

Another common attribute resulting in negative absolute error scores is active channel complexity, with absolute error scores of '-1' being derived for eleven of the twenty-four reaches. The L&G2015 methodology requires observation of the "*presence of exposed bars and backwaters connected to the main channel at their downstream end*' and then '*delineate path length. For three cross-sections (top, mid and bottom of reach), sum number of bars and backwaters and average for whole reach*". The scoring criteria for active channel complexity is targeted at a classic actively meandering river type which would be characterised by evenly spaced bends and associated point bars (scoring criteria assigns a greater score for a lower *ratio of bend apices to exposed bars and backwaters*).

Applying the methodology to English rivers resulted in a maximum IFS of '1', for active channel complexity with IFAE scores being restricted to between '-1' and '+1'. The methods for measuring and scoring this attribute are therefore considered unsuitable for application of the methodology to English rivers due to the relatively low geomorphic (active channel) complexity of English rivers compared to rivers globally. This underrepresents the value of active channel complexity (albeit relatively low) when applying the methodology at a national scale.

There are several reasons for error associated with this attribute (albeit limited to +/-1). In some instances, error is attributed to the river channel being obscured by riparian vegetation meaning this feature is not visible in GE™, resulting in a default score of '0' being assigned when undertaking the desk-based assessment. This is expected to result in widespread erroneous data where riparian vegetation is encountered, as is the case with several other attributes.

For other reaches, this error is associated with misalignment of the upper, middle and lower quartile of the study reach in which data is extracted from (i.e. the cross sections were misaligned between the desk-based and field-based application of the methodology). While this could further be rectified by improved GPS accuracy, it highlights that there is a risk of missing ‘hotspots’ associated with data collection regardless of desk- of field-based application of the methodology if the upper, middle and lower quartile of a study reach falls between the presence of the attributes.

Finally, user subjectivity (mixed with low resolution imagery / vegetation cover) resulted in further erroneous data. For example, during field data collection, exposed cobble/boulder bars in many of the upland study reaches were observed, which are not related to bend apices as described by L&G2015 (see Figure 4-9for examples). Given the vague definition of a ‘bar’ by L&G2015, these features were interpreted as a ‘bar’ for the purposes of the application of the methodology. The reason for this is due to their influence on the channel geometry and wetted perimeter and thus their influence on habitat complexity whereby boulders provide habitat and affect fish movement in the river (Branco et al., 2013). Going forward, further thought is needed as to whether boulders, among other meso-habitat patches should be recognised as individual riverscape attributes due to their prevalence across headwater streams.

Figure 4-9 Examples of boulder/cobble side bars encounter in study reaches in upland rivers, typical of much of the English river network. Photo 1 shows a boulder/cobble side 'bar' observed along SP002, through field data collection. Photo 2 shows a cobble/boulder side bar observed along C007, through field data collection

Similar to active channel complexity, the rules for delineation and measurement of the attribute secondary channels or braiding and the scoring criteria outlined in L&G2015 needs refinement for application to English rivers. The L&G2015 methodology requires observation of "*anabranching channels from the main channel; separated by vegetated islands and/or unvegetated bars*" and then "*delineate path length, and for top, mid and bottom of reach, sum number of active thalwegs across corridor and average to gain a value for sector"*. This attribute is targeted at classic braided or wandering river types, of which very few, true examples can be found in England.

Negative absolute error scores were derived for six out of the twenty-four study reaches, all of which were assigned a GESS of '1'. While this suggests the attribute was not visible due to either tree cover or poor resolution imagery, the erroneous data was found to be down to user subjectivity of how to interpret the delineation and measurement of the attribute. The study reaches resulting in negative error were all located in upland river reaches (impacted by tree cover or poor resolution imagery) however, the reasons they were recorded in the field as having more than one 'active channel thalwegs' was due to river flow splitting around large boulders (for example, see Figure 4-10). These were arguably recorded incorrectly should the L&G15 methodology have be followed precisely yet judgement on site was that flow splits around large boulders led to two active thalwegs. Further investigation into the suitability and refinement of the scoring criteria of this attribute for application of the methodology to English rivers is therefore required.

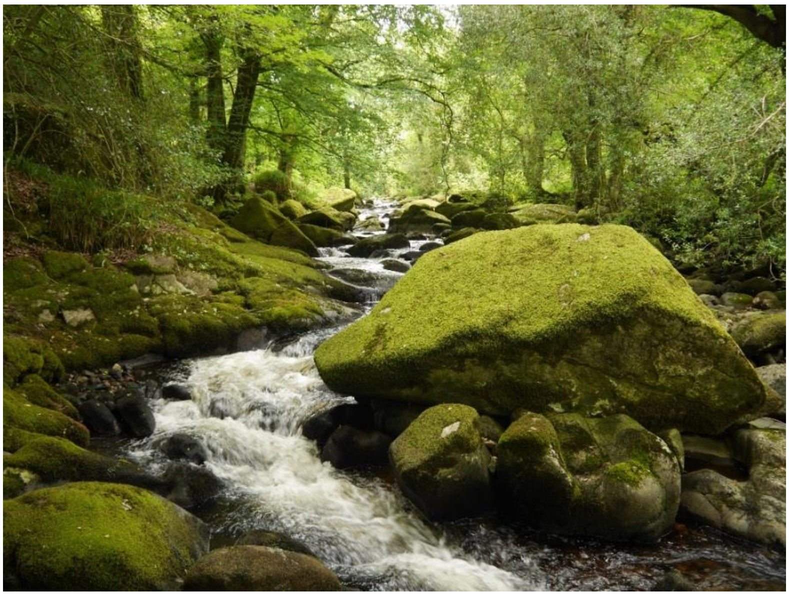


Figure 4-10 Photograph showing flow split around a large boulder in reach C007 meaning two active channel thalwegs were recorded in the field.

4.3.1.3 Outlying attributes: Embankments

Embankments are an attribute observed as 'narrow linear, clearly artificial features paralleling channel', they are measured by 'estimating the length' and scored according to their extensiveness. Despite measuring embankments as an attribute in the L&G2015 methodology, their score does not contribute to the provision of any of the ecosystem service scores.

In terms of results of the twenty-four study reaches, this attribute did not yield highly erroneous scores (Table 4-8), although this could simply be due to the limited number of study reaches assessed which contained embankments. However, it was recognised during field survey that the presence of embankments could easily be overlooked when applying the desk-based L&G15 methodology.

As an example, reach PR006 scored an absolute error value of -2, whereby embankments scored an IFS of ‘0’ in the desk-based application of the methodology and a ‘2’ in the field-based application of the methodology, meaning the data extracted from GE™ recorded this attribute as absent from the study reach yet they were ‘discontinuous but extensive’ when observed in the field. Figure 4-11 and Figure 4-12 demonstrate the lack of observation of the attribute from GE™, despite the reach scoring a GESS of ‘3’. Figure 4-13 shows the attribute observed during field data collection. As demonstrated in this example, earth embankments in particular are often concealed/obscured in GE™, particularly in agricultural settings, due to them blending in with the surrounding land cover.

Further investigation into the delineation of this attribute and the contribution to the provision of ecosystem services is required in order to refine the methodology for application to English rivers.

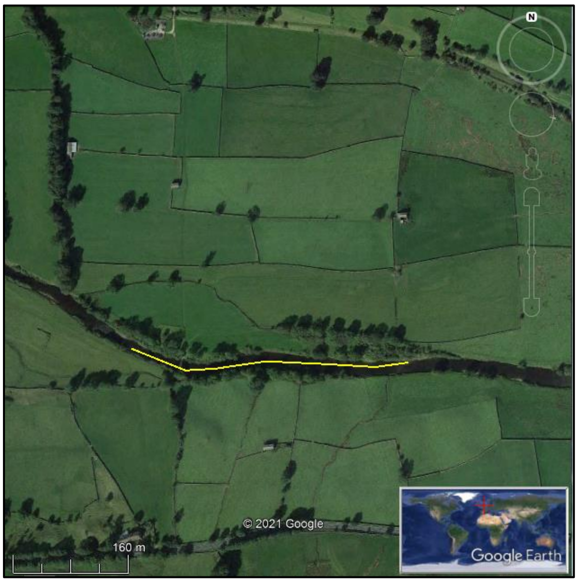


Figure 4-11 Screen grab of reach PR006 from GETM which was assigned a GESS of '3',

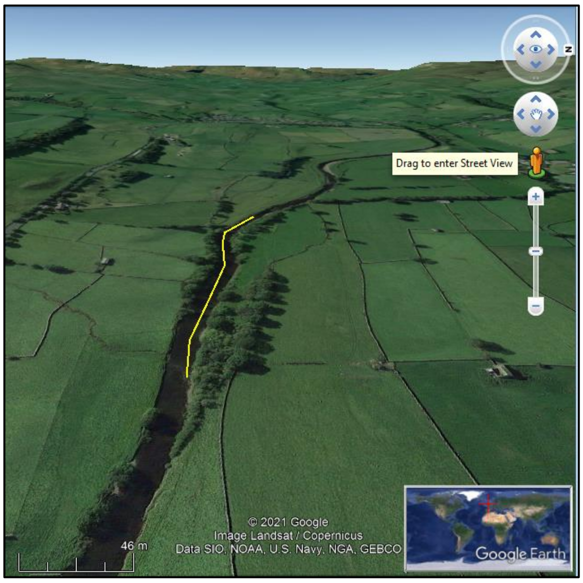


Figure 4-12 Screen grab of reach PR006 from GETM using oblique angle views to observe the study reach

Figure 4-13 Photograph showing a length of embankment alongside reach PR006, as observed during field data collection

4.3.2 Reach scale total + FAE and total –FAE scores

T+FAE scores and T-FAE scores per study reach are given in Figure 4-14 with the bar colours representing the assigned GESS. This provides insight into the reach-scale positive and negative error accumulated by summing the positive IFAE and negative IFAE scores for each study reach.

The results demonstrate that reaches with a GESS of ‘3’ (close to 100% feature visibility) have the lowest range of absolute error derived from the two datasets, as expected. The error range is between +3 and -6 (again, positive error is derived where features are over-estimated in GE™; negative error is derived where features are under-estimated in GE™). Four out of five of these reaches are considered large rivers, similar in scale to the ones tested by L&G2015 and so supports the findings that GE™ is more reliable for extracting individual attribute measurements on larger, main stem rivers with little riparian cover, although some error was still encountered and has been discussed in the previous section.

In contrast, nearly all study reaches scoring a GESS of 1 (>50% of riverscape attributes are obscured) had an average river width of less than 10m and were located in upland areas, as selected to test the applicability of the methodology beyond the main stem rivers. The TFAE range is greater for the study reaches assigned a GESS of ‘1’ and ‘2’ with the error range between +6 and -12.

As discussed in Section 5.3.1, IFAE which results in TFAE is commonly due to attributes being obscured by tree cover and poor resolution aerial imagery generally yielding less reliable/inaccurate results where the L&G2015 methodology is applied to smaller (generally, low order) rivers or rivers with heavily wooded river corridors, representative of much of the English river network. These common issues are difficult to overcome using the L&G2015 methodology in its current format due to its dependency on delineating and extracting measurements for each of the riverscape attributes via the GE™ platform. Other issues encountered are discussed in greater detail in the previous section.

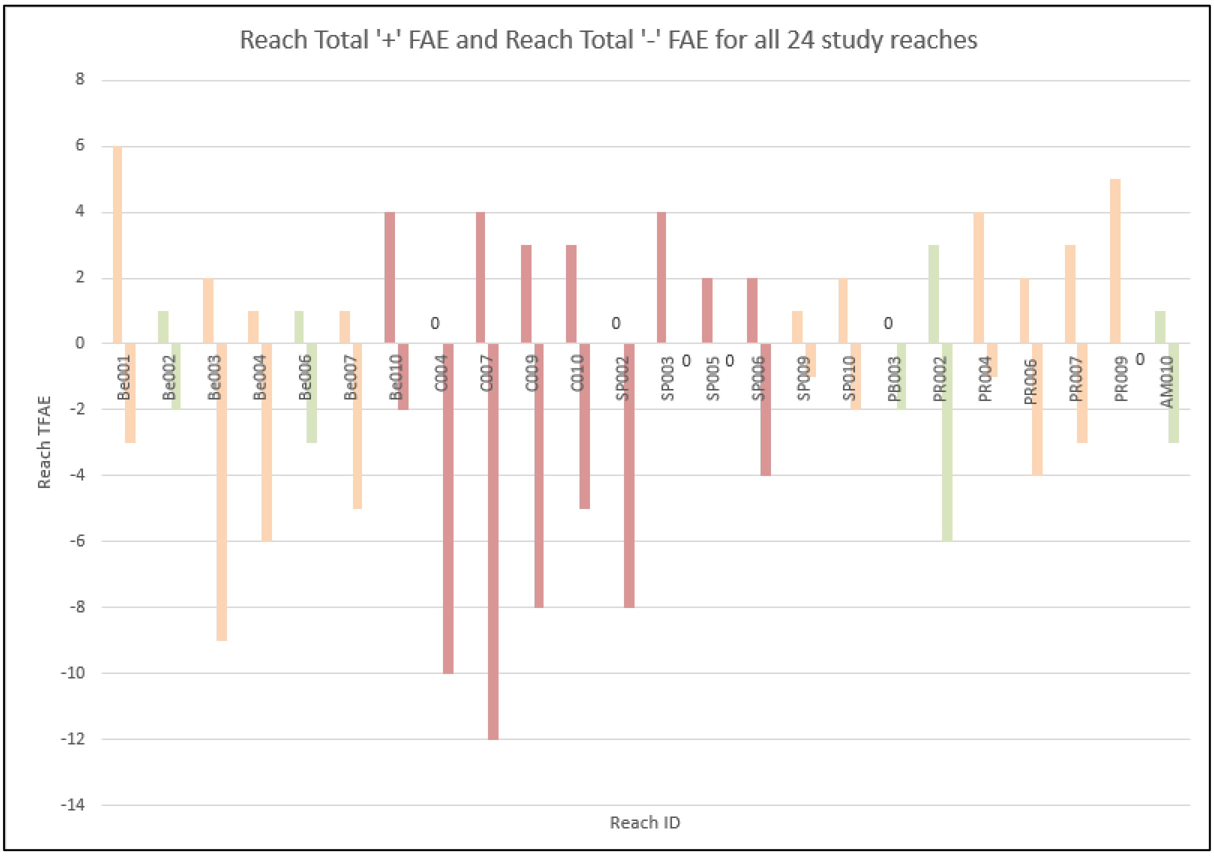


Figure 4-14 Graph showing Reach T'+' FAE and Reach T '-' FAE scores. Red =GESS of 1; orange = GESS of 2 and green = GESS of 3.

4.3.3 Individual ecosystem service attribute indices

Individual ecosystem service scores (reach IESS) and total ecosystem service scores (reach TESS) per study reach, for each of the two datasets have been calculated (according to the methods outlined in Table 4-4) and are presented in Table 4-10.

Individual ecosystem service absolute error scores have been calculated to highlight the amount of error accumulated when calculating ecosystem service scores from the two data collection methods, as provided in Table 4-11. Ecosystem service scores are entirely dependent upon the underlying individual feature scores ascertained from the data collected and thus error in the latter is translated into the ecosystem service scores derived, as demonstrated in the IESAE scores. Given individual feature scores are summed to derive ecosystem service scores, the amount of error in ecosystem service scores could be amplified if for example, multiple erroneous individual feature scores contribute to a particular ecosystem service.

Total '+' and total '-' individual ecosystem service absolute error scores for each study reach have also been calculated (Table 4-11). Positive absolute error scores demonstrate that ecosystem service provision has been over-estimated in the desk-based assessment due to individual attributes being over-estimated for the various reasons discussed in the previous sections. Negative absolute error scores demonstrate that ecosystem service provision has been under-estimated in the desk-based assessment due to individual attributes being under-estimated for the various reasons discussed in the previous sections.

Table 4-12 shows the sum of +IESAE scores and sum of –IESAE scores for each of eight ecosystem services to highlight which of the ecosystem service resulted in the greatest amount of error across the twenty-four study reaches. This table also presents the individual attributes which contribute to the provision of each of the ecosystem services according to the theoretical linkages provided in the L&G2015 methodology.

Table 4-10 Individual ecosystem service scores for all 24 study reaches (reach IESS and reach TESS)

	Field (F) / Desk (D)	***Be001 (2)***	***Be002 (3)***	***Be003 (2)***	***Be004 (2)***	***Be006 (3)***	***Be007 (2)***	***Be010 (1)***	***C004 (1)***	***C007 (1)***	***C009 (1)***	***C010 (1)***	***SP002 (1)***	***SP003 (1)***	***SP005 (1)***	***SP006(1)***	***SP009 (2)***	***SP010 (2)***	***PB003 (3)***	***PR002 (3)***	***PR004 (2)***	***PR006 (2)***	***PR007 (2)***	***PR009 (2)***	***AM010 (3)***
Fisheries (P)	F	8	7	7	11	5	10	2	13	8	8	4	11	6	4	6	3	3	6	5	7	7	9	1	7
	D	8	8	4	6	4	7	6	7	6	4	2	7	6	5	3	4	4	6	8	8	6	9	1	8
Water Supply [P]	F	3	3	3	2	2	2	1	3	3	2	1	2	2	3	1	0	2	2	0	1	2	1	2	1
	D	3	3	3	2	2	2	2	0	0	3	0	0	2	3	0	1	2	2	2	4	3	2	2	1
Flood mitigation [R]	F	6	9	11	9	8	8	6	10	8	6	5	9	4	6	5	5	4	8	8	7	8	7	10	9
	D	8	8	6	5	8	5	7	4	3	7	1	4	7	8	4	6	4	7	8	8	10	7	12	8
Carbon Sequestration [R]	F	2	2	4	5	2	4	1	6	2	2	1	5	2	2	1	0	2	1	1	1	1	3	4	3
	D	3	2	2	2	2	2	2	3	2	3	0	3	2	3	0	1	2	1	3	2	2	4	4	1
Biodiversity [C]	F	14	13	15	15	9	14	7	18	16	13	8	16	7	10	11	7	7	11	11	11	12	14	15	13
	D	13	13	9	10	8	9	10	8	7	8	4	8	10	12	9	7	8	11	11	13	11	12	17	12
Water quality [R]	F	4	6	7	7	6	6	4	7	6	4	3	7	2	4	3	3	3	4	5	4	5	5	6	7
	D	5	5	5	4	5	3	5	3	2	6	0	3	5	6	3	4	3	4	6	5	6	5	7	5
Timber [P]	F	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	D	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Agricultural crops [P]	F	0	3	0	0	3	2	3	0	0	0	0	0	3	0	0	0	0	3	3	3	3	1	3	3
	D	3	3	2	0	3	3	3	0	2	0	2	0	3	0	0	0	0	3	3	3	3	2	3	3
Reach TESS	F	37	43	49	49	35	46	24	57	43	35	22	50	26	29	27	18	21	35	33	34	38	40	51	43
	D	43	42	31	29	32	31	35	25	22	31	9	25	35	37	19	23	23	34	41	43	41	41	56	38

Table 4-11 Results showing +/-IESAE score and total '+' and '-' ecosystem service absolute error scores for each of the study reaches

Ecosystem service	Reach ID																							
	Be001 **(2)**	Be002 **(3)**	Be003 **(2)**	Be004 **(2)**	Be006 **(3)**	Be007 **(2)**	Be010 **(1)**	C004 **(1)**	C007 **(1)**	C009 **(1)**	C010 **(1)**	SP002 **(1)**	SP003 **(1)**	SP005 **(1)**	SP006**(1)**	SP009 **(2)**	SP010 **(2)**	PB003 **(3)**	PR002 **(3)**	PR004 **(2)**	PR006 **(2)**	PR007 **(2)**	PR009 **(2)**	AM010 **(3)**
Fisheries (P)	0	1	-3	-5	-1	-3	4	-6	-2	-4	-2	-4	0	1	-3	1	1	0	3	1	-1	0	0	1
Water Supply [P]	0	0	0	0	0	0	1	-3	-3	1	-1	-2	0	0	-1	1	0	0	2	3	1	1	0	0
Flood mitigation [R]	2	-1	-5	-4	0	-3	1	-6	-5	1	-4	-5	3	2	-1	1	0	-1	0	1	2	0	2	-1
Carbon Sequestration [R]	1	0	-2	-3	0	-2	1	-3	0	1	-1	-2	0	1	-1	1	0	0	2	1	1	1	0	-2
Biodiversity [C]	-1	0	-6	-5	-1	-5	3	-10	-9	-5	-4	-8	3	2	-2	0	1	0	0	2	-1	-2	2	-1
Water quality [R]	1	-1	-2	-3	-1	-3	1	-4	-4	2	-3	-4	3	2	0	1	0	0	1	1	1	0	1	-2
Timber [P]	0	0	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Agricultural crops [P]	3	0	2	0	0	1	0	0	2	0	2	0	0	0	0	0	0	0	0	0	0	1	0	0
Reach T+IESAE	7	1	2	0	0	1	11	0	2	5	2	0	9	8	0	5	2	0	8	9	5	3	5	1
Reach T-IESAE	-1	-2	-20	-20	-3	-16	0	-32	-23	-9	-15	-25	0	0	-8	0	0	-1	0	0	-2	-2	0	-6

Table 4-12 Summary statistics of total '+' and total '-' individual ecosystem service absolute error scores derived for each individual ecosystem service across all 24 study reaches

	Sum of '+' scores	**Sum of '-' scores**	**Total error range**	**Contributing individual feature scores**
Fisheries (P)	13	34	47	Sinuosity, secondary channels/braiding, active channel complexity, riparian/river bank woodland, floodplain forest, floodplain lakes, channel instability/naturalness
Water supply [P]	10	10	20	Palaeochannels, wetlands, floodplain forest, floodplain lakes, channel instability/naturalness
Flood mitigation [R]	15	36	51	Sinuosity, secondary channels/braiding, active channel complexity, slope, river/river corridor ratio, floodplain forest, woodland plantation, channel instability/naturalness
Carbon Sequestration [R]	10	16	26	No of tribs, wetlands, floodplain lakes, channel instability/naturalness
Biodiversity [C]	13	60	73	Sinuosity, secondary channels/braiding, no of tribs, active channel complexity, valleyside connectivity, river/river corridor ratio, riparian/bank woodland, floodplain habitat mosaic, Palaeochannels, wetlands, floodplain forest, floodplain lakes, channel instability/naturalness
Water quality [R]	14	27	53	Active channel complexity, river/river corridor ratio, palaeochannels, wetlands, floodplain forest, floodplain lakes, naturalness, channel instability/naturalness
Timber [P]	0	2	2	Woodland plantation
Agricultural crops [P]	11	0	11	Agriculture

4.3.3.1 Cumulative error in ecosystem service scores

Ecosystem services scores are calculated by summing scores of individual riverscape attributes, as outlined in Table 4-12. The scores for ecosystem service provision are entirely dependent upon the quality of the individual riverscape attribute scores which are summed to derive them. The greater number of individual attributes which contribute to an individual ecosystem service score, the greater the potential error in that individual ecosystem service. For example, the score for the provision of the ecosystem service ‘biodiversity’ is derived from summing scores for twelve of the eighteen individual riverscape attributes, including three of which score the greatest individual feature error (Valleyside connectivity; river / river corrido width ratio and channel instability/naturalness). When applying the methodology to the twenty-four river reaches, this resulted in ‘biodiversity’ scoring the greatest total error range with a score of 73. Water quality is derived from summing eight of the eighteen individual riverscape attributes, including two of which score the greatest individual feature error (river / river corrido width ratio and channel instability/naturalness) resulting in a total error range of 53 and flood mitigation is also derived from summing eight of the eighteen individual riverscape attributes, including two of which score the greatest individual feature error (river / river corrido width ratio and channel instability/naturalness) resulting in a total error range of 51.

T+ESAE scores and T-ESAE scores per study reach are given in Figure 4-15 with the bar colours representing the assigned GESS. This provides insight into the reach-scale positive and negative error accumulated by summing the positive ESAE and negative ESAE scores for each study reach. The graph follows the pattern observed in Figure 4-14 confirming that total individual feature absolute error pre reach translates into total ecosystem service error per reach.

As recognised in the previous section, there is a need to develop ways to improve the accuracy of extracting measurements of certain riverscape attributes in particular and a further need to refine the scoring criteria for English river networks.

Furthermore, there is a need to draw on the underpinning evidence basis linkage matrix to advance the methodology beyond theory.

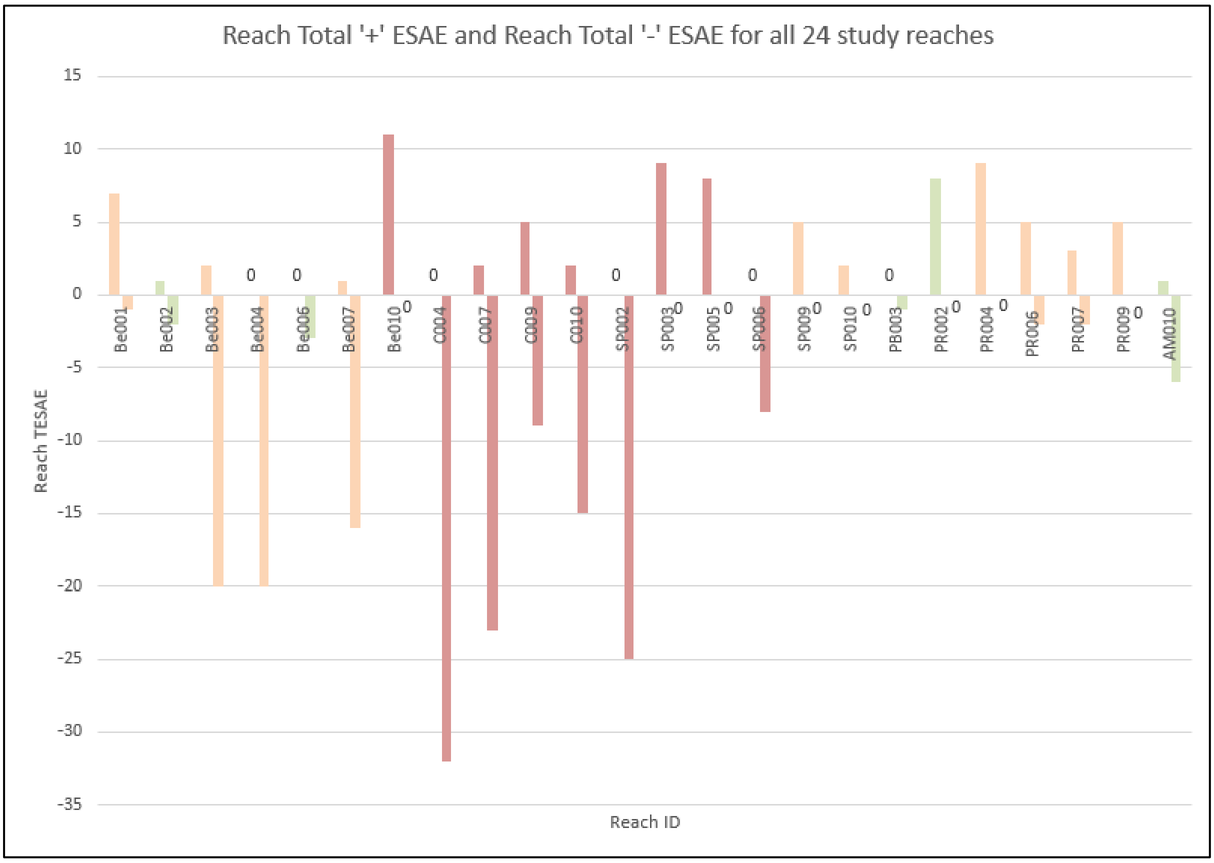


Figure 4-15 Graph showing Reach T'+' ESAE and Reach T '-' ESAE scores. Red =GESS of 1; orange = GESS of 2 and green = GESS of 3.

4.4 **Discussion**

Undoubtably, the GE™ platform has huge potential to support river science research and river management (Henshaw *et al.,* 2020; Keele *et al.,* 2019; Large and Gilvear, 2015; Fisher *et al.,* 2012) and the methodology presented by L&G2015 provides a good starting point for undertaking river ecosystem service assessments. However, there remains a number of practical issues regarding the use of the GE™ platform to undertake river ecosystem service assessments, as demonstrated by applying the existing methodology to English rivers in this Chapter and the previous Chapter. Furthermore, it is argued that the existing L&G2015 methodology is not fit for purpose across English river networks, in particular, small headwater streams and / or heavily wooded valleys.

The main issues are discussed in sections 4.4.1 to 4.4.3 and opportunities for addressing these are highlight in the following section.

4.4.1 Quantification of critical parameters from imagery data /delineation of riverscape attributes from imagery data (i.e. GE™)

Ultimately, visibility of the riverscape attributes and image quality needs to be good for the assessment to provide consistent, accurate and meaningful results. At present, image and data quality is inconsistent which can create problems in some locations in terms of feature recognition and measurement, especially in low order/headwater streams where stream width is small (Large and Gilvear., 2015).

The primary aim of the application of the methodology to twenty-four study reaches in England was to test the reliability and accuracy of the methods and highlight the challenges with the methodology, focusing on headwater streams and on streams displaying a range of tree cover densities (in England, these often go hand in hand). The GESS system applied to the twenty-four study reaches has been used as an indicator of this. The results broadly demonstrate that reaches with a lower GESS produced less reliable results when comparing the scores from the two data collection methods (field and desk-based) than those reaches with a higher GESS, although some riverscape attributes are clearly more sensitive to the GESS than others.

The results demonstrate that study reaches with heavily wooded river corridors provide the greatest challenge for accurate delineation of several riverscape attributes, namely ‘active channel complexity’; ‘river / river corridor width ratio’, ‘valley side connectivity’ and ‘secondary channels or braiding’ due to them not being visible using GE™ imagery alone. Attempts were made to utilise the ‘timeline’ feature in GE™ as a means of providing temporal variability in the imagery data however, it was found that the majority of imagery data covering England is obtained during summer months when leaf cover is at its fullest. Similarly, over-hanging riparian vegetation, even where only a narrow, often discontinuous strip was present, prevented accurate delineation of ‘active channel complexity’ and ‘valley side connectivity’ due to the vegetation obscuring the channel features and channel margins, retrospectively.

The challenges relating to vegetation have previously been recognised (Henshaw *et al*., 2020; Mather *et al*., 2015; Large and Gilvear., 2015; Fisher *et al*., 2013) but largely over-looked. Large and Gilvear (2015) suggest that on "low order streams, ubiquitous vegetation cover becomes the dominant driver of the ecosystem". While this might be true it doesn’t provide a means of overcoming the issue when applying the methodology. It is further argued that the challenges relating to vegetation are not exclusive to low order streams, as all rivers have the capacity to support a complex bank-top vegetation structure (Gurnell *et al*., 2020), albeit it is accepted that the challenge is more prevalent on low order streams. Further development of the methodology to take vegetation cover into account is needed to allow for application across entire river networks in England.

Another challenge which is particularly prevalent on headwater streams in England is that of image quality. Much of the imagery available in GE™ for lower order streams in England is of poorer quality (resolution is too coarse) due to the size of these streams. The prevalent challenge here is the delineation of in-channel features which are often unidentifiable. The methodology has not been applied to headwater streams before, with the previous applications of the methodology remaining focused on main stem rivers despite recognising their importance for understanding ecosystem service provision across river networks (Keele *et al*., 2019; Large and Gilvear., 2015).

Delineation of river corridor width provides a further challenge for the application of the methodology to English rivers, sometimes due to the challenges already outlined above but also due anthropogenic augmentation of the river channel and adjacent floodplain. Often, in low-lying landscapes of England, there are few apparent breaks of slope, with floodplain land cover appearing extremely homogenous and in upland valleys in England, field patterns can obscure where the edges of the valley floor meet valley sides (Large and Gilvear, 2015). Despite the suggestion to use GE™ elevation data and oblique angle views, the application of the methodology demonstrates that these options are unable to provide an adequate solution to this challenge on the whole, with elevation data being to coarse to yield accurate results. These challenges were also apparent when delineating embankments. Elevation data is too coarse to identify subtle changes where embankments are present and anthropogenic augmentation of the floodplain can obscure the attribute, particularly where embankments are consistent with the surrounding land use (e.g. on agricultural land as is often the case across low lying floodplains in England). As discussed previously, using a set boundary as a template for which to undertake the assessment such as the boundaries of 1 in 100-year indicative flood maps could provide a consistent solution for this.

The resolution of elevation data also proved to be too coarse for measuring channel slope, with some reaches resulting in the river ‘flowing upstream’. Slope was recorded as the greatest difficulty by L&G2015 and is one of the parameters most heavily impacted by scale. Rather than suggest alternative approaches for measuring slope, it is suggested that slope should be removed as a riverscape attribute as it is not considered a reliable indicator of ES provision.

4.4.2 Critical evaluation of the scoring criteria of riverscape attributes as applied to English rivers

Valuation of ecosystem services becomes a societal decision and differs depending on geographical location (Large and Gilvear, 2015). Rivers across the world display a wide range of scales, channel form, and degree of dynamism (Kondolf *et al*., 2003) and thus assessing and scoring ecosystem services must reflect this.

The L&G2015 methodology adopts "an integer-based scoring system for individual riverscape attributes whereby 0 meant ‘absent’ or of virtually no value to ecosystem service provision and 3 implies the ‘optimal’ or near maximum possible potential for ecosystem service provisioning. Values of 1 and 2 are assigned for intermediate states in relation to potential delivery of ecosystem service benefits. A rule-based approach focused on the measured riverscape attributes was used to assign scores" as summarised in Section 3.2.1.

On a global scale, English riverscapes are typically small and exhibit a low degree of dynamism due to the history of anthropogenic modification, for example agricultural intensification has been linked to the loss of functional geomorphic units and associated habitats and biodiversity (Entwhistle *et al*., 2019). This is reflected in the results derived for the twenty-four study reaches assessed whereby some of the riverscape attributes such as active channel complexity, secondary channels or braiding and wetlands score consistently low (a maximum score of 1 was derived across all twenty-four study reaches). While L&G2015 is intended to be globally applicable, this chapter supports the view that river ecosystem service assessments need bespoke refinement to suit the geographical region in which they are used (Keele *et al*., 2019), with valuation (monetary or otherwise) needing to be reflective of where in the world it is being implemented (Burkhard *et al.* 2012; Costanza, 2008). It is therefore suggested that a robust riverine ecosystem service assessment for English river networks must appropriately reflect the scale, form and degree of dynamism that is characteristic of English rivers. Incorporation of thirteen geomorphic river types commonly found in England (after Gurnell *et al*., 2020) is recommended to be adopted to inform the development of a bespoke ecosystem service assessment for rivers in England.

Furthermore, the relationship between riverscape attributes and ecosystem service provision is currently limited to identifying positive relationships i.e. the riverscape attributes positively enhance ecosystem service provisioning where a theoretical linkage has been identified. However, in reality these relationships are often complex and managing rivers for the provision of an ecosystem service can results in trade-offs with other ecosystem services. Assessing and managing rivers for the provision of ecosystem services therefore requires an understanding of negative relationships as well as positive ones as they are often not mutually exclusive (Potschin & Haines-Young, 2011; Rodríguez *et al*., 2006; Seppelt *et al*., 2011; Keele *et al*., 2019). For example, generation of hydropower provides a source of energy but may impair the provision other ecosystem services such as fish production, water quality, and habitat provision (Ziv *et al*., 2012; Keele *et al*., 2019). Across the English landscape, trade-offs between agricultural land use and most other ecosystem services (biodiversity, water and soil regulation and water supply) are pertinent (Rodriguez *et al*., 2006).

A recent study by Entwistle et al. (2019) provides a comprehensive nationwide assessment of England's floodplain condition and trends of change between 1990 and 2015, using land use and floodplain area information. They argue that agricultural intensification represents "the most pervasive change wrought by humans on fluvial systems across England", with around 65% of the total floodplain area having undergone extensive alteration due to agriculture. The data presented reveals that just over 0.5% of total floodplain area remaining is functional floodplain occupied by wetland habitat, with fen, marsh, swamp and bog habitats. Clearly then, maximising the provision of agricultural land has adversely impacted the capacity of the floodplain to deliver other ecosystem services and thus it is argued that negative linkages must be recognised in riverine ecosystem service assessments to inform sustainable river management. It is suggested that positive and negative relationships between riverscape attributes and ecosystem service provision are identified and incorporated into the scoring system. Developing an evidence-based linkage matrix which recognises positive and negative relationships between riverscape attributes and ecosystem services and assigning levels of confidence to those linkages is recommended to provide a robust riverine ecosystem services assessment.

Finally, L&G15 "deliberately apply equal weighting across all eight ecosystem services but acknowledge that in reality, this becomes a societal decision depending on where elsewhere in the world the method might be applied" (Large and Gilvear, 2015). It is recommended that weighting of scores should strive to reflect current UK policies and Government ambitions as well as local stakeholder preferences.

4.5 **Conclusions and research needs**

Headwater streams represent a significant proportion of the channel length within a river network (Downing *et al*., 2012) yet they receive disproportionately little attention by researchers and water managers and are largely excluded from water management planning (Biggs *et al*., 2017). There is a clear need to better integrate headwater streams into the management of catchments and landscapes given that numerous riverine ecosystem services are initially mediated by headwater streams and some, such as carbon cycling, may be dominated by them (Biggs *et al*., 2017).

As highlighted, previous applications of the L&G2015 methodology focused on large main stem rivers, over-looking the importance of headwater streams (Large and Gilvear, 2015; Keele *et al*., 2019). Furthermore, the limitations associated with tree cover obscuring in-channel riverscape attributes and image resolution have not previously been resolved. The results from this chapter found that these limitations are more prevalent in headwater streams with the results derived from applying the desk-based L&G2015 methodology and the field-based version of the methodology to the twenty-four study reaches confirming this. The results revealed differences in individual riverscape attributes scores, with the scores from headwaters streams and study reaches with dense tree cover generating the greatest differences. In addition, this chapter has emphasised the importance of acknowledging scale, channel form and degree of dynamism when identifying and scoring ecosystem service provision across English rivers. It is therefore concluded that the L&G2015 riverine ecosystem service assessment methodology is unreliable for use across English river networks and further development of the methodology is needed to address the limitations identified in both this Chapter and the previous Chapter (Chapter 3). Recommendations for further research are outline below.

- Firstly, it is recommended that evaluation of ecosystem services across English river networks should be informed by an understanding of the hydrogeomorphic character of the river reach using a geomorphic river typing classification. It is hypothesised that incorporation of a river typing classification, which recognises geomorphic river types commonly found in England, could improve understanding of the riverscape attributes and ecosystem services associated with a reach of a given river type, allowing assumptions to be made regarding attributes which are not visible using GE™ imagery alone. It is also anticipated that this will allow for comparison between observed condition of a reach and that which is *expected* for a given river type, providing a means of identifying appropriate river management interventions to maximise ecosystem service provision which is compatible with the characteristics of that river type. The riverscape attributes and scoring criteria defined in the L&G2015 methodology is deemed to be unsuitable for the scale, channel form and degree of dynamism typical of English river types and thus there is a need to revise the riverscape attributes assessed and the scoring criteria used to derive ecosystem service scores to reflect the hydrogeomorphic character of English river types.
- As a consequence of the above, there is also a need to refine the linkages between riverscape attributes and ecosystem service provision. It is recommended that this is achieved through an extensive review of existing publications to develop a linkage matrix which assesses the level of confidence in a range of linkages between riverscape attributes and land cover classes and ecosystem services pertinent to English river types.
- Finally, it is recommended that the use of additional hydrological and riverscape attribute datasets available through the DEFRA data services platform is explored. While it is accepted that GE™ can provide an invaluable starting point for geomorphological analyses (Tooth, 2013), it is argued that incorporating other national datasets into the assessment, such as the 1 in 100 year flood maps for England, will improve the reliability of the approach and resolve some of the limitations encountered.

5 A bespoke geomorphologically-based riverine ecosystem service assessment framework for English river corridors

5.1 Introduction

River characteristics naturally vary along a continuum and in response to human interventions, meaning generalisations can be challenging. Nonetheless, developing spatially hierarchical frameworks to help describe the functioning of river ecosystems has been a focus of research (Naiman *et al*., 1992; Kondolf *et al.,* 2003; Gurnell *et al*., 2016). Spatially hierarchical frameworks based on hydromorphological principles provide a physically and ecologically meaningful basis for classifying riverine ecosystems. In particular, classifying river types based on geomorphic typologies has been widely used for river management purposes (Newson *et al*., 1998; Schmitt *et al*., 2007; Rosgen, 1994, 1996; Snelder and Biggs, 2002; Brierley and Fryirs, 2005; Gurnell *et al*., 2016; Gurnell *et al*., 2020) and has been recognised as having good potential for evaluating riverine ecosystem services (Thorp *et al.* 2010).

Therefore, the main aim of this chapter is to develop and test a bespoke geomorphologically-based riverine ecosystem service assessment framework for English river types incorporating the recommendations given in Chapter 3 and Chapter 4. It is predicted that this will provide a robust framework for assessing ecosystem service provision throughout river networks across England. It will be underpinned by scientific evidence whereby a linkage matrix will identify established linkages between riverscape attributes and ecosystem services which are associated with common geomorphic river types common in England and will be informed by understanding of eco-hydromorphological principles which inform the biophysical structure and ecological condition of riverine ecosystems.

To fulfil this aim, this chapter makes use of existing river typing frameworks (e.g. Gurnell *et al*., 2020; Rinaldi *et al*., 2016) and existing riverine ecosystem service assessment methodologies (Large and Gilvear., 2015; Keele *et al*., 2019) to inform the development of a bespoke geomorphologically-based riverine ecosystem service assessment methodology for application to English river corridors. An evidence based riverscape attribute-ecosystem service linkage matrix (referred to as 'linkage matrix' hereafter) has been developed through an extensive literature review, which consolidates linkages between riverscape attributes and ecosystem services of relevance for English rivers. Each linkage is assigned a confidence score based on the strength of evidence and number of studies available to support the linkage (positive or negative). The linkages have been placed within the Riverine Ecosystem Service Cascade Model (RESCaM) outlined in Figure 5-1, based on Potschin and Haines-Young (2011) and adapted from Large and Gilvear (2015), to assess riverine ecosystem service delivery from source to mouth.

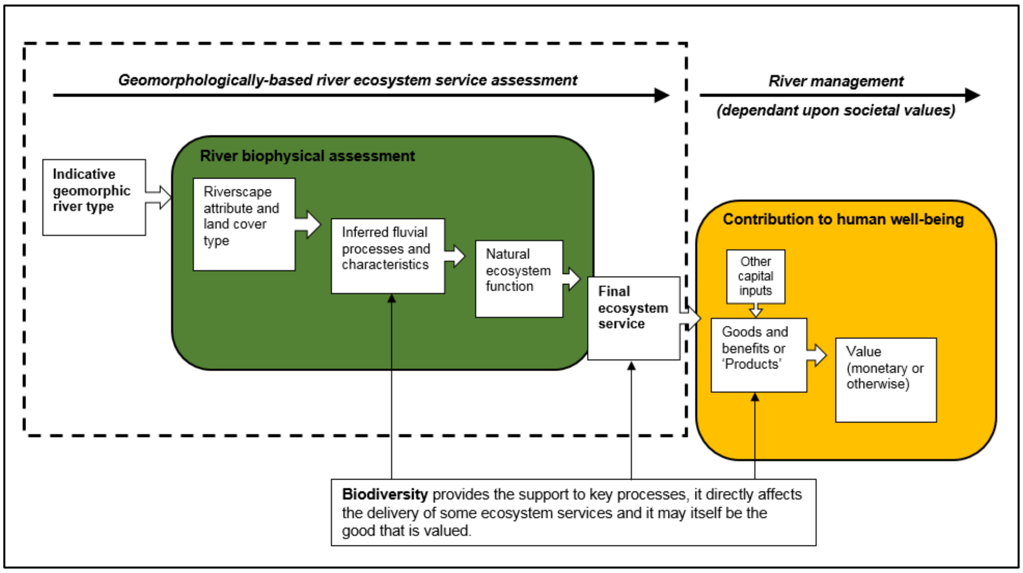


Figure 5-1 River Ecosystem Service Cascade Model (RESCaM) framework, adapted from Large and Gilvear (2015). The dashed line signifies the limit of the approach presented here.

A methodology for extracting and scoring twenty-seven riverscape attributes using a combination of aerial imagery (via GE^{TM}) and a range of widely available hydrological and asset spatial databases is proposed. Thirteen indicative river types are assigned at the reach level and guidance on the maximum individual riverscape attribute scores (and subsequently reach IESS and reach TESS) that are expected to be realised by a naturally functioning river reach of a specific type are given. This underpins the river biophysical assessment by ensuring scores for individual riverscape attributes and subsequently values for ecosystem service provision can be interpreted either as “expected” for a given river type or as “below expected”. The methodology is piloted and tested on four rivers (each consisting of 10 river reaches) which represent a range of geomorphic river types. Furthermore, attempts have been made to address a variety of the issues and limitations identified in Chapters 3 and 4.

The objectives of this Chapter are:

1. To develop a scientific evidence based ‘riverscape attributes- ecosystem service linkage matrix’ to underpin the cascade from riverscape attributes to ecosystem service provision and place the linkages within the RESCaM framework (adapted from Large and Gilvear, 2015)
2. To develop a bespoke desk-based methodology for extracting and scoring riverscape attribute information using aerial imagery (via the GE^{TM} platform) and supplementary hydrological and asset databases for English rivers to assess river ecosystem service provision
3. To evaluate ecosystem service provision by describing the hydrogeomorphic character of thirteen indicative geomorphic river types found in England (based on Gurnell *et al*., 2020)
4. To apply the methodology to four rivers representing seven geomorphic river types and trial hypothetical restoration scenarios which maximise ecosystem service provision in order to test the utility of the framework for riverine ecosystem service management purposes

5.2 **Study sites**

Four English rivers were chosen to apply the geomorphologically-based riverine ecosystem service assessment methodology (Figure 5-2). The rivers have been selected based on professional judgement to represent a range of geomorphic river types and biogeographical settings across England. The study sites are located on: Glenderaterra Beck, Cumbria, River Wharfe, North Yorkshire, River Bollin, Greater Manchester and River Stour, Dorset. Each study site includes ten consecutive river reaches whereby the length of each river reach is calculated as twenty times the average river width (Milner and Gilvear., 2012) and rounded to the nearest 10. The study sites are described in more detail throughout Sections 5.2.1 to 5.2.4.

Figure 5-2 Locations of four rivers across England for piloting and testing the river ecosystem service assessment methodology

5.2.1 Glenderaterra Beck

Glenderaterra Beck rises in the Lake District High Fells at approx. 400m elevation, nested between Lonscale Fell to the West and Blencathra to the East. The beck is located approximately 3km east-northeast of the major town of Keswick, lying within the Lake District National Park, Northern England (Figure 5-3). Glenderaterra Beck is an upland stream with a total length of approximately 4.3km from source to its confluence with the River Greta. Glenderaterra Beck and its major tributary Whit Beck is have a total catchment area of 12 square kilometres. The surveyed length of Glenderaterra Beck measures 2.2km from NGR NY2961426575 to the confluence with the River Greta at NGR NY2990324745.

The catchment lies within the designated Skiddaw Group Site of Special Scientific Interest (SSSI)[10] and the Lake District High Fells Special Area for Conservation (SAC)[11]. "The main biological interest of the SSSI lies in the range of upland vegetation types represented and in particular the extensive tracts of sub-montane blanket bog and heather moorland. Skiddaw Group supports the largest areas of both heather moorland and blanket bog in the Lake District"[10]. Lake District High Fells (SAC) is designated for a range of habitat types considered to be representative of one of the best areas in the United Kingdom[11]. Land use surrounding reaches 5-8 contain areas of ancient woodland which are designated as a LWS's, known as Glenderaterra Beck Wood and Brundholme Wood.

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[10] SSSI detail (naturalengland.org.uk)

[11] Lake District High Fells - Special Areas of Conservation (jncc.gov.uk)

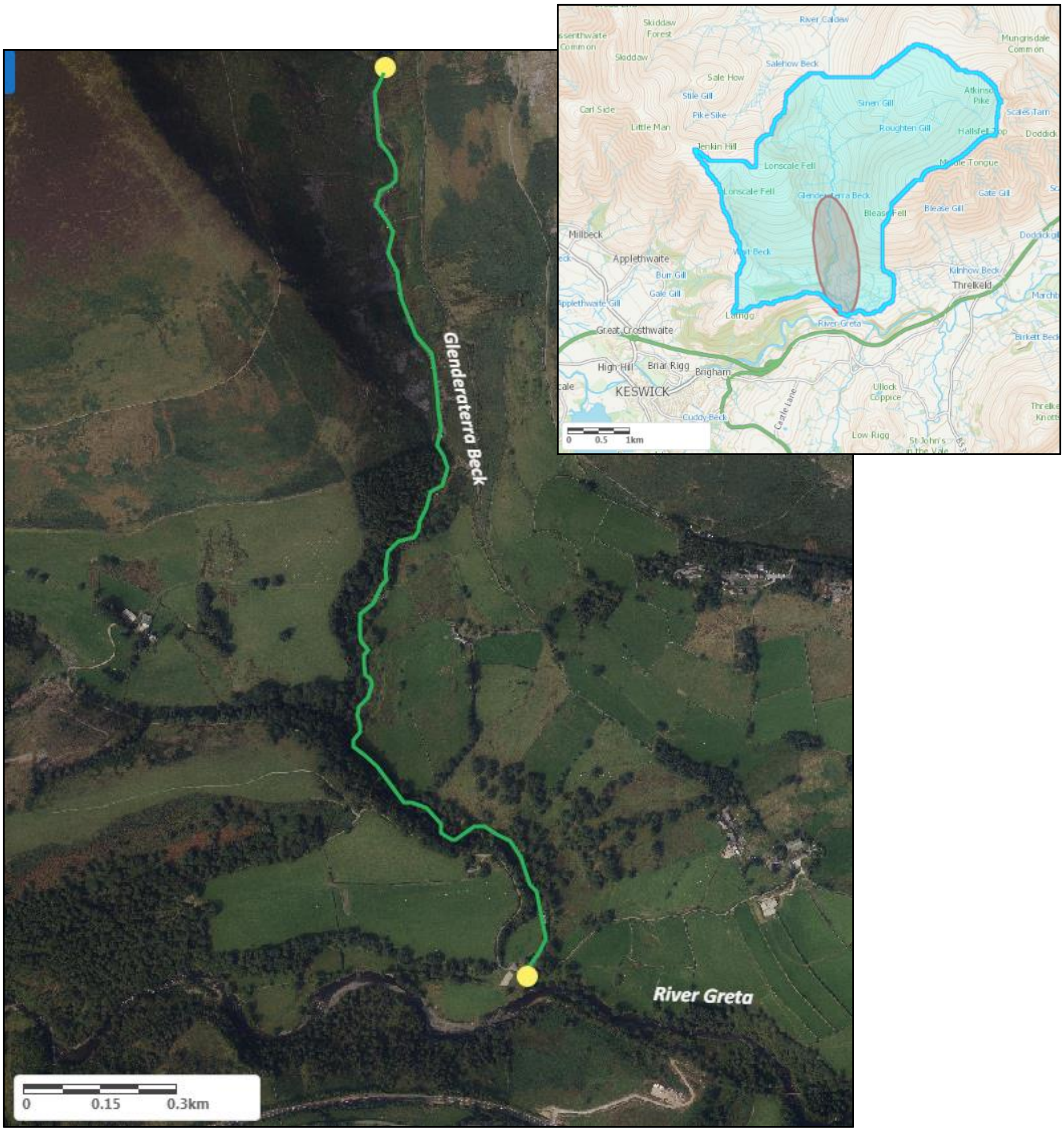


Figure 5-3 The location and course of the Glenderaterra Beck, Cumbria. Flow direction: north to south

5.2.2 River Wharfe

The River Wharfe rises in the region of Pen-Y-Ghent and Ribblehead as a series of steep narrow first order streams, namely Oughtershaw Beck and Green Field Beck, which confluence in Langstrothdale to become the River Wharfe at an elevation of around 300m. The River Wharfe winds its way for a total length of 120km to join the River Ouse near Cawood. The Wharfe has a catchment area of just over 100 km². The Upper and middle parts of the Wharfe catchment lie within the Yorkshire Dales National Park. The study reach is located in the upper part of the middle Wharfe catchment. The total surveyed length extends for 6km between two tributaries, Barben Beck (NGR SE0381160549) and Barden Beck (NGR SE0585456748), both of which are regulated by reservoirs (Figure 5-4).

The floodplain land use surrounding the study area is dominated by agricultural land. Parts of the surrounding catchment drains the North Pennine Moors SAC[12]. In addition, there are small patches of ancient woodland lying within or adjacent to the floodplain.

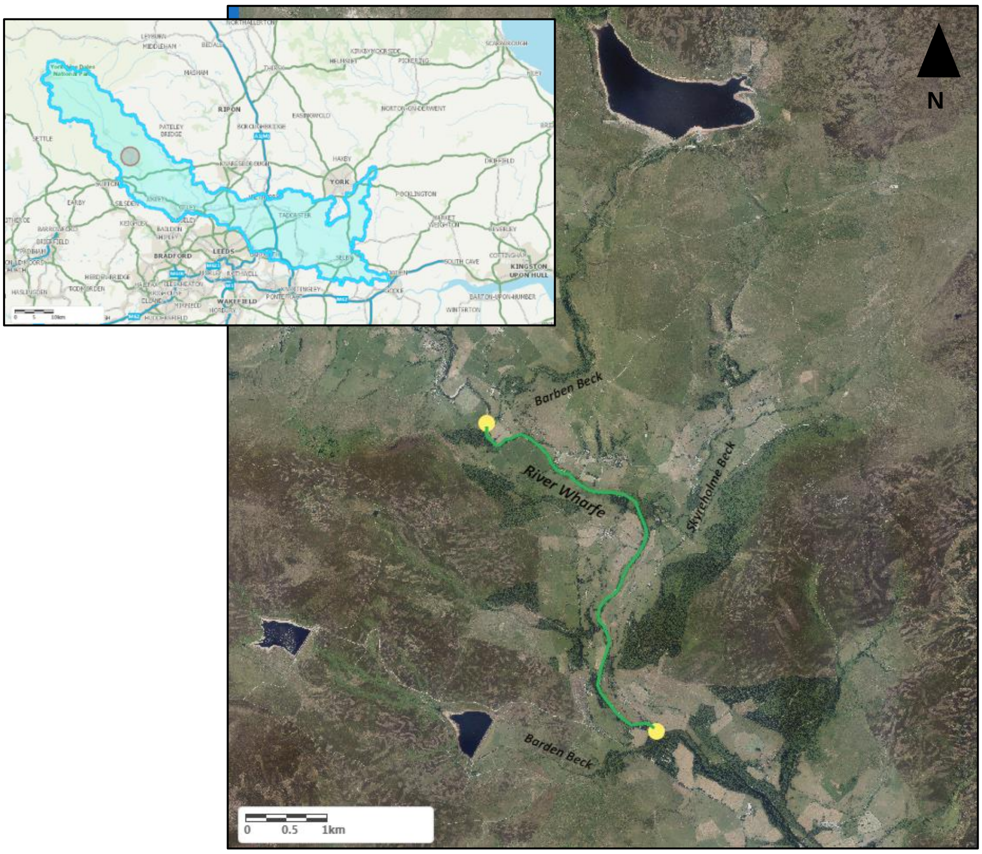


Figure 5-4 The location and course of the River Wharfe study reach (Flow direction: north-west to south-east)

[12] North Pennine Moors - Special Areas of Conservation (jncc.gov.uk)

5.2.3 River Bollin

The River Bollin rises at approximately 400m AOD in Macclesfield Forest at the western end of the Peak District, around 5km SE of Macclesfield, Greater Manchester. The River Bollin is a major tributary of the River Mersey in NW England and flows for a length of 49km from source to its confluence with the Mersey near Oughtrington, around 7km east of Warrington. The River Bollin is joined by the River Dean about half way down its length, to give a combined catchment area of 273 km2.

The study site is located in the Upper part of the River Bollin catchment at an elevation of around 80 -m AOD. The river is regulated through a series of dams and reservoir units in the headwaters. The study site starts ~15km downstream from the lowest reservoir at NGR SJ8839979945 and extends for 2km to NGR SJ8754180468 (Figure 5-5). There are just two minor tributaries channels joining the Bollin between the headwaters and the study area. The upper reaches of the study area have been physically modified through channel straightening whereas the lower reaches display a more ‘natural’ character and meandering planform, acknowledged by the designation as a Local Wildlife Site (LWS), site reference Bollin valley, Wilmslow park and Mottram Bridge LWS. Special features acknowledged under the designation include unimproved and semi-improved grassland, river, ox-bow lakes and flushes.

Figure 5-5 The location and course of the River Bollin study site (Flow direction: South-east to north-west)

5.2.4 River Stour

The River Stour rises in Stourhead woods at an elevation of around 140m AOD. It flows for around 98km in length, through Wiltshire and Dorset in southern England to the sea at Christchurch, 7km east of Bournemouth. The catchment area for the river and its tributaries is 1,240 km^2.

The study reach is located in the lower part of the River Stour catchment at an elevation of around 15 -m AOD, between NGR SZ0162099209 and SZ04984978 42, extending for a length of 6km (Figure 5-6). The river channel is embanked on both sides albeit some lengths of embankment are set-back from the channel edge. The surrounding land use is occupied by a mixture of agricultural land, developed land

and wetland habitat containing patches of rough grassland and mosaics of small ponds.

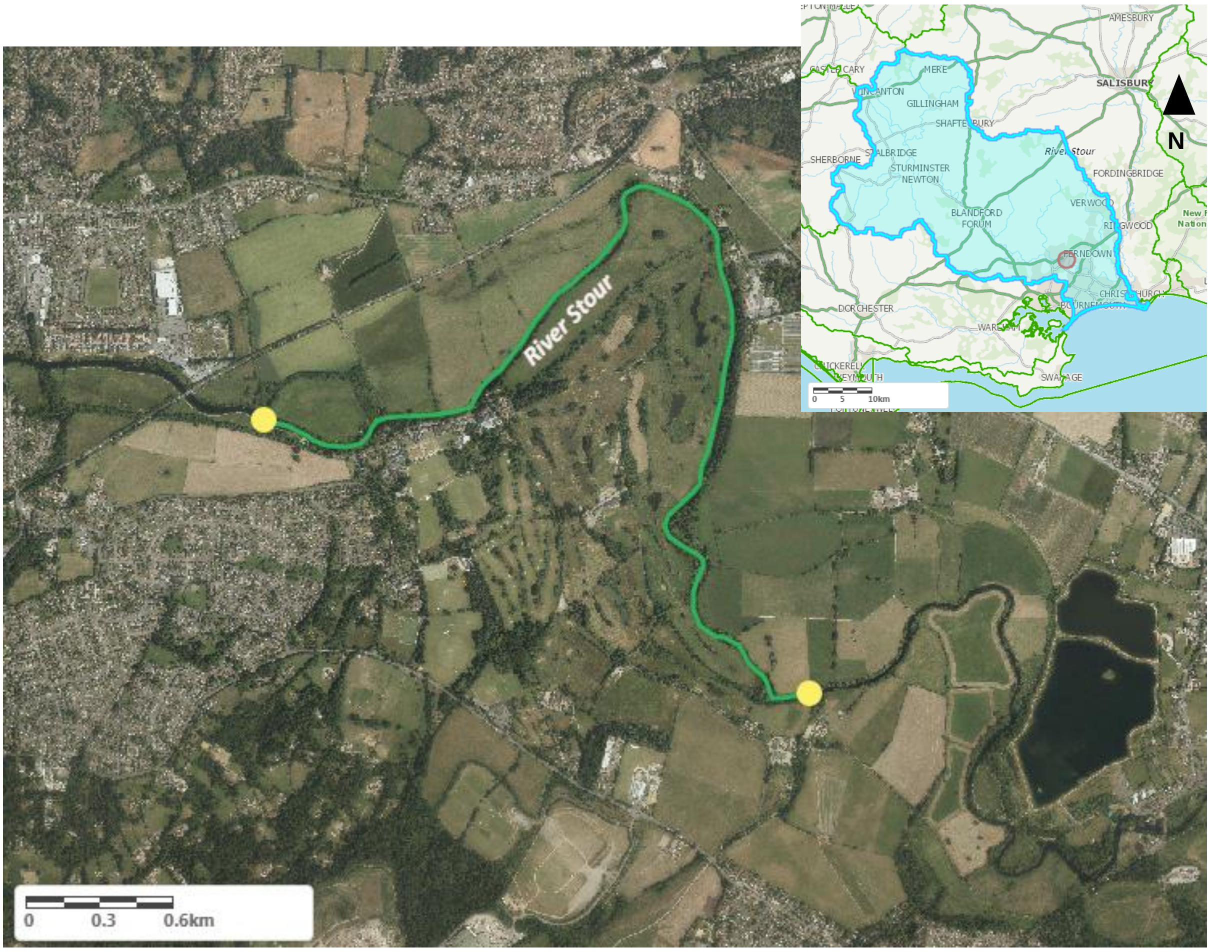


Figure 5-6 The location and course of the River Stour study site (Flow direction: from west to east)

5.3 Procedure for assessing ecosystem services provided by English river types

This section outlines the procedure for carrying out the methodology for assessing river ecosystem services provided by English river types. The methodology broadly follows the approach of L&G2015 but includes significant developments for bespoke application to English rivers. Key developments include: refinement of the linkage cascade between riverscape attributes and ecosystem services using scientific evidence to assign confidence levels in a linkage matrix; refinement of the scoring system to reflect the characteristics of English rivers; the addition of a geomorphic river typing classification (as recommended by Thorp *et al*., 2010) which provides guidance on the maximum riverscape attribute scores that are expected to be achieved by a river reach of a specific geomorphic river type and the inclusion of hydrological and asset datasets available from the DEFRA data services platform which provide readily available spatial information for a range of riverscape attributes.

The method comprises four basic stages that were used to design the assessment procedure: (1) the identification of the relevant riverscape attributes and land-cover types that determine the type and level of ecosystem service; (2) the development of a system for extracting the riverscape attributes and land cover type data from aerial imagery and hydrological and asset datasets at the river reach scale; (3) the establishment of a protocol for assigning riverscape attributes to individual river ecosystem services through a robust method for scoring and producing ecosystem service metrics and river indices; and (4) the incorporation of a classification for assigning indicative geomorphic river types at the reach scale.

5.3.1 Stage 1: 'Riverscape attribute- ecosystem service Linkage matrix'

Previously, theoretical linkages between riverscape attributes and ecosystem services have been described (L&G2015) based on principles of the RES (Thorp *et al*., 2008). Here, a literature review of available scientific studies has been undertaken to determine a confidence-based linkage matrix between ten ecosystem services (Table 5-1), which were identified as pertinent to English rivers and twenty-seven riverscape attributes, which are characteristic of English river types in order to ensure the basis for the bespoke riverine ecosystem service assessment methodology is robust. The riverscape attributes and land cover types have been placed within the RESCaM framework (Figure 5-1) to demonstrate the linkages between riverscape attributes and land cover types, fluvial processes and characteristics, natural ecosystem functions and ecosystem services delivered (Table 5-2). Of the ten ecosystem services, five are categorised as provisioning services (fisheries / biological quality; agricultural crops; timber production; water supply; HEP production) and five are categorised as regulating services (Water regulation; carbon sequestration and other GHGs; water quality; erosion regulation and microclimate regulation).

Table 5-1 Ecosystem service definitions. P is provisioning, R is regulating

Ecosystem Service	Adopted definition for linkage review
Fisheries and other aquatic species (P)(Fisheries)	The ability of the ecosystem to support fish supply and aquatic organisms and to maintain functional habitat for the life cycle of fish and other species which benefit fish In the English landscape, fisheries can also be considered a cultural ecosystem service as it provides recreation.
Agricultural crops (P)	Space on the valley floor used to provide agricultural produce including crops, grazing for livestock etc
Timber(P)	The provision of materials (timber) for construction and fuel etc.
Water Supply (P)	The storage and retention capacity of an ecosystem to supply water for domestic, industrial and agricultural purposes.
Hydroelectric power or HEP (P)	Generation of hydroelectric power through utilisation of weirs and dams
Water regulation (R)	The ability of the river to regulate hydrological flows in a catchment, in particular, its capacity to buffer extreme discharges and mitigate against flooding and drought.
Carbon sequestration and other greenhouse gases (GHGs) (R)	The process of capture and long-term storage of atmospheric carbon dioxide and other GHGs
Water quality (R)	The ability of the ecosystem to purify water which involves retention, recovery, and removal of excess nutrients and other pollutants and to regulate the quantity of nutrients reaching the stream network (adapted from Straton and Zander, 2009; Balvanera *et al*., 2013; Bogdan *et al*., 2016)
(Micro-)climate regulation - (R)	Climate regulation refers to the thermal regulating ability of the ecosystem and the ability to dampen temperature extremes and providing shade and shelter. (adapted from Burroughs, 2001; Houghton, 2004; Beaumont *et al*., 2007; Bonan, 2008; Fowler *et al*., 2009; Straton and Zander, 2009; UKNEA., 2011).
Erosion regulation (R)	The ability of an ecosystem to regulate (excessive) erosion and retain soils and sediments as channel bedforms and on the floodplain.

Table 5-2: Linkages between riverscape attributes and land cover types, fluvial processes and characteristics, natural ecosystem function and ecosystem services delivered

Riverscape attributes and land cover	Inferred fluvial processes and characteristics	Natural ecosystem function	Ecosystem services identified
Riverscape connectivity (lateral and longitudinal)			
River / floodplain area ratio	With higher ratios, increased residence time of floodwaters and associated deposition of sediment from suspension	Flood attenuation; sediment storage and filtration of pollutants; channel dynamism; habitat creation; refugia	Fisheries / BQ; Water regulation; carbon sequestration and other GHGs; water quality; erosion regulation
Channelisation / embankments	Increased channel capacity to contain flood flows; reduced lateral connectivity with floodplain; increased sediment loading	Hydrological alteration; loss of natural land cover; increased habitat homogeneity	Fisheries/BQ; Water regulation; Water quality
Washlands	Water storage	Flow attenuation	Water regulation
Weirs			
Weirs (original)	Reduced longitudinal connectivity for water, sediment, aquatic species and mammals	Hydrological alteration; increased habitat homogeneity; decreased sediment transfer	Fisheries/BQ
Weirs (with HEP)	Reduced longitudinal connectivity for water, sediment, aquatic organisms and mammals	Hydrological alteration; increased habitat homogeneity; decreased sediment transfer	HEP production Fisheries / BQ
Weirs (with fish pass)	Reduced longitudinal connectivity for water, sediment, aquatic species and mammals (but increased connectivity for aquatic species compared with weirs without fish pass)	Hydrological alteration; increased habitat homogeneity; decreased sediment transfer	Competing evidence
Reservoir and dam unit	Reduced longitudinal connectivity for water, sediment, aquatic species and mammals	Hydrological alteration; increased habitat homogeneity; decreased sediment transfer; loss of natural land cover	Water supply; Water regulation Fisheries / BQ
Geomorphic complexity			
Bar	Variability in hydraulic and substrate characteristics; sediment transfer	Increased wetted perimeter; habitat creation	Fisheries/BQ
Backwater	Variability in hydraulic and substrate characteristics; sediment transfer	Increased wetted perimeter; refugia; hydraulic diversity	Fisheries/BQ

Pool	Variability in hydraulic and substrate characteristics; sediment transfer	Increased wetted perimeter; refugia	Fisheries/BQ
Riffle	Variability in hydraulic and substrate characteristics; sediment transfer	Hydraulic diversity; sediment storage; spawning habitat	Fisheries/BQ
Woody material	Variability in hydraulic and substrate characteristics; scour promotion	Hydraulic diversity; refugia; sediment storage	Fisheries/BQ; erosion regulation; water regulation
Boulder	Variability in hydraulic and substrate characteristics; scour promotion	Hydraulic diversity; refugia; sediment storage	Fisheries/BQ
Mid-channel island	Variability in hydraulic and substrate characteristics; sediment transfer; substrate stabilisation	Increased wetted perimeter; sediment storage; vegetation succession	Fisheries/BQ
Aquatic vegetation (macrophytes)	Substrate stabilisation	Enhanced nutrient cycling and storage; refugia	Fisheries/BQ; water quality
Palaeochannel*	Semi-aquatic habitats; plant and animal succession processes; sites for nutrient storage and transformation	Carbon sequestration, phosphorous uptake and denitrification; habitat heterogeneity, flow attenuation, refugia, channel dynamism	Insufficient evidence
Land cover type			
(Semi-)natural land			
Upland semi-natural habitats	Water storage; plant and animal succession processes; sediment retention	Enhanced nutrient cycling and storage; flow attenuation; habitat heterogeneity	Water regulation; carbon sequestration and other GHGs
Lowland wetland	Semi-aquatic habitats; water storage; plant and animal succession processes; sediment retention	Enhanced nutrient cycling and storage; flow attenuation; refugia; , phosphorous uptake and denitrification; habitat heterogeneity	Carbon sequestration; water regulation; water quality; climate regulation; water supply
Floodplain forest (broadleaf/mixed woodland)	Substrate stabilisation; enhanced hydraulic roughness;	Flow attenuation; enhanced nutrient cycling and storage; habitat complexity	Water regulation; water quality; fisheries/BQ; carbon sequestration and other GHGs
Natural lake	Water storage; nutrient cycling	Refugia; nursery areas for fish and amphibians; habitat heterogeneity	Insufficient evidence

Riparian woodland buffer	Shading, allochthonous leaf litter and woody debris input; substrate stabilisation; enhanced hydraulic roughness	Habitat creation; hydraulic diversity; refugia; cooling of water; food source; enhanced nutrient cycling and storage	Fisheries / BQ; Water quality; Erosion regulation
Riparian herbaceous buffer	Substrate stabilisation; enhanced hydraulic roughness	Enhanced nutrient cycling and storage	Insufficient evidence
Altered/converted land			
Woodland plantation	Substrate stabilisation; enhanced hydraulic roughness	Flow attenuation; biomass increase	Timber production
Felled plantation	Substrate destabilisation; increased runoff response; enhanced fine sediment input	Hydrological alteration; loss of natural land cover; excess sediment loading to river channel	Water regulation
Agricultural land	Potential for increased runoff response; enhanced fine sediment input; habitat fragmentation	Loss of natural land cover; hydrological alteration; excess sediment loading to river channel; increased habitat homogeneity	Agricultural crops Carbon sequestration and other GHGs; water quality; water regulation; erosion regulation
Amenity land	Potential for increased runoff response; potential for increased fine sediment input; habitat fragmentation	Loss of natural land cover; hydrological alteration; excess sediment loading to river channel; increased habitat homogeneity	Insufficient evidence
Developed land	Potential for increased runoff response; potential for increased fine sediment input; habitat fragmentation	Loss of natural land cover; hydrological alteration; excess sediment loading to river channel; increased habitat homogeneity	Carbon sequestration and other GHGs; water quality; water regulation;

The twenty-seven riverscape attributes and land cover types have been selected to represent *riverscape connectivity attributes*, *geomorphic complexity attributes* and *land cover types* which are characteristic of English river types. Riverscape connectivity attributes recognise hydrological connectivity longitudinally, which influence the movement of sediment and biota and laterally, which facilitates the exchange of water, carbon and nutrients between the river channel and the floodplain, influencing the biological productivity of the entire river system (Thoms and Parsons, 2003). Geomorphic complexity attributes represent 'physical patches' within the riverscape which can be defined by their hydrological, sedimentological and morphological attributes which influences ecological form and function (e.g. Thoms, 2006; Pringle *et al*., 1988, Townsend 1989; Winemiller *et al*., 2010). The type and array of geomorphic complexity attributes present across the different geomorphic river types are predictable based on river typing classifications and provide an indication of natural river functioning. Land cover types are divided into semi-natural land and altered / managed land types and include a suite of land cover classes which are easily identifiable from aerial imagery and are either prevalent or a priority for nature conservation across English riverscapes. Upland semi-natural habitats and lowland wetlands[13] are intentionally broad land cover type categories to facilitate quick and easy deployment of the methodology.

> *"Upland semi-natural habitats include large expanses of blanket bog and upland heathland, more moderate tracts of inland rock outcrop and scree habitats, mountain heaths and willow scrub, upland flushes, fens and swamps, and upland calcareous grassland, and smaller amounts of limestone*

[13] JNCC UK terrestrial & freshwater habitat descriptions 2015 https://hub.jncc.gov.uk/assets/b0b5e833-7300-4234-8ae5-bdbf326e854c Accessed on 27.07.21

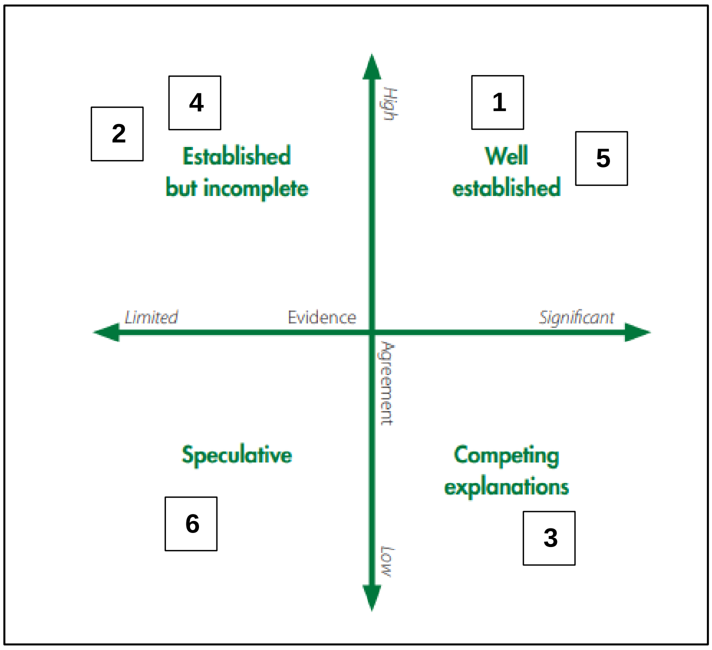
pavement and calaminarian grassland13. Typically, such habitats occur above the upper limits of agricultural enclosure, usually over 250–400 m altitude. Lowland wetland habitats include lowland raised bog and lowland fen which are typically found in topographical depressions or at the head of estuaries or along river floodplains[13]."

All twenty-seven riverscape attributes and land cover types are identifiable and measurable either through observations of aerial imagery using GE™ satellite imagery (where imagery quality /visibility allows) or with supplementary hydrological and asset datasets as GIS layers available for the whole of England (discussed in Section 5.3.2). There are likely to be incidences where professional judgement or field survey is required to gain an accurate assessment of ecosystem provision, however, efforts were made to minimise this. Riverscape attributes and land use types have been chosen to provide ease of data capture and to represent the river functions which give rise to ecosystem services. Efforts were also made to avoid double counting for individual riverscape attributes whereby more than one riverscape attribute was accounting for a single riverscape function. Double counting would potentially produce a bias towards individual ecosystem services.

Supporting / habitat services (e.g. biodiversity) are excluded from the assessment based on the adopted definition of supporting services provided by Mace *et al*. (2012). Furthermore, cultural services have been disregarded from this assessment although it is recognised that methods for measuring cultural services provided by rivers exist (Keele *et al*., 2019) and could be considered for inclusion in subsequent iterations of the methodology.

An extensive literature search of more than 280 articles was used to establish individual linkages between the twenty-seven riverscape attributes and ten ecosystem services. The literature review process involved searching the extant literature (scientific journals, technical papers, etc) and making decisions about the suitability of the material to be considered in the linkage matrix. The 'uncertainty approach' of the UK NEA (2011) which consists of a set of qualitative uncertainty terms derived from a 4-box model was adapted to assign each article with an Individual Confidence Score (ICS) of 1 - 6 describing the strength and relevance of empirical evidence (Figure 5-7) as opposed to matrices that do not present measures of uncertainty which are of limited use (Jacobs *et al*., 2015). The review considers works that have been central or pivotal to a particular linkage and may include empirical studies or conceptual papers. To gather relevant evidence, searches of key words were performed in various engines such as 'science direct' for example, "fisheries" + "geomorphic diversity" and "carbon sequestration" + "riparian woodland". Returned search results were recorded in an Excel spreadsheet and then reviewed to assess whether it provided evidence to support an individual linkage. Each article was assigned an individual confidence score.

Appendix 3.1 presents a complied list containing references to all of the individual scientific journals or technical papers which have been screened for inclusion within the linkage matrix and subsequently assigned an ICS.



Individual confidence Score	Confidence score description
1	Well established positive linkage based on significant quantitative evidence
2	Moderately established positive linkage based on limited evidence (qualitative/theoretical).
3	Competing explanations for linkage
4	Moderately established negative linkage based on limited evidence (qualitative/theoretical).
5	Well established negative linkage based on significant quantitative evidence
6	Speculative evidence

Figure 5-7 Individual confidence score descriptors applied to the literature reviewed, placed within the 4-box model, adapted from UK NEA., 2011 certainty terms

In order to determine the overall level of confidence for each linkage identified, an overall confidence score (OCS) was assigned to each linkage based on the criteria given in Table5-3. The criteria describe linkages as “well-established = 1”; “moderately established = 2” or “speculative = 3” and uses green and red coding to represent whether the linkage is positive or negative, respectively. OCSs of 1, 2 or 3 was assigned if 1 - 2, 3 - 4 or > 5 articles were identified, respectively. No score meant that evidence of a linkage was not apparent from the literature. Finally, linkages represented by articles which present competing or contradictory evidence are coded purple and possible linkages with insufficient evidence currently identified are coded blue.

Table5-3 Overall confidence score descriptors applied to each linkage in the Linkage Matrix

Overall confidence Score	Confidence score description
	River corridor feature positively contributes to ecosystem service capacity
	River corridor feature negatively contributes to ecosystem service capacity
1	Well-established linkage with strong scientific evidence supprting linkage
2	Moderately-established linkage with incomplete scientific evidence supprting linkage
3	Speculative linkage with limited scientific evidence supporting linkage
	Competing evidence: Evidence is available but contradicting and/or a range of other variables must be known to more accurately determine linkage
	More research required: Insufficient evidence currently available but a linkage is possible

The linkage matrix identifies a total of fifty-eight linkages, both positive and negative, scoring an OCS of 1 – 3. Of the fifty-eight linkages, 12 score an OCS of 3 meaning the linkage is speculative and have subsequently been excluded from contributing to the assessment going forward. Linkages showing competing evidence or insufficient evidence are also excluded. Therefore, forty-six linkages with good levels of confidence are taken forward. It is recognised that confidence scores may be subject to change as evidence becomes available to support a linkage, positive or negative and thus the linkage matrix should be viewed as a snapshot in time.

Table5-4 presents the Linkage Matrix with the full range of OCSs (Table5-3) assigned to each linkage. Palaeochannels, riparian herbaceous buffer, natural lakes and amenity land are not used in the assessment to assign scores to ES provision, due to the reasons given above and so a total of twenty-three riverscape attributes and land cover types are used for scoring. However, they remain listed due to the potential for future research to establish these linkages with greater confidence.

Table5-4 Linkage matrix identifying OCSs between riverscape attributes and land cover and ecosystem service provision

	Provisioning					Regulating				
Riverscape attributes and land cover	Fisheries/ BQ	Agricultural crops	Timber production	Water Supply	HEP production	Water regulation / NFM	Carbon sequestration and other GHGs	Water quality	Erosion regulation	Climate regulation
Riverscape connectivity (lateral and longitudinal)										
River / floodplain area ratio	1					1	1	1	3	
Channelisation / embankments	1					3		3		
Washlands (formal)						1				
Weirs										
Original	1									
Modified for HEP	1				2					
Modified for fish passage										
Reservoir and dam unit	3			1		3		*		
Geomorphic complexity										
Bars	2									
Backwaters	1									
Pools	2									
Riffles	2									
Woody material	1					2			1	
Boulders	1							*		
Mid-channel islands	2									
Aquatic vegetation	1							2		
Palaeochannels										
Land cover type										
(Semi-)natural land										
Upland semi-natural habitats						2	1			

Lowland wetlands	*			3		2	2	2		1
Floodplain forest (broadleaf/mixed woodland)	1					1	1	2		*
Riparian woodland buffer	1					1	2	1	1	1
Riparian herbaceous buffer	3							3	3	
Natural lake				3						*
Altered/converted land										
Woodland plantation			1							*
Felled plantation	*					3	*	2	*	
Agricultural land		1					1	1	3	
Amenity land										
Developed land						1	2	1		

5.3.2 Stage 2: Extraction of riverscape attributes and land cover classes remotely

Data on riverscape attributes and land cover type is extracted using multiple data sources including GE^{TM} aerial imagery and Environment Agency hydrological and assets datasets containing spatial information on river structures; flood defences; land management assets and flood zone maps for planning (Table 5-5). Table 5-6 lists the riverscape attributes considered in the assessment, the evidence as observed in GE^{TM}, the protocols for measurement and any supplementary datasets which are used to facilitate delineation and measurement of some riverscape attributes. All extracted data is recorded in an excel spreadsheet.

Table 5-5 Datasets used in the assessment to supplement the extraction of riverscape attributes and land cover types (various sources, listed in footnote).

Title	Description
Google Earth imagery [1]	Satellite imagery
Flood Map for Planning (Rivers and Sea) - Flood Zone 3 [2]	"The Flood Map for Planning (Rivers and Sea) includes several layers of information. This dataset covers Flood Zone 3. It is our best estimate of the areas of land at risk of flooding, when the presence of flood defences are ignored and covers land with a 1 in 100 (1%) or greater chance of flooding each year from Rivers; or with a 1 in 200 (0.5%) or greater chance of flooding each year from the Sea. This dataset is designed to support flood risk assessments in line with Planning Practice Guidance; and raise awareness of the likelihood of flooding to encourage people living and working in areas prone to flooding to find out more and take appropriate action. The information provided is largely based on modelled data and is therefore indicative rather than specific. Locations may also be at risk from other sources of flooding, such as high groundwater levels, overland run off from heavy rain, or failure of infrastructure such as sewers and storm drains".
AIMS Structure [2]	"An asset used to control the flow of water Asset Sub-Types include: Control Gate, Draw Off Tower, Fish Pass, Hydrobrake, In Channel Stoplogs, Inspection Chamber, Jetty, Outfall, Screen, Spillway, Stilling Basin, Weir"
AIMS Spatial Flood Defences (inc. standardised attributes) [2]	"The Environment Agency's (EA) Spatial Flood defences layer is the only comprehensive and up-to-date dataset in England that shows flood defences currently owned, managed or inspected by the EA. Flood defences can be structures, buildings or parts of buildings. Typically these are earth banks, stone and concrete walls, or sheet-piling that is used to prevent or control the extent of flooding. A defence is any asset that provides flood defence or coastal protection functions. This includes both man-made and natural defences. Natural defences may include man-made elements to make them more effective or protect them from erosion. Normally a number of assets will be used together to manage the risk in a particular area, working in combination within a risk management system".

AIMS Land[2]	An area of land that is involved in water management. Asset Sub-Types include: Mudflats, Residual Land, Salt Marsh, Washland
Wetland vision layer[3]	"A 50 year Vision for England's Wetland Landscape: Securing a future for nature, people and the historic environment The Wetland Vision is to restore wetlands for the benefit of society through the conservation of their biodiversity, the preservation of the historic environment and other benefits such as flood mitigation and carbon sequestration". "©Wetland Vision, a partnership between Environment Agency, English Heritage, Natural England, RSPB, and The Wildlife Trusts. Derived from data supplied by the Environment Agency © and Database Rights the Environment Agency 2008. Derived from data supplied by Natural England Natural England 2008. This map is based upon Ordnance Survey material with the permission of Ordnance Survey on behalf of the Controller of Her Majesty's Stationery Office © Crown copyright. Unauthorised reproduction infringes Crown copyright and may lead to prosecution or civil proceedings. Natural England 100046223 2008"

[1] Available at: https://www.google.com/earth/index.html
[2] Available through the DEFRA data services platform at https://environment.data.gov.uk/
[3] Available at https://www.arcgis.com/home/item.html?id=92412589e2aa47abb0861a3224707c0c

Table 5-6 Riverscape attributes and land cover types and their observable evidence in Google Earth and supplementary dataset together with their method of delineation and measurement (modified from Large and Gilvear., 2015 and Keele et al., 2019)

Riverscape attributes and land cover	Observable evidence	Measurement protocol	Supplementary datasets
Riverscape connectivity (lateral and longitudinal)			
River / river corridor ratio	River width: Wetted width and unvegetated exposed sediment River corridor width: Use 1 in 100 year flood map outline to define floodplain extent	Measure the channel width; average of three measurements; upper, middle and lower quartile / length to get channel area Measure the floodplain area using flood maps to delineate floodplain extent. Minus channel area from floodplain area.	1 in 100 year flood map
Channelisation / embankments	Includes straightened reaches and reaches with reinforced bed and banks. Can sometimes be observed as raised parallel features of earth or constructed material EA Asset dataset contains England wide asset information on EA managed and third party managed embankments and can be used to aid identification	Measure the length of channel that is channelised or embanked and convert to percentage. Sum of both banks = 100%	EA asset database (defences).
Washlands	Area of land within the floodplain, designated as a formal washland. Usually contained by embankments with a flow control structure / spillway regulating flows.	Estimate the percentage area covering floodplain	EA asset database
Weirs			
original	Uniform structure extending laterally across the full width of channel; uniform water surface ponded behind it	Count the number of weirs present. If unclear on condition/modification, assume worst case scenario i.e. weir present represents 'original'	EA asset database (structures)
with HEP	Structure extending laterally across the full width of the channel with turbine unit; uniform water surface ponded behind it	Count the number of weirs present. If unclear on condition/modification, assume worst case scenario i.e. weir present represents 'original'	EA asset database (structures)
with fish passage	Structure extending laterally across the full width of channel appearing modified with non-uniform section to one-side; uniform water surface ponded behind it	Count the number of weirs present. If unclear on condition/modification, assume worst case scenario i.e. weir present represents 'original'	EA asset database (structures)
Reservoir and dam unit	A large concrete structure holding back water with a lower elevation below the structure. Reservoir unit is clearly visible	Present of absent	
Geomorphic complexity			
Bars	Exposed sediment within channel margin; unvegetated	Estimate percentage abundance of exposed bars	

Backwaters	Anabranching channels from main channel; can be dry in normal - low flow conditions	Estimate percentage abundance of backwaters channel in relation to main channel	
Pools	Darker area of water, usually on outside of bend	Estimate percentage abundance of pools occupying river channel	
Riffles	Lighter area of more turbulent water extending full width of channel	Estimate percentage abundance of riffles occupying river channel	
Woody material	Elongated obstruction protruding through water surface. May be a single tree/branch/root ball or multiple; may extend full width or partial width of channel.	Estimate percentage abundance of woody material occupying river channel	
Boulders	Large boulders protruding through water surface; water surface often appears turbulent around it	Estimate percentage abundance of exposed boulders occupying river channel	
Mid-channel islands	Vegetated island with water flowing around both sides	Estimate percentage area of mid-channel islands within river channel	
Aquatic vegetation (macrophytes)	Linear, submerged strands following direction of flow; limited to low gradient; lower energy rivers.	Estimate percentage area of channel containing aquatic vegetation	
Land cover type			
(Semi-)natural land			
Upland semi-natural habitat	Dark or rough looking patches of vegetation, may contain areas of open water. Non-uniform, textured appearance. Evidence of sheep possible in low densities.	Estimate the percentage cover in close proximity to channel	
Lowland wetland	Located in lowland areas, dark or rough looking patches of vegetation located proximal to the channel, may contain areas of open water.	Estimate percentage cover within the defined river corridor	Wetland vision layer
Floodplain forest (Broadleaf/mixed woodland)	A patch of broadleaf forest within the river corridor; usually visible as mottled, darker patches of non-uniform vegetation	Estimate the percentage cover within the defined river corridor	1 in 100 year flood map
Riparian buffer			
Woodland	A narrow, linear strip of trees bordering the channel. Up to 10m from rivers edge, beyond this it is classed as floodplain forest	Estimate the percentage length of river bank containing a woodland buffer and the density of the buffer (Sparse / dense)	
Managed land			
Woodland plantation	Dark green dense forest, trees have narrow canopies and often appear in linear patterns	Estimate the percentage cover adjacent to the river corridor	

Felled plantation	Bare disturbed ground, with or without tree stumps. May be surrounded by mature trees	Estimate the percentage cover adjacent to the river corridor	
Agricultural land	Arable: Fields with boundaries containing evidence of crops including plough lines and linear lines of vegetation and straight drainage channels Livestock: Rough grassland or grassy fields with evidence of livestock	Estimate the percentage cover adjacent to the river corridor	
Amenity land	Managed area of grassland adjacent to the channel; may contain evidence of mowing lines or recreational features such as sports pitch markings/posts, golf bunkers or picnic benches etc.	Estimate the percentage cover within the defined river corridor	1 in 100 year flood map
Developed land	Areas of human settlement; often uniform in shape with straightened boundaries	Estimate the percentage cover within the defined river corridor	1 in 100 year flood map

Riverscape connectivity attributes

The methodology requires the river width and river corridor width to be defined which provides a riverscape boundary within which to extract measurements for most other riverscape attributes and land cover types. In low-lying landscapes it can be difficult to identify the river corridor limit due to limited change in relief and upland valleys it can be difficult to determine where the edges of the valley floor meet the valley side (see L&G2015 and Chapters 3 & 4). As a way of resolving this issue for unconfined and partly confined river channels, river corridor width (or floodplain width) is set by the boundary of the 1 in 100-year indicative flood maps for planning, available for the whole of England. These maps provide the best estimate of the areas of land at risk of flooding, when the presence of flood defences are ignored (Figure 5-8).

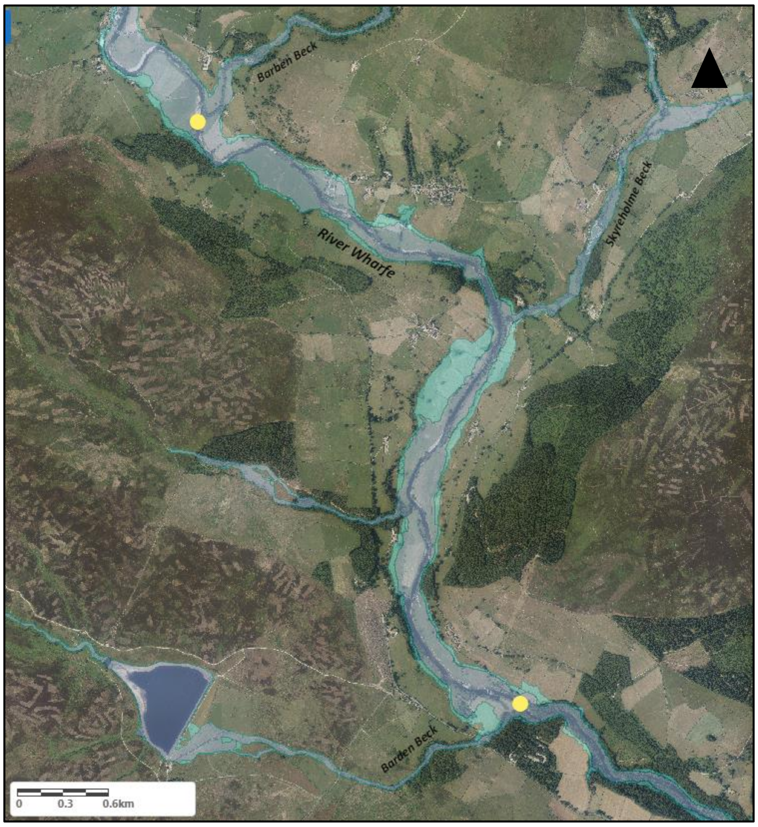


Figure 5-8 1 in 100 year (purple) and 1 in 1000 year (blue) flood map as shown for the study site on the River Wharfe

For confined river types, typically found in upland areas across England the river corridor extent is manually delineated to include an area of the valley side deemed to have the capacity to influence ecosystem service provision. Although this area is not inundated during high flows, it has the capacity to positively or negatively influence ecological functionality and thus ecosystem service provision, thus warrants recognition. For example, a wooded valley side can provide shading, a food source for aquatic organisms and supply of woody material to the river channel as well as stabilising soils on the valley side and intercepting run-off from surrounding land use practices. These processes and functions are important in upland river types for enhancing fisheries and BQ, water quality, water regulation and carbon sequestration.

Delineating the river corridor width along confined river types requires professional judgement of what is deemed to be a suitable width (minimum recommendation is 2-3 times channel width) and should be aided by aerial imagery, OS contour lines and linear features such as roads or railways for example, Figure 5-9.

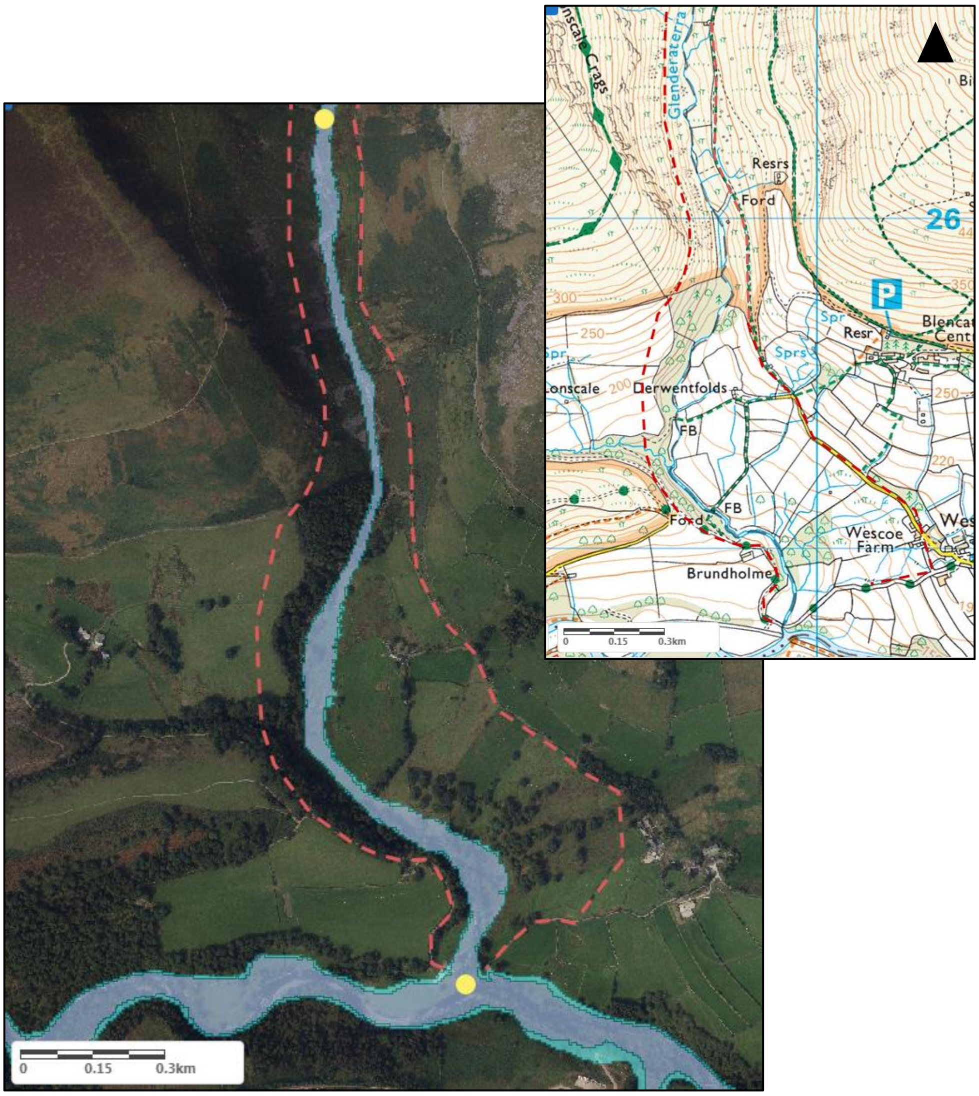


Figure 5-9 Example of manually delineated river corridor width (red dash line) for Glenderaterra Beck, Cumbria study site (indicative river types B and C)

Once the river corridor width is defined, the study sites are divided into individual river reaches which are calculated as twenty times the average channel width (as per Milner, 2010 and Gurnell *et al*., 2016). While L&G2015 recommend a minimum reach length of 500m, for application to English river corridors this is considered too coarse a spatial resolution (see Chapter 3 and 4). River reaches are delineated manually using the path and link tool in GE^{TM} (Figure 5-10). Further development could be undertaken to automate this process for widespread application.

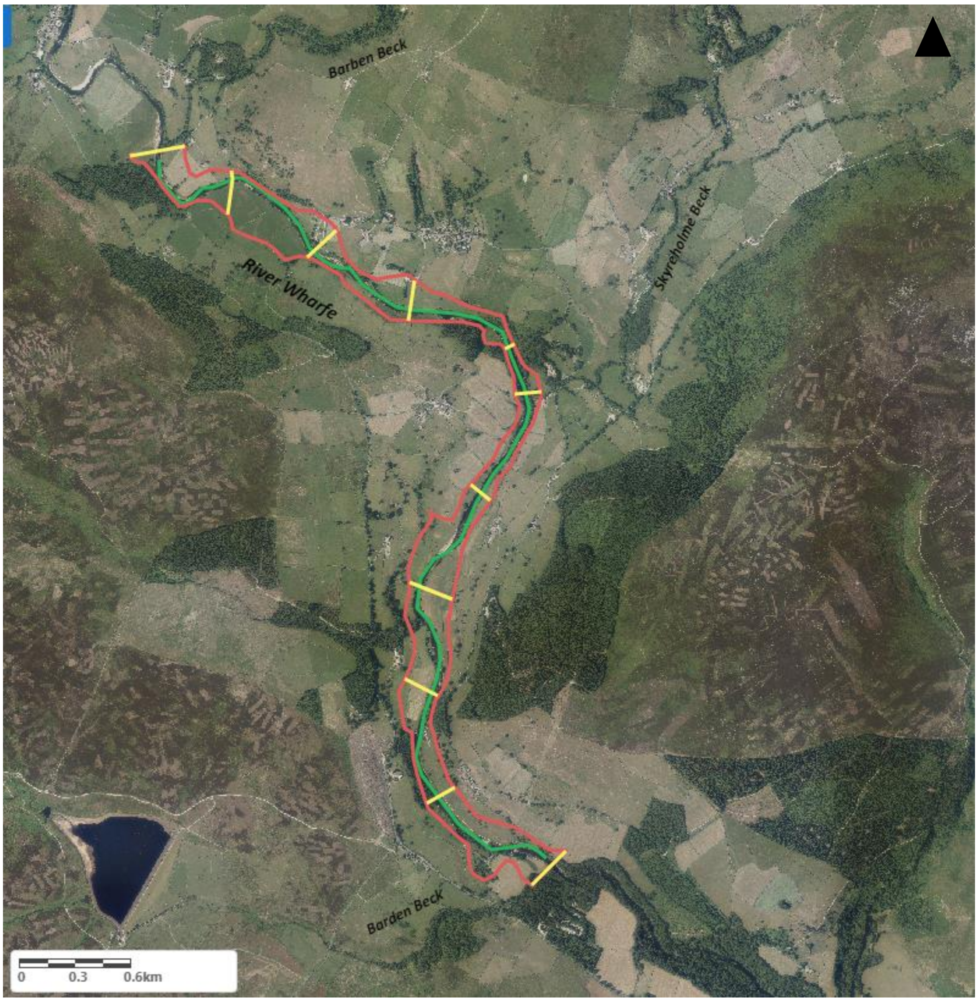


Figure 5-10 Aerial image showing the delineation of the floodplain, using the 1in100 year flood map for England (red) and division of individual reach lengths (yellow) and the river centreline (green).

Physical modifications associated with river engineering

Flood embankments have been identified as often difficult to delineate from aerial imagery, with the results of Chapter 4 confirming this attribute was often under-estimated along several study sites validated through field survey. The visibility of the attribute was often concealed due to them blending into the surrounding land cover, particularly in lowland agricultural settings. Embankments in this present study are therefore delineated using the EA AIMS Spatial Flood Defence dataset which provides a comprehensive and up-to-date dataset showing flood defences currently owned, managed or inspected by the EA, across England. This dataset displays flood defences as linear polylines (Figure 5-11). Embankments can then be accurately measured and recorded in Excel for each river reach.

Figure 5-11 Aerial image of River Ure showing EA AIMS embankment dataset whereby embankments are present along both banks. Inset demonstrates that these are not clearly visible in GE imagery,

Mills and associated river modifications such as the weirs, sluices, mill channels (leats) and mill ponds have been a feature of many English rivers for over 1000 year. While most mills are no longer operational, many of the associated river modifications such as weirs remain in place, which reduce physical habitat and hydraulic diversity and alter the assemblage of aquatic biota (Brooks *et al*., 2018).

In the assessment, weirs are sub-divided into three categories: original, modified for fish passage and modified for HEP. Some weirs may by modified for both fish passage and HEP. In this study, weirs are delineated using the EA AIMS Structure dataset which shows the spatial distribution of weirs and fish passes (amongst other structures) across England, displayed as points (Figure 5-12).

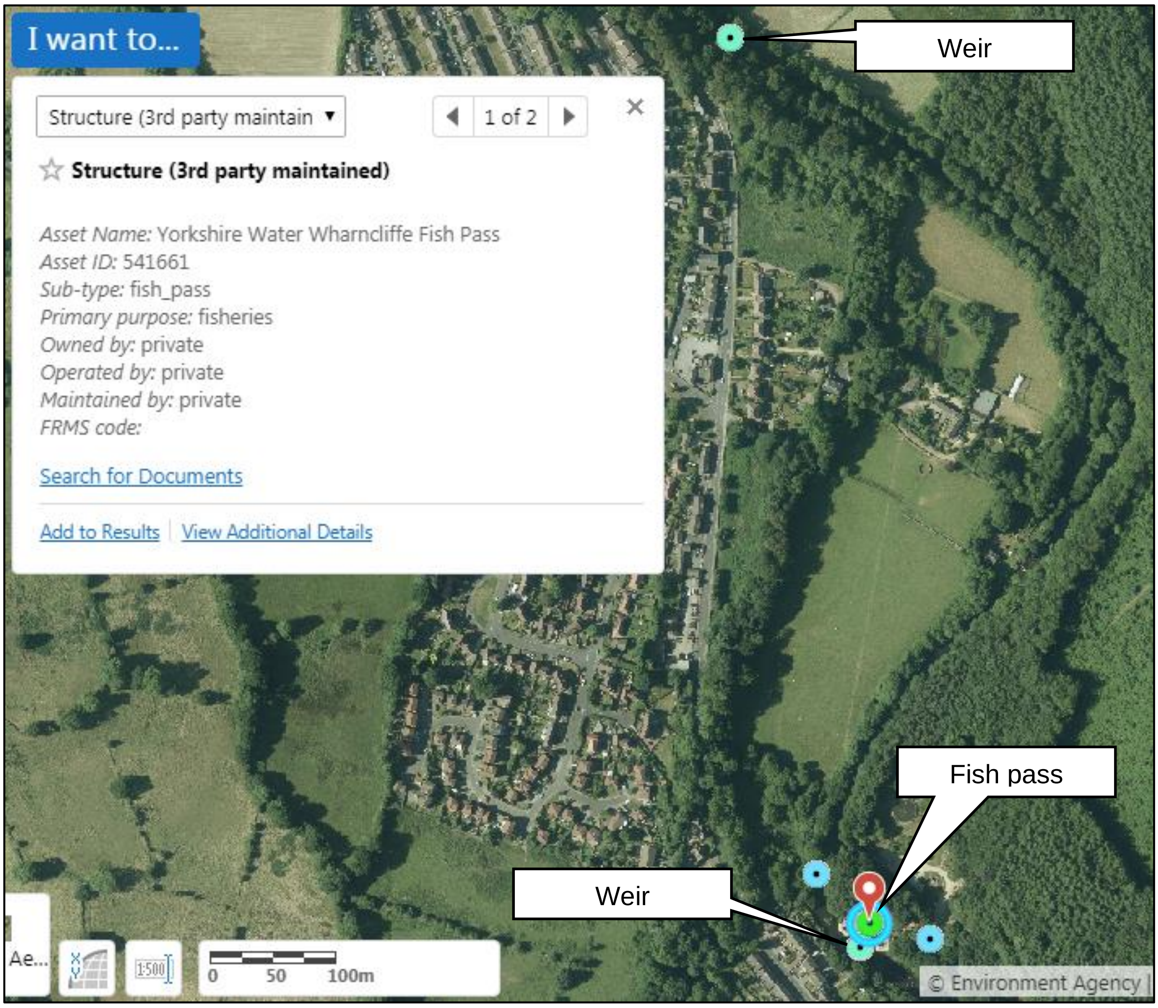


Figure 5-12 Screengrab showing EA AIMS Structure dataset point data. Example showing two weirs on the upper River Don, one with and one without a fish pass

Washlands, defined here as "an area of managed embanked floodplain that is deliberately flooded by a river or stream during times of high flow to reduce flooding in other parts of the catchment" (English Nature, 2001a), provide a method of flood defence, commonly used throughout England (Environment Agency, 2002). They are also considered to provide an opportunity for potential wetland habitat creation and to enhance biodiversity, which could contribute to the Ramsar Convention (Article 1.1) commitments; the Water Framework Directive, the UK Biodiversity Action Plan (BAP) targets, Biodiversity 2030 ambitions and the UK Government's 25Year Environment Plan (Morris *et al*., 2008). Due to their role in flood mitigation and potential for wetland habitat creation, they have been included in the assessment. Washlands are delineated using the AIMS Land dataset which provides sub-type categories for areas of land involved in water management including washlands, displayed as polygons (Figure 5-13). This layer is used to identify and measure the area of floodplain defined as a washland.

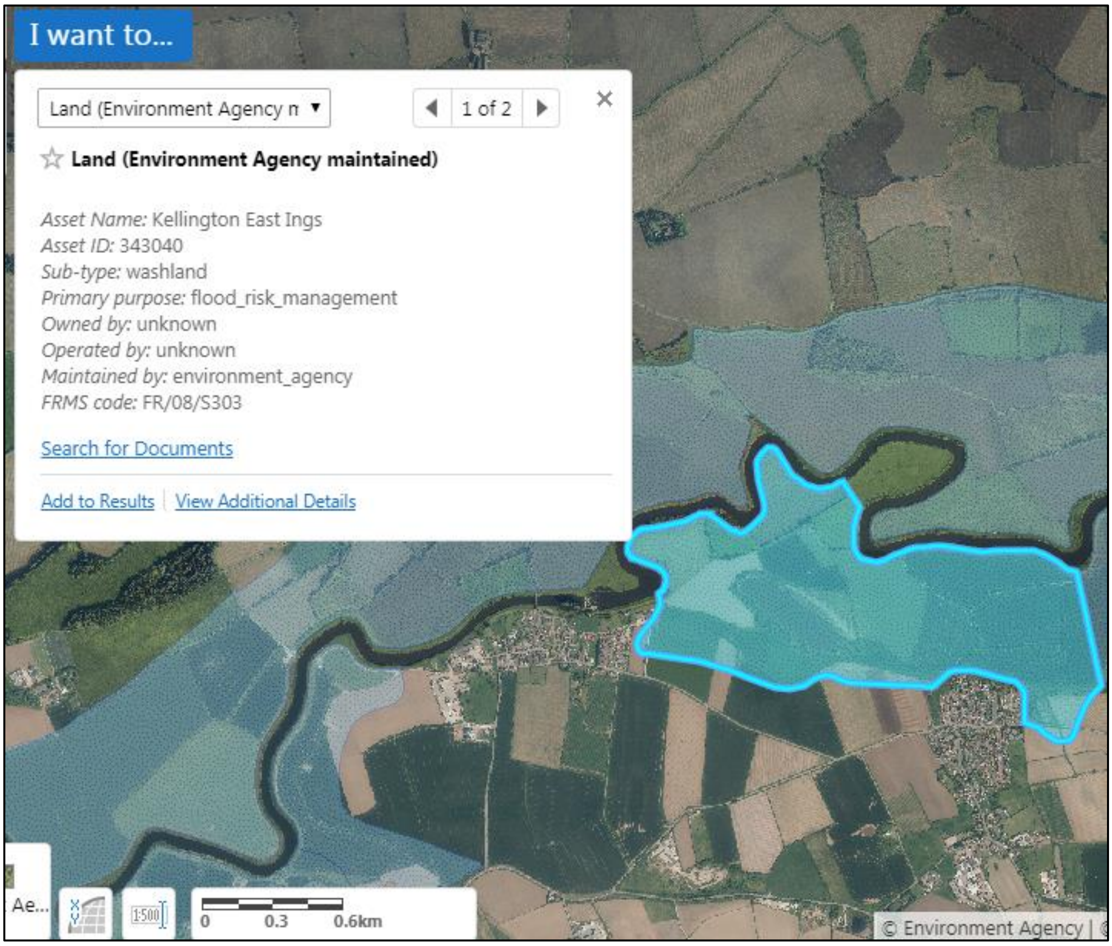


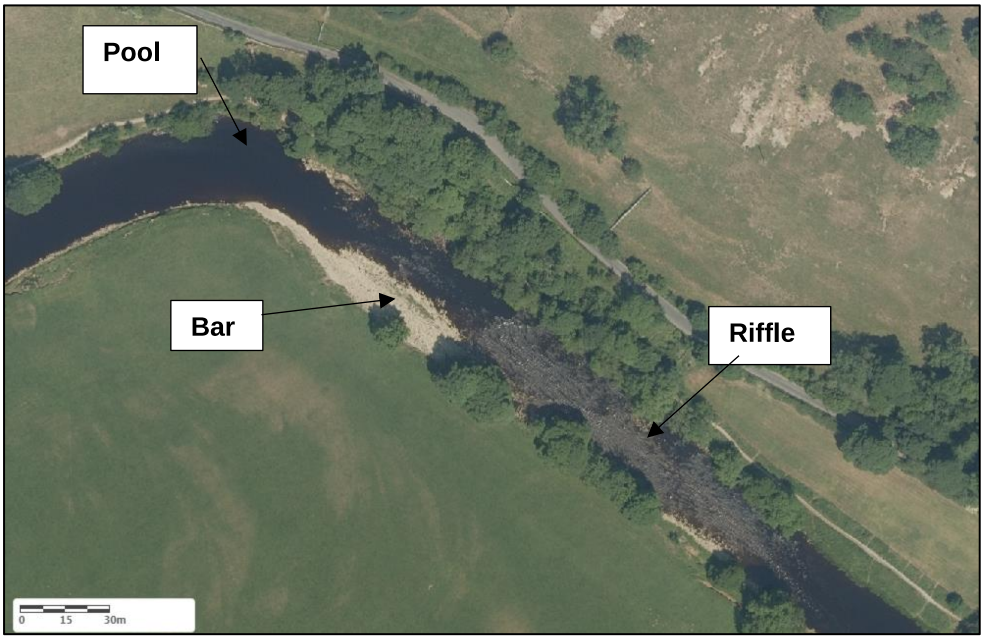
Figure 5-13 Example screengrab showing EA AIMS Land dataset showing areas of land identified as formal 'washlands'. Example given is on the lower River Aire, near Kellington

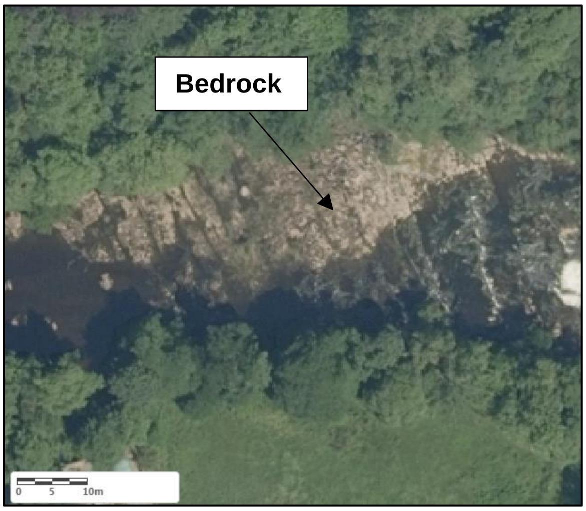
Geomorphic complexity attributes

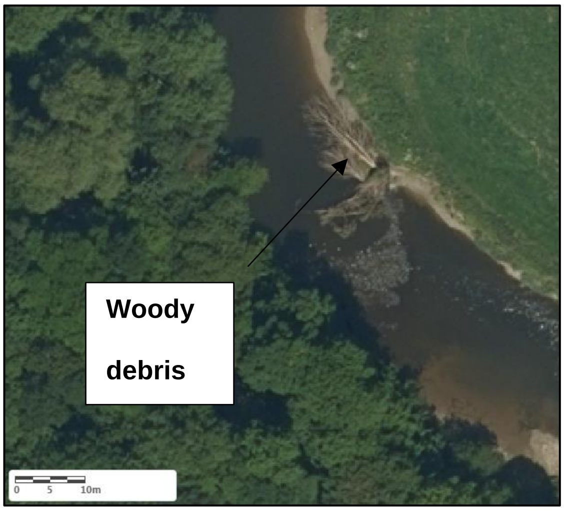
Meso-scale geomorphic complexity of a reach is the second sub-division of the riverscape attributes and includes ten individual attributes which are considered to be identifiable from aerial imagery. These attributes are typically visible during periods of low flow and thus delineation and extraction of data should seek to use GE^{TM} images that represent low flow conditions, where possible. These attributes are considered to represent individual geomorphic units (at the 10^0-10^2m scale) which are described as "an area containing a landform created by erosion of deposition of sediment, sometimes in association with vegetation" (after Gurnell *et* *al.,* 2016). Arrays of geomorphic units within close proximity to one another provide habitat heterogeneity, offering organisms a choice of habitat types, typically small streams possess considerable physical heterogeneity (Hawkins *et al.,* 1993). The attributes can form within the channel, along the channel edges or on the floodplain. Geomorphic complexity attributes include bars, backwaters, pools, riffles, woody material, boulders, mid-channel islands, aquatic vegetation and palaeochannels, all of which are considered to be characteristic of English river types. Examples of each attribute are given in

Figure 5-14, using a screengrab from GE^{TM}. Visibility of geomorphic complexity attributes will continue to present an issue in river reaches were dense tree cover or low-resolution imagery occur. To resolve this, supplementary field survey is proposed in the first instance. If this is not possible, the recommended solution is to take an average of the scores derived for the attributes not visible from reaches immediately upstream and downstream and sense check this against the indicative river type.

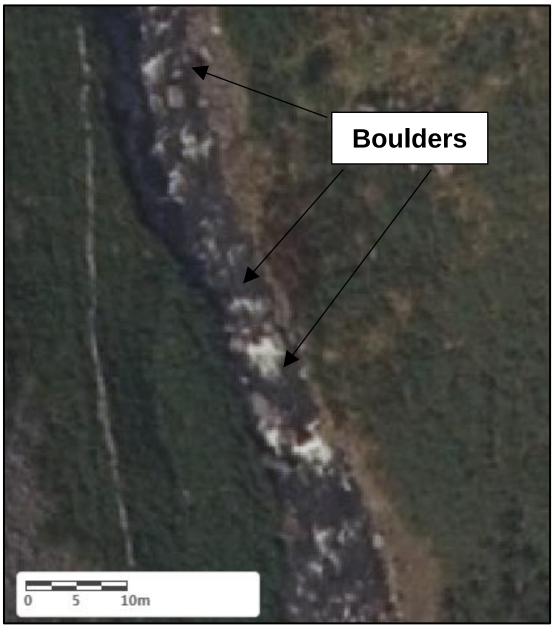
Figure 5-14 A selection of screengrabs providing examples of low flow reach-scale geomorphic complexity attributes from Google Earth imagery

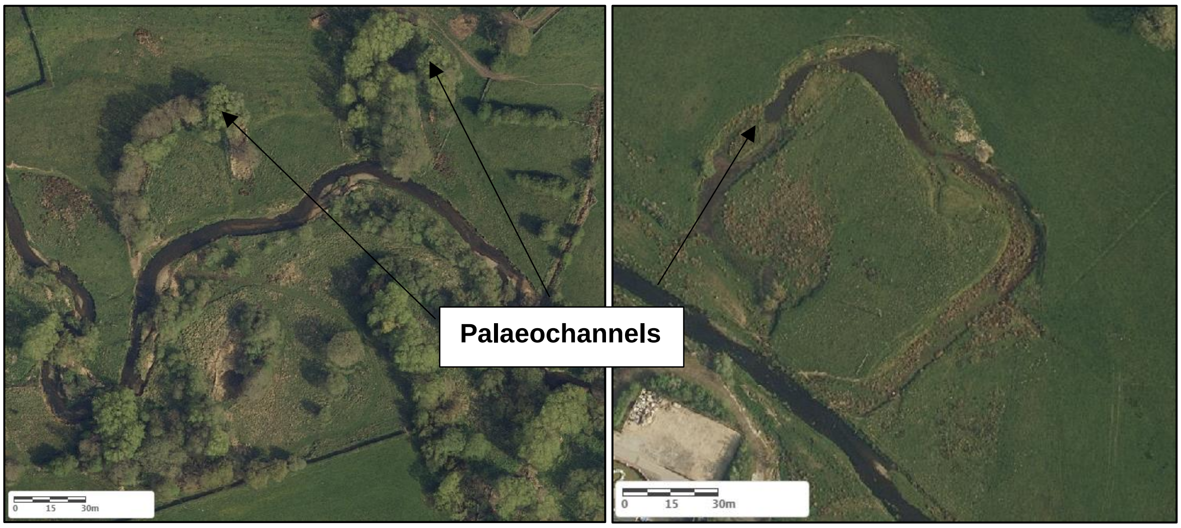



Bedrock


Woody
debris


Mid-channel
island
0 15 30m


Boulders
0 5 10m


Palaeochannels

Land cover type attributes

Finally, eleven land cover type attributes were considered in the assessment with nine of them taken forward for deriving ecosystem service provision. Methods for extracting data on these attributes broadly follow those of L&G2015. Exceptions include the addition of felled plantation and upland semi-natural habitats and changes to delineation and measurement of lowland wetlands and riparian woodland buffers. In this assessment, lowland wetlands are delineated using the Wetland Vision layer outlining the 50 year Vision for England's Wetland Landscape (Figure 5-15).

Riparian woodland buffer is identified from GE^{TM} and require visual estimates of the percentage length of river bank containing a wide riparian woodland the percentage length of river bank containing a narrow riparian woodland given the research suggests that wider buffers strips are more effective at removing nitrogen (Mayer *et al*., 2007) and providing the best protection from non-point source pollution (Hickey and Doran, 2004).

Figure 5-15 Current wetlands along the River Stour surveyed length, as indicated by the Wetlands vision layer

5.3.3 Stage 3: Scoring system for assigning riverscape attributes to individual river ecosystem services and calculation of river indices

A rule-based approach that focused on the measured riverscape attributes was used to assign scores to individual riverscape attributes at the reach-scale, as summarised in Table 5-7. This scoring system is an integer-based scoring system whereby 0 represents 'absent' or virtually no detectable contribution to ecosystem provision and 5 implies the 'optimal' or near maximum possible potential for ecosystem service provisioning. Values of 1 – 4 are assigned to intermediate states in relation to potential provision of ecosystem services. Individual riverscape attribute scores are then used to calculate river indices (Section 1.3.4).

Exceptions to this scoring system have been adopted for geomorphic complexity attribute scores, which are capped at 3 for bars, backwaters, pools, riffles, woody material, boulders and mid-channel islands and 4 for aquatic vegetation. The rationale for this is that geomorphic complexity attributes represent physical heterogeneity and thus predominantly influence the provision of 'fisheries and BQ'. For a given river reach, it is common for multiple geomorphic complexity attributes to be present and thus assigning a score of 5 could lead to disproportionately high scores for fisheries and BQ, skewing the results.

Furthermore, weirs (original) and weirs modified for fish passage can only score a maximum of 3 and 2, respectively. Weirs in their original state are deemed to cause a negative linkage with fisheries and BQ and so the scores are limited to '3' due to their presence having a negative impact but being unlikely to completely diminish fisheries and BQ provision. The rationale behind the scoring of weirs modified for fish passage is 'the greater number of weirs present within a reach, despite having fish passage structures, the less efficient the reach is at facilitating fish passage due to delays / reduced efficiency compared to a reach devoid of weirs'. So, if a reach contains 3 weirs with fish passes, it scores a 0, if it contains 2 it scores a 1 and if it has 1 it scores a 2. These scores contribute to fisheries and BQ ES. While this suggests a positive relationship between a weir with fish passage and fisheries and BQ ES provision, the balance comes from the fact that the weir will impact upon the geomorphic complexity attributes by reducing their presence and thus scores will reflect this at the reach scale.

Table 5-7 Rules for assigning scores to individual riverscape attributes and land cover types based on the data extracted on riverscape attributes and land cover types from aerial imagery and hydrological and asset datasets.

	Individual attribute score					
Riverscape attributes and land cover	0	1	2	3	4	5
Riverscape connectivity (lateral and longitudinal)						
River / floodplain area ratio	<100%	100-200%	200-500%	500-700%	700-900%	>900%
Channelisation / embankments	<5%	>5% -20%	>20% - 40%	>40% - 60%	>60% - 80%	>80%
Weirs						
Original	0	1	2	3+		
Modified for HEP / water supply	0	1	2	3	4	5+
Modified for fish passage	3+	2	1			
Reservoir and dam unit						
Geomorphic complexity						
Bars	Absent	Trace (<=10%)	Present (>10% - <=30%)	Extensive (>30%)		
Backwaters	Absent	Trace (<=10%)	Present (>10% - <=30%)	Extensive (>30%)		
Pools	Absent	Trace (<=10%)	Present (>10% - <=30%)	Extensive (>30%)		
Riffles	Absent	Trace (<=10%)	Present (>10% - <=30%)	Extensive (>30%)		
Woody material (individual or cluster)	Absent	Trace (<=10%)	Present (>10% - <=30%)	Extensive (>30%)		
Boulders	Absent	Trace (<=10%)	Present (>10% - <=30%)	Extensive (>30%)		
Mid-channel islands	Absent	Trace (<=10%)	Present (>10% - <=30%)	Extensive (>30%)		
Aquatic vegetation (macrophytes)	Absent (<5%) or choked (>75%)	Trace (<=10%)	Present (>10% - <=30%)	Extensive (>30% - <=500%)	Very extensive (>50%- <75%)	
Land cover type						

(Semi-)natural land						
Upland semi-natural habitats	<5%	>5% -<=20%	>20% - <=40%	>40% - <=60%	>60% - <=80%	>80%
Lowland wetland	<5%	>5% -<=20%	>20% - <=40%	>40% - <=60%	>60% - <=80%	>80%
Floodplain forest	<5%	>5% -<=20%	>20% - <=40%	>40% - <=60%	>60% - <=80%	>80%
Riparian woodland buffer	<5%	>5% -<=20%	>20% - <=40%	>40% - <=60%	>60% - <=80%	>80%
Altered/converted land						
Woodland plantation	<5%	>5% -<=20%	>20% - <=40%	>40% - <=60%	>60% - <=80%	>80%
Felled plantation	<5%	>5% -<=20%	>20% - <=40%	>40% - <=60%	>60% - <=80%	>80%
Agricultural land	<5%	>5% -<=20%	>20% - <=40%	>40% - <=60%	>60% - <=80%	>80%
Amenity land	<5%	>5% -<=20%	>20% - <=40%	>40% - <=60%	>60% - <=80%	>80%
Urban land cover	<5%	>5% -20%	>20% - 40%	>40% - 60%	>60% - <=80%	>80%

Calculations of river indices were done using simple mathematical tools available in the universally accessible Excel software. A spreadsheet has been created which lists the twenty-three riverscape attributes and their individual attribute reach scores (determined based on the extraction and scoring protocols outlined in Table 5-6 and Table 5-7, respectively). Formulae have been input into the spreadsheet to allow automatic generation of the variety of indices. In this application, entire river scale indices have not been determined due to the limited extent of the study sites (ten river reaches). The indices are given in Table 5-8. Equal weighting is applied across all ten ecosystem services assessed; however, further work could be undertaken to adjust the weighting if it is a deemed unsuitable for a particular application of the methodology, for example, in some catchments, some ecosystem services may be more desirable than others and thus are of greater value for society.

Table 5-8 Description of river indices calculated

Indices	Description
Reach ‘individual ecosystem service’ score (reach IESS)	Sum of each individual riverscape attribute score contributing to each ecosystem service, per river reach (based on rules for scoring Table 5-7)
Reach ‘total ecosystem service’ score (reach TESS).	Sum of all Reach IESS
River ‘total individual ecosystem system score (river TIESS)	Sum of all reach IESS for the surveyed length of river
River total ecosystem services score (River TESS)	Sum of all river TIESS for the surveyed length of river
Reach Provisioning Ecosystem Service score (reach PESS)	Reach IESS grouped according to provisioning category
Reach Regulating Ecosystem service score reach RESS	Reach IESS grouped according to regulating category
River Provisioning Ecosystem Service score (river PESS)	River IESS grouped according to provisioning category
River regulating ecosystem service score river RESS	River IESS grouped according to regulating category

The formulae used to derive reach IESS scores are given in Table 5-9 and account for both positive and negative relationships amongst individual riverscape attributes and individual ecosystem services, based on the findings of the linkage matrix. This has been a significant advancement on the L&G2015 methodology which only recognises positive relationships despite the recognition that managing landscapes for ecosystem services also requires consideration of adverse impacts (Potschin & Haines-Young, 2011; Rodríguez *et al*., 2006; Seppelt *et al*., 2011). Negative linkages are associated with physical modifications (embankments, weirs and reservoirs and dam unit) and managed land use types associated with anthropogenic augmentation of the surrounding land cover (felled plantations, agricultural land and developed land) whereby it is recognised that anthropogenic use of land and water has adversely impacted the delivery of some ESs (Ekka *et al*., 2020), at the expense of providing other ecosystem services. Whilst the formulae accounts for both positive and negative interactions, the reach IESS cannot score less than zero. Zero is the minimal permissible score for an individual ecosystem service as we agree with the argument made by Keele *et al.* (2019) whereby "a negative ecosystem service is conceptually not feasible".

Table 5-9 Formulae for calculating reach IESS using individual riverscape attribute scores

Individual Ecosystem Service	Formulae for calculating reach IESS
Fisheries	= (river floodplain area ratio – channelization / embankment but score cannot go below 0) + ((bars + backwaters + pools + riffles + woody material + boulders + mid channel islands + aquatic vegetation) – (weirs: original +HEP) score cannot go below 0) + floodplain forest + riparian woodland buffer
Agricultural crops	= Score for agricultural land
Timber production	= Score for timber production
Water Supply	= reservoir and dam unit + ((natural lakes + lowland wetlands) / 2))
HEP production	= score for weirs modified for HEP (weighting?)
Water regulation	= river floodplain area ratio + washlands + (woody material where river type is A – D) + floodplain forest (broad/mixed leaf woodland) + riparian woodland buffer + upland semi-natural habitats + lowland wetland
Carbon sequestration and other GHGs	= River floodplain area ratio + upland semi-natural habitat + floodplain forest (broad/mixed leaf woodland) + riparian woodland buffer + lowland wetland – (agricultural land + developed land) (as this emits more carbon)
Water quality	= (river floodplain area ratio – embankments but cannot = <0)+floodplain forest (broad/mixed leaf woodland) + upland semi-natural habitat + lowland wetlands + aquatic macrophytes + (riparian woodland buffer-(felled plantation + agricultural land)/2) score cannot go below '0')
Erosion regulation	= woody material + riparian woodland buffer
Microclimate regulation	= riparian woodland buffer + lowland wetland

To illustrate, the rationale for the formulae used to calculate water quality provision, whereby riverscape attributes contribute to both positive and negative interactions, is given as an example. A water quality score is calculated using the formulae:

WQ = (river floodplain area ratio – embankments but cannot = <0) +
floodplain forest + lowland wetlands + aquatic macrophytes +
(riparian woodland buffer-(felled plantation + agricultural land)/2)

Water quality is strongly influenced by the degree of lateral connectivity between the river and floodplain whereby, exchanges of nutrients and sediments occur during times of inundation (Brookes and Shields, 1996; Acreman *et al*., 2003). The presence of physical modifications (e.g. flood embankments) can disrupt lateral connectivity and reduce the capacity of the ecosystem to regulate water quality. To take account of this, the score for embankments is deducted from the score for river floodplain area ratio (minimum permissible score is '0') on the basis that embankments interrupt lateral interactions between river and floodplain and thus diminish the provision of water quality. The score cannot be less than 0. Embankment removal is being adopted as a river restoration technique across parts of England, in part incentivised by the Rural Payments Agency and Natural England's 'Making space for water' incentive[14] with the aim of restoring ecological and hydrologically functionality across the river and floodplain.

Furthermore, agricultural and forestry practices have the potential to degrade water quality and physical habitats within streams (Broadmeadow and Nisbet, 2004) typically due to poor management practices and the loss of naturally functioning floodplain, although the impacts can be reduced where riparian woodland buffers are present (Hickey and Doran, 2004; Mayer *et al*., 2007; Broadmeadow and Nisbet, 2004). Riparian woodland buffers are promoted across England with the support of government incentives such as 'England Woodland Creation Offer (EWCO)' and 'The Woodland Creation and Maintenance Grant (WCM)'[15]. Therefore, the formulae for water quality considers riparian woodland buffer cover and width in relation to dampening the impacts of agricultural and forestry practices adjacent to English rivers. To capture this, the scores for agriculture and felled plantation are summed and then divided by 2, this is then deducted from the score for riparian woodland

[14] Available at https://www.gov.uk/countryside-stewardship-grants/making-space-for-water-sw12 22.07.21

[15] Available online at https://www.gov.uk/guidance/create-woodland-overview Date accessed: 22.07.21

buffer. Finally, individual scores for floodplain forest, wetlands and aquatic macrophytes are added to generate the reach IESS.

It should be noted that agriculture is still recognised as providing the ecosystem service ‘agricultural crop’ however, felled plantation is not recognised as providing the ecosystem service ‘timber provision’ as the presence of woodland plantation provides timber provision. Including both land cover types would lead to double counting of timber provision on the basis that once the woodland is felled, the capacity to provide timber provision has been removed.

5.3.4 Stage 4: Assigning indicative geomorphic river types

Recognition of the biophysical structure of the river landscape where ecosystem services are generated has been absent in ecosystem service research (Ekka *et al*., 2020). Applying a geomorphic river typing framework is proposed as a way of recognising the biophysical structure where ecosystem services are generated to inform management decisions. The proposed methodology adopts the geomorphic river type classification recently given in Gurnell *et al*., (2020) whereby river reaches are assigned one of thirteen indicative river types that may be found across England (Figure 2-10; Section 2.4.3). The decision tree shown in Section 2.4.3, Figure 2-11 is used to assign a reach of an English river to an indicative geomorphic river type using the river type variables given in Table 5-10 and the values for the river type variables given in Table 5-11.

Table 5-10 Descriptions of river type variables (source: Gurnell et al., 2020).

River type variables	Description
A1 Braiding index (BI) a	"BI assesses whether the river reach typically shows a single flowing thread of water or more than one thread. The threads of water may be separated by mid-channel bars or split into distinct channels by vegetated islands. The BI is the average number of distinct flowing threads counted across 10 equally-spaced cross-sections of the river corridor (typically spaced by at least the width of the bankfull river channel) under baseflow conditions. Reaches may be single thread (BI <=1.1) or multithread (BI>1.1) and multithread reaches may be split into wandering (BI<1.5) or braided (BI>=1.5). Note, however, that for application in England, the BI index is mainly used in coarse-bed rivers (where A8 is gravel or coarser) to discriminate single thread from multi-thread (wandering or braided) rivers. Wandering and braided rivers are not separated because both are extremely rare in England."
A2 Sinuosity index (SI)	"SI is assessed for river reaches that typically show a single thread (BI <= 1.1). SI is the ratio of the river reach length along the centre line of the (main) river channel divided by the length of the broad river or valley course. For confined rivers the valley course length should be measured along the valley centre line. For partly confined and unconfined river sections join the points of inflection between major bends with straight lines to define the valley course unless the valley side is encountered, where the line must be deflected to remain in the valley bottom. Reaches may be straight (SI <= 1.05), sinuous (1.05 < SI < 1.5), or meandering (SI >= 1.5)."
A3 Anabranching index (AI)	"AI assesses for multi-thread reaches, how many threads are typically separated by well-vegetated areas (islands) into distinct channels rather than flowing around bare or sparsely vegetated bars. The AI is the average number of distinct flowing channels separated by islands, counted across 10 equally-spaced cross-sections of the anabranching river system (typically spaced by at least the width of the anabranching belt) under baseflow conditions. Although rivers with occasional islands (1.05 < AI < 1.5) could be discriminated, for application in Britain, this index is only used in rivers where A8 is sand or finer to discriminate single thread from multi-thread, anabranching rivers. The latter are very rare and are discriminated where AI > 1.5."
A4 Level of confinement (U, PC, C)	"Unconfined, partially confined and confined is estimated from the approximate proportion of the river reach's bank length that is in contact (close proximity) to valley side slopes or ancient terraces. This can be estimated visually from map contours or from a 3-D visualisation of the reach (e.g. on Google Earth). Confined reaches have more than 90% of the total river bank length in contact Unconfined reaches have less than 10% of their total river bank length in contact Partly confined reaches have an intermediate level (between 10 and 90%) of bank-hillslope contact."
A5 Valley gradient	"Valley gradient is the difference in elevation between the start and end of the river reach divided by the length of the broad valley course. For single thread rivers the valley course length is estimated as described for index A2. For multithread reaches, the valley course length is estimated from the approximate centre line of the area enclosing the multiple river threads and any surrounding un-vegetated bars. Valley gradient is unreliable from GE™ and so assumptions are made based on other variables."
A6 Bedrock reaches	"Bedrock reaches are recorded where extensive bedrock outcrops are observed in GE (>33% length of river channel exhibits bedrock outcrops)"
A7 Coarsest bed material size class	"Assumption based on A4 and recorded geomorphic complexity attributes boulders, bars, aquatic vegetation and riffles."
A8 Average alluvial bed material size class	"Assumption based on location within catchment, A6, A7 and geomorphic complexity attributes present."

Table 5-11 Summary of river type variable values for each of the thirteen indicative river types

River type indicators	A	B	C	D	E	F	G	H	I	J	K	L	M
A1: Braiding index					>1.1	≤1.1	≤1.1						
A2: Sinuosity index						<1.5	≥1.5	<1.5	≥1.5		<1.5	≥1.5	
A3: Anabranching index								<1.5	<1.5	≥1.5	<1.5	<1.5	≥1.5
A4: Level of valley confinement	C	C	C	C	PC / U	PC / U	PC / U	PC / U	PC / U	PC / U	PC / U	PC / U	PC / U
A5: Valley gradient				≥0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01			
A6: Bedrock reaches	Extensive bedrock	Possible	Possible										
A7: Coarsest bed material size class		Bedrock or boulder	Bedrock or boulder	Bedrock or boulder	Bedrock, boulder or cobble	Bedrock, boulder or cobble	Bedrock, boulder or cobble	Gravel	Gravel	Gravel	Sand, silt or clay	Sand, silt or clay	Sand, silt or clay
A8: Average alluvial bed material size class		Boulder	Cobble	Gravel or sand	Gravel or cobble	Gravel or cobble	Gravel or cobble	Sand	Sand	Sand	silt or clay	silt or clay	Silt or clay

An indication of the maximum individual attribute scores likely to be assigned to each indicative river type when functioning naturally are presented in Table 5-12. The indicative river type does not take account of any human interventions as the aim is to test whether the river reach is displaying appropriate riverscape attributes for its assigned river type. An indication of the maximum reach IESS and reach TESS based on the formulae outlined in Table 5-9 **Error! Reference source not found.**, are presented in Table 5-13 and Figure 5-16.

Table 5-12 Likely maximum scores for individual riverscape attrbibutes for river types A – M when functioning naturally

Riverscape attributes	A	B	C	D	E	F	G	H	I	J	K	L	M	Comments
Riverscape connectivity (lateral and longitudinal)														
River / floodplain area ratio	1	1	1	1	3	3	3	5	5	5	5	5	5	Floodplain extent likely to increase with decreasing valley confinement
Channelisation / embankments	0	0	0	0	0	0	0	0	0	0	0	0	0	
Washlands	0	0	0	0	3	3	3	5	5	5	5	5	5	
Weirs														
Original	0	0	0	0	0	0	0	0	0	0	0	0	0	
modified for HEP	0	0	0	0	0	0	0	0	0	0	0	0	0	
modified for fish passage	0	0	0	0	0	0	0	0	0	0	0	0	0	
Reservoir and dam unit	5	5	5	5	0	0	0	0	0	0	0	0	0	
Geomorphic complexity														
Bars	0	0	0	0	3	2	3	2	3	0	0	0	0	Attribute typical of unconfined and partly confined river types with dominant bed size materials gravel and sand
Backwaters / high flow channels	0	0	0	0	3	2	3	2	3	2	3	3	3	Attribute typical of unconfined and partly confined river types
Pools	0	0	2	0	2	2	2	2	2	2	2	2	2	
Riffles	0	0	0	0	3	3	3	2	2	0	0	0	0	Greatest abundance in unconfined and partly confined river types with dominant bed size materials gravel and sand
Woody material	2	3	3	3	2	2	2	2	2	2	2	2	2	Little difference in potential, but steep, coarse bed streams may show higher wood retention and root exposure
Boulders	2	3	3	3	0	0	0	0	0	0	0	0	0	Boulders in modified channels may be artificial (collapsed walls; failed infrastructure) of placed as a restoration effort
Mid-channel islands	0	0	0	0	3	1	2	1	1	0	0	0	0	Attribute typical of unconfined and partly confined river types with dominant bed size materials gravel and sand
Aquatic vegetation (macrophytes)	0	0	0	0	0	0	0	2	2	2	3	3	3	Extensive, aquatic vegetation restricted to low gradient/low energy streams

Land cover type														
(Semi-)natural land														
Upland semi-natural habitat	5	5	5	5										
Lowland wetland								5	5	5	5	5	5	
Floodplain forest (Broadleaf/mixed woodland)					5	5	5							Land cover typical of partly confined or unconfined river types where floodplains are extensive
Riparian woodland buffer	5	5	5	5	5	5	5	5	5	5	5	5	5	Complex riparian buffer should be achievable on all rivers
Altered/converted land														
Woodland plantation	0	0	0	0	0	0	0	0	0	0	0	0	0	
Felled plantation	0	0	0	0	0	0	0	0	0	0	0	0	0	
Agricultural land	0	0	0	0	0	0	0	0	0	0	0	0	0	
Amenity land	0	0	0	0	0	0	0	0	0	0	0	0	0	
Urban land cover	0	0	0	0	0	0	0	0	0	0	0	0	0	

Table 5-13 Potential maximum reach IESS and reach TESS for river types A – M

Ecosystem service		A	B	C	D	E	F	G	H	I	J	K	L	M
Fisheries / biological quality	Reach IESS	10	12	14	12	29	25	28	23	25	18	20	20	20
Agricultural crops		0	0	0	0	0	0	0	0	0	0	0	0	0
Timber production		0	0	0	0	0	0	0	0	0	0	0	0	0
Water Supply		5	5	5	5	5	5	5	5	5	5	5	5	5
HEP production		0	0	0	0	0	0	0	0	0	0	0	0	0
Water regulation		13	14	14	14	15	15	15	17	17	17	17	17	17
Carbon sequestration and other GHGs		11	11	11	11	13	13	13	15	15	15	15	15	15
Water quality		11	11	11	11	13	13	13	17	17	17	18	18	18
Erosion regulation		7	8	8	8	7	7	7	7	7	7	7	7	7
Microclimate regulation		5	5	5	5	10	10	10	5	5	5	5	5	5
	Reach TESS	62	66	68	66	92	88	91	89	91	84	87	87	87
Provisioning	Reach PESS	15	17	19	17	34	30	33	28	30	23	25	25	25
Regulating (reach RESS)	(reach RESS)	47	49	49	49	58	58	58	61	61	61	62	62	62

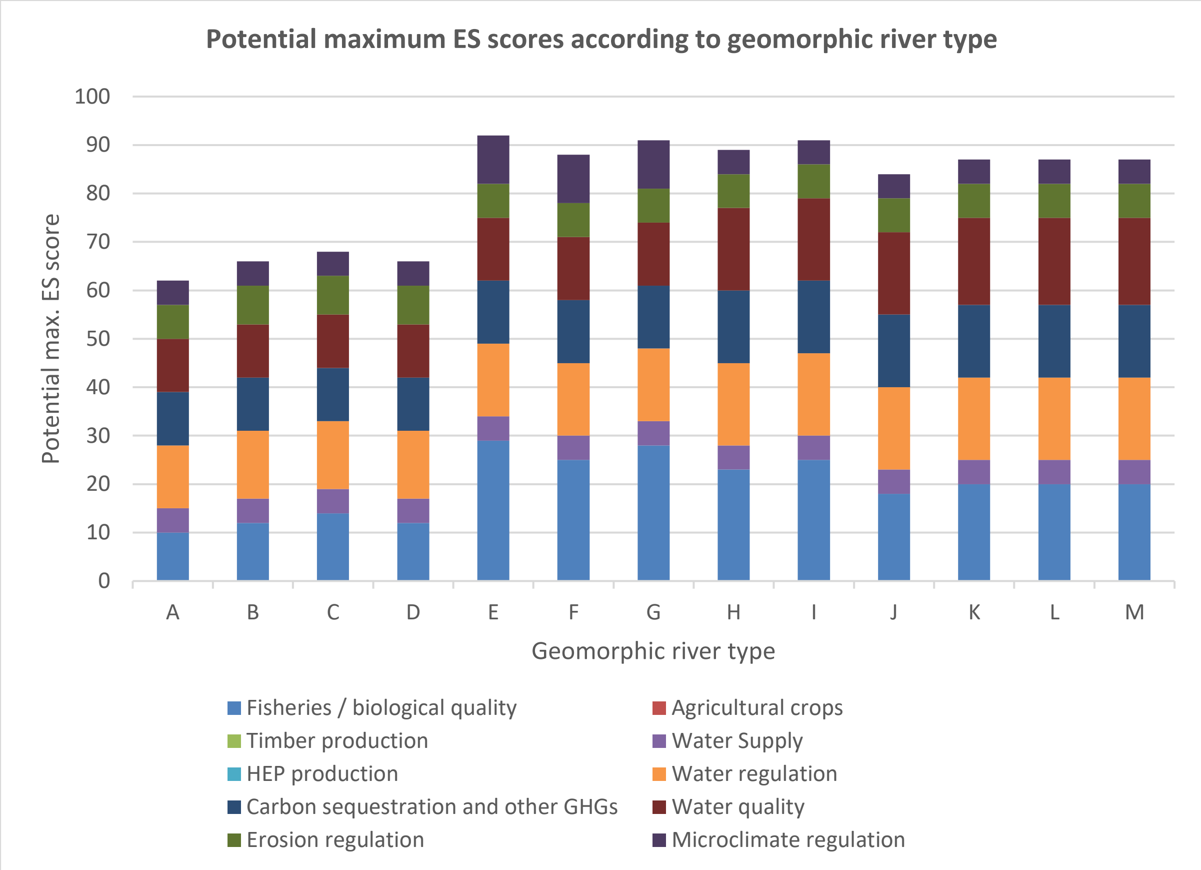


Figure 5-16 Potential maximum ES scores according to geomorphic river type for English rivers

River types A – D typically represent confined upland rivers found in England and have the lowest potential TESS of all thirteen indicative river types, with reach potential maximum TESS of between 62 - 68. This is attributed to river types A – D typically having no functional floodplain and a higher degree of channel stability and gradient which reduces the potential for geomorphic complexity and lateral connectivity between river and floodplain.

River types E to I typically represent rivers within partly confined and unconfined valleys with gravel or sand as the average bed material size. These river types show little potential variation in maximum ES scores, with potential reach TESSs between 89 – 92. Geomorphic complexity attribute potential scores are greatest in these river types representing the lower degree of channel stability and increased levels of channel dynamism.

River types K and L represent typically unconfined stable or incising lowland rivers which are common across low lying parts of England in response to historic channel modification. These river types have the potential to provide reach TESSs of 87, only slightly lower than the previous river types. However, land use change in these river types is widespread and they are typically the most ecological degraded.

River types J to M represent anastomosing river types which are rare in England and provide similar potential maximum scores to the previous (reach TESS 84 – 87).

The four study sites encompass reaches which represent seven of the thirteen geomorphic river types, covering the full spectrum from confined to unconfined and thus is considered a representative sample to demonstrate the applicability of the approach across all English river types.

5.3.5 Hypothetical restoration scenarios

Simple hypothetical scenarios have been tested the River Wharfe (reach 2) and the River Stour (reaches 5-8) to represent implementation of common river restoration techniques, with the aim of understanding the impacts these have on reach TESSs. The river restoration techniques have been selected to be compatible with the indicative geomorphic river type of the reaches based on the information outlined in Table 5-12.

Two scenarios have been tested on the River Wharfe. Scenario one includes small scale interventions within and along the river channel corridor (Figure 5-17). These are installation of woody debris and riparian woodland buffer improvements (limited to planting of a sparse riparian woodland buffer). The first intervention involves simulating the placement of large woody debris (wood), which is a common technique used to improve riverine fish habitat in streams (Roni *et al*., 2014). The second intervention involves riparian tree planting which is another widespread technique being implemented across England with the support of government incentives such as ‘England Woodland Creation Offer (EWCO)’ and ‘The Woodland Creation and Maintenance Grant (WCM)’[16]. The scores have been adjusted to represent these interventions.

Scenario two represents larger scale river and floodplain restoration (Figure 5-18) as incentivised by the Rural Payments Agency and Natural England’s ‘Making space for water’ incentive[17]. In this scenario interventions include embankment removal to improve river and floodplain hydrological connectivity by encouraging the river to flood its floodplain more frequently, to facilitating erosion, sediment transfer and depositional processes. These processes are important for creating both in-channel and floodplain ecological and morphological diversity. In addition, this scenario includes the creation of an optimal riparian woodland buffer and further tree planting within the floodplain to create patches of floodplain forest (or wet woodland).

To simulate this intervention, the scores have been changed to reflect the conversion of agricultural land use into wetland dominated habitats and the additional of an optimal riparian woodland buffer. In response to these interventions, it is also assumed that in-channel geomorphic complexity will increase through promotion of channel dynamism and heterogeneity and with increased woody debris recruitment

[16] Available online at https://www.gov.uk/guidance/create-woodland-overview Date accessed: 22.07.21
[17] Available at https://www.gov.uk/countryside-stewardship-grants/making-space-for-water-sw12 22.07.21

to the channel. The scores for the associated attributes have also been changed to reflect this This scenario would represent a permanent loss of agricultural services.

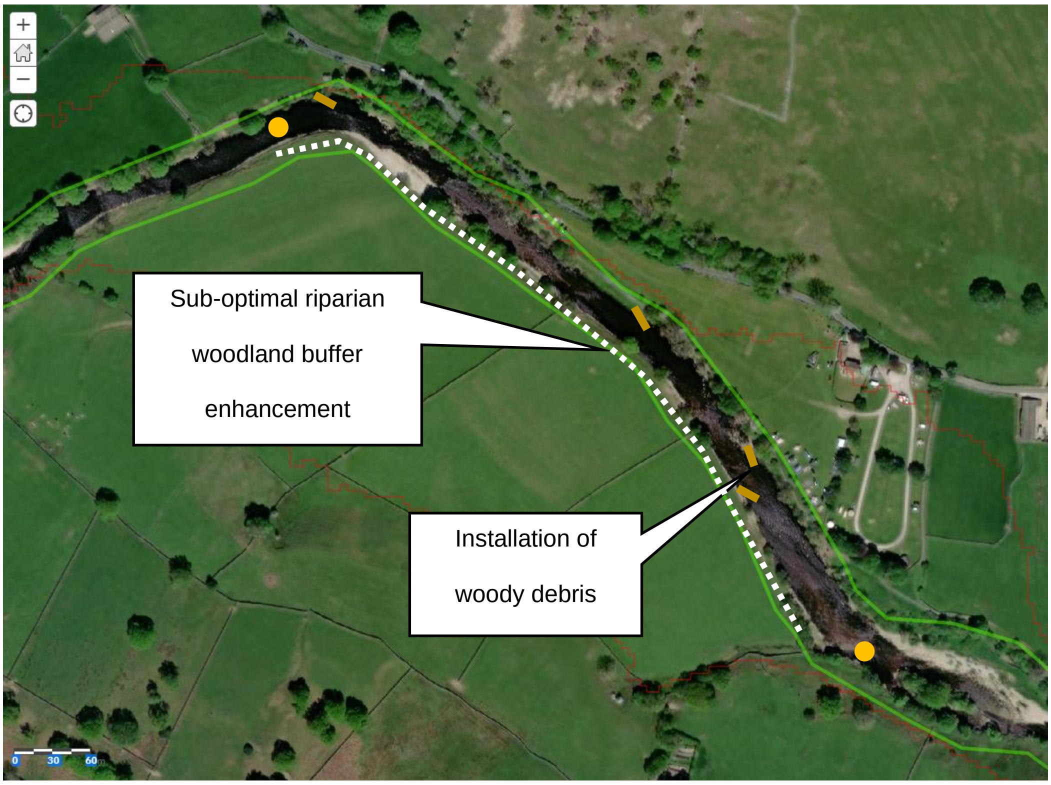


Figure 5-17 Scenario one inteventions proposed for Reach 2 of the River Wharfe. White dashed-line represents extent of sub-optiaml riparian woodland buffer creation; green line represents existing high-ground; brown lines represents installation of woody debris. Yellow dots indicate upstream and downstream limit of reach 2.

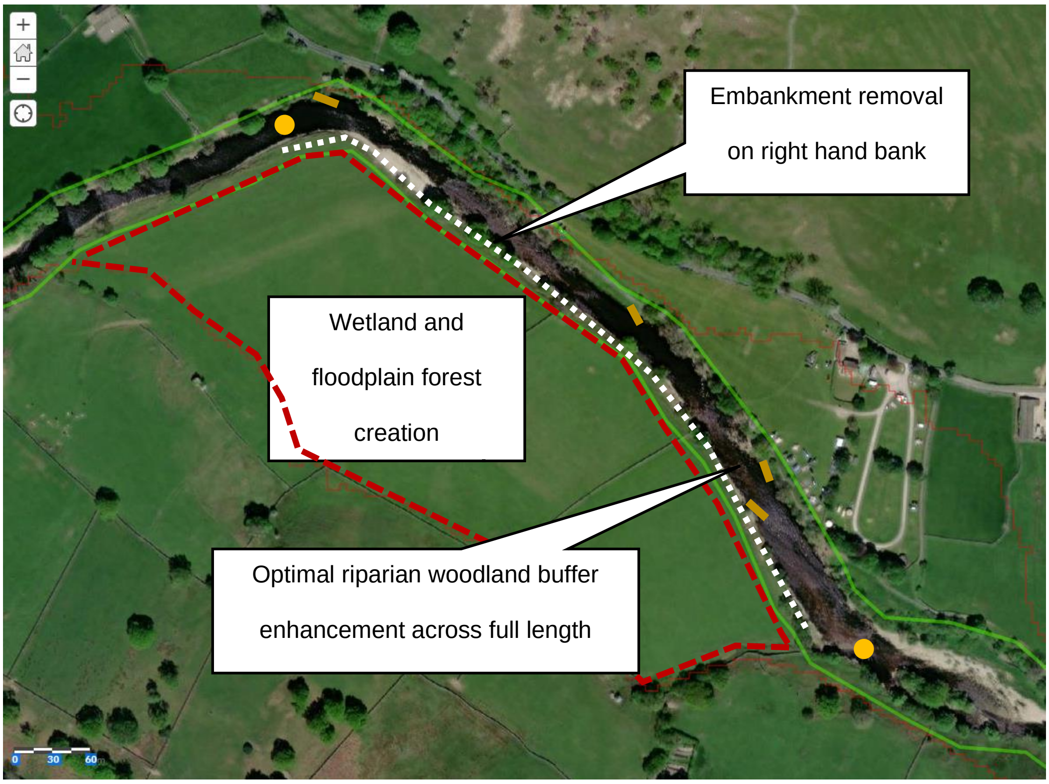


Figure 5-18 Scenario two inteventions proposed for Reach 2 of the River Wharfe. Green line represents existing high-ground/embankments; white dashed-line represents extent of riparian woodland buffer creation and embankment removal; brown lines represents installation of woody debris; red dashed-line represents area of wetland and floodplain forest creation. Yellow dots indicate upstream and downstream limit of reach 2.

One scenario has been tested on the River Stour which represents creation of lowland wetland habitats based upon the 'Wetlands Vision' layer indicating areas across England with the greatest potential for future wetland creation (Figure 5-19). The Wetland Vision is to:

> *"…restore wetlands for the benefit of society through the conservation of their biodiversity, the preservation of the historic environment and other benefits such as flood mitigation and carbon sequestration. This layer shows where future wetlands have the greatest potential to benefit biodiversity and the historic*

environment, and where we should be looking for a range of other socio-economic benefits[18.]"

The wetland vision layer suggests that large areas of land adjacent to the river Stour through the study site has been identified as having the potential to sustain wetland habitat. To create and sustain lowland wetland habitat, it is assumed that interventions would need to include the removal of lengths of “informal” river embankments (which line the entire length of the surveyed reach) to improve river and floodplain hydrological connectivity and the existing agricultural land use management would be required to cease. In response to these interventions, it is expected that lowland wetland functions will recover and as a knock-on effect, it is assumed that aquatic vegetation growth will in turn increase. These responses have been reflected in the scores given to simulate the scenario.

[18] Available at https://www.arcgis.com/home/item.html?id=92412589e2aa47abb0861a3224707c0c Accessed: 23.07.21

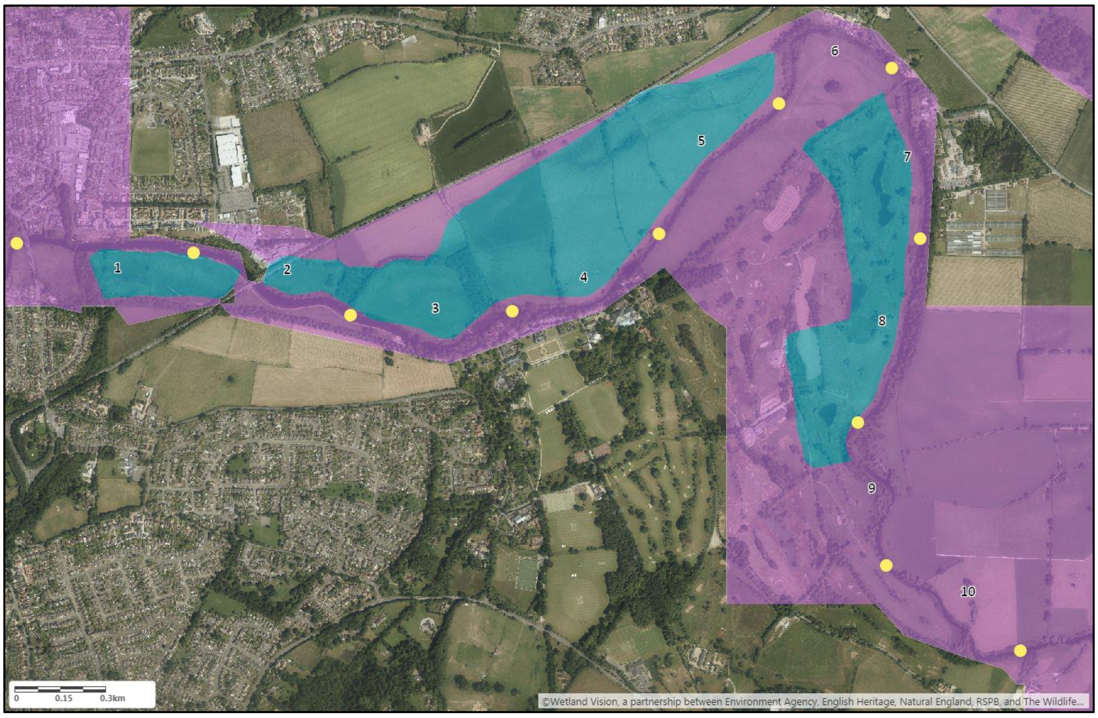


Figure 5-19 Surveyed length of River Stour showing existing wetlands (blue) and potential future wetlands (purple),

5.4 **Results**

The results are presented in Appendix 3.2 which provides the raw data extracted on riverscape attributes and the individual attribute and ecosystem service scores derived for all four study sites, in an Excel spreadsheet. Summary results for each of the study sites are given in the sections 5.4.1 to 5.4.4.

5.4.1 Glenderaterra Beck

The surveyed length of Glenderaterra Beck measures 2.2km from NGR NY2961426575 to the confluence with the River Greta at NGR NY2990324745. The average channel width is between 8 and 12m throughout the surveyed length, therefore the surveyed length has been divided into eleven individual river reaches, each reach measuring 200m in length (approximately, twenty times average channel width). Applying the criteria outlined in section 5.3.4, the indicative river types assigned to each reach are classified as either Type B or Type C.

River types B and C represent predominantly confined coarse alluvial river types, with a steep valley gradient and average alluvial bed material size class of boulder or cobble, respectively. These river types have very low river width to floodplain width ratios reducing the potential to enhance the provision of certain ecosystem services which rely on riverscape connectivity (laterally). The river corridor width is manually delineated in these river types, indicated by the red dash line in Figure 5-9, which is then used as the template for extracting data on land cover types.

Individual ecosystem service scores (Reach IESS) and total ecosystem service scores (Reach TESS) were derived for each 200m reach. The scores for each reach were amalgamated to provide reach scores for provisioning and regulating categories of services. The results are presented in Table 5-14 and Figure 5-20. Reach IESS and Reach TESS for each river reach have been compared to the potential maximum scores, according to geomorphic river type (Table 5-15 and Figure 5-21). The minimum and maximum derived reach TESS along the surveyed length of river is 17 and 66, respectively. The maximum reach TESS for the given river type is 66 for Type B and 68 for Type C. All of the river reaches assessed, with the exception of reach 10, score significantly less than there potential maximum according to river type with moderate reach-to-reach variability.

Reach 10 scored a reach TESS of 66 compared to its potential maximum score according to river type being 68. Further interrogation of reach individual attribute scores (reach IAS) and reach IESS for reach 10 reveals that the reach is partially confined (rather than confined which is typical of the river type) and thus exhibits a wider floodplain area, as defined by the 1 in 100 year flood map, than other reaches of the same river type. This resulted in a score of ‘5’ being derived for river / floodplain area ratio compared to the assigned potential maximum score according to river typing being a score of ‘1’. This subtlety in the score resulted in higher than expected ecosystem service scores for fisheries and BQ; water supply; water regulation and microclimate regulation demonstrating the significance of floodplain connectivity in raising ES provision. Furthermore, reach 10 scored a ‘2’ for agricultural crops compared to its expected score of ‘0’ for the river type which contributed further to raising reach TESS. This similarly resulted in reach IESSs for agricultural crops being higher than expected for the river type for multiple reaches (reaches 5 to 11).

Table 5-14 Glenderaterra Beck, individual and total ecosystem service scores per river reach

		Reach no. (indicative river type)										
Ecosystem service		1(C)	2(C)	3(B)	4(B)	5(B)	6(B)	7(C)	8(C)	9(C)	10(C)	11(C)
Fisheries / BQ	Reach IESS	10	9	8	7	10	11	12	13	12	17	8
Agricultural crops		0	0	0	0	1	5	4	4	2	2	5
Timber production		0	0	0	0	2	0	0	0	0	0	0
Water Supply		0	0	0	0	0	0	0	0	0	1	0
HEP production		0	0	0	0	0	0	0	0	0	0	0
Water regulation		7	6	8	6	7	6	6	8	7	12	3
Carbon sequestration and other GHGs		7	6	8	6	6.5	3.5	4	6	6	11	0.5
Water quality		7	6	8	6	6.5	3.5	4	6	6	11	0.5
Erosion regulation		0	0	1	0	4	4	3	5	5	5	0
Microclimate regulation		0	0	1	0	4	4	3	5	5	7	0
Reach TESS		31	27	34	25	41	37	36	47	43	66	17
Provisioning (Reach PESS)		10	9	8	7	13	16	16	17	14	20	13
Regulating (Reach RESS)		21	18	26	18	28	21	20	30	29	46	4

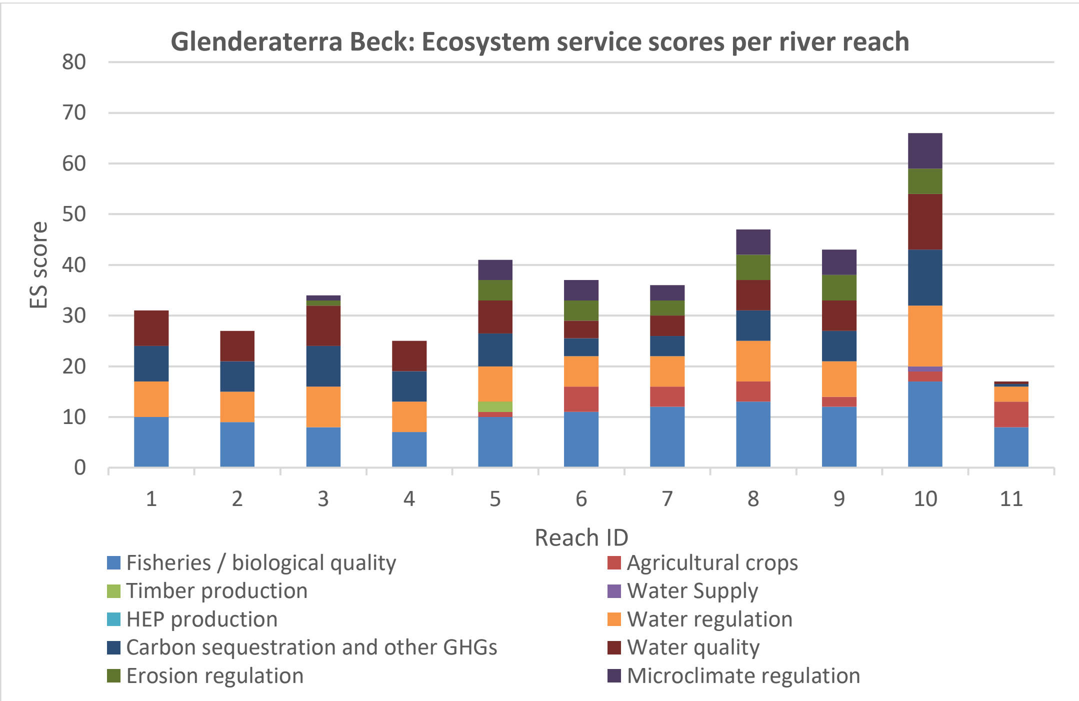


Figure 5-20 Graph showing individual and total ecosystem service scores per river reach, derived across the surveyed length of Glenderaterra Beck.

Table 5-15 Maximum potential individual and total ecosystem service scores per river reach, for indicative river types B and C

Ecosystem service		Type B	Type C
Fisheries / biological quality	Reach IESS	12	14
Agricultural crops		0	0
Timber production		0	0
Water Supply		5	5
HEP production		0	0
Water regulation		14	14
Carbon sequestration and other GHGs		11	11
Water quality		11	11
Erosion regulation		8	8
Microclimate regulation		5	5
Reach TESS		66	68

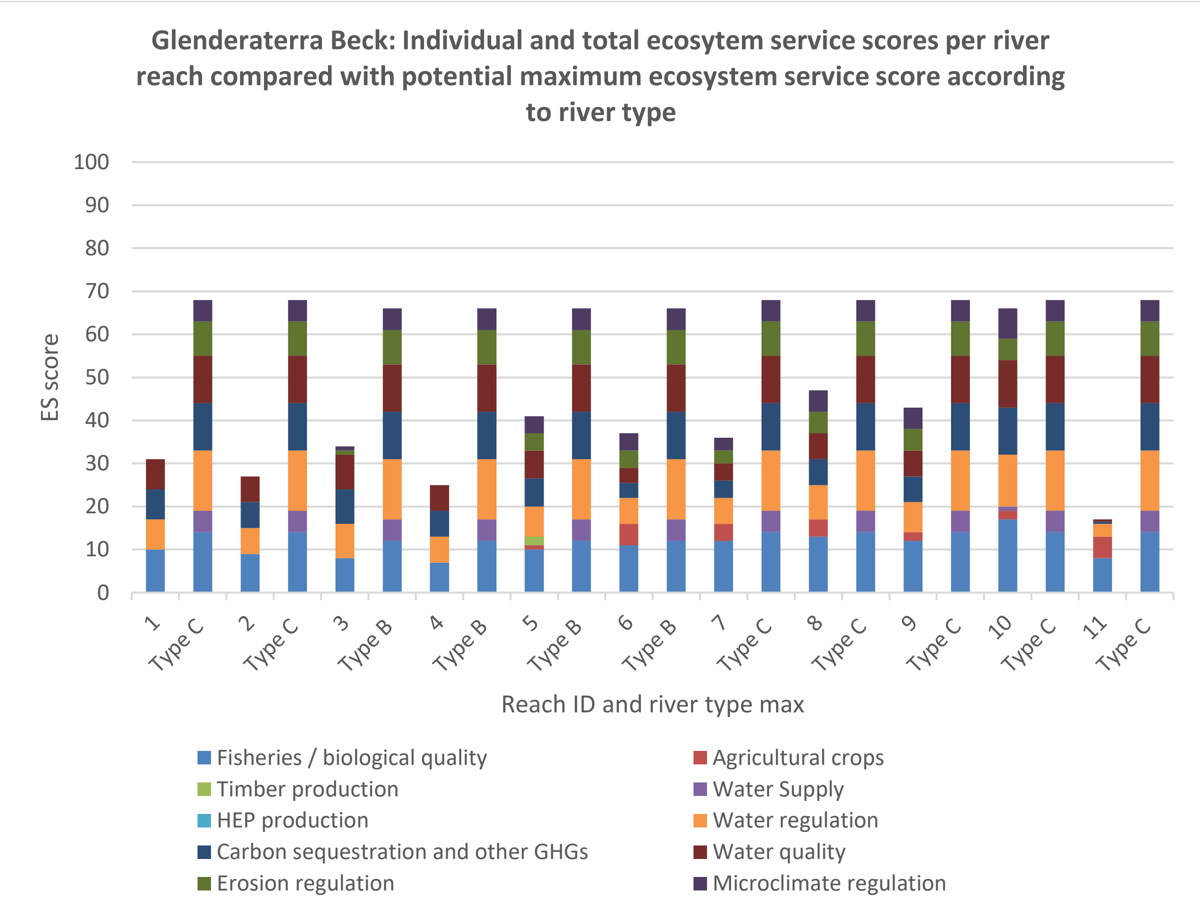


Figure 5-21 Individual and total ecosystem service scores per river reach plotted next to the maximum potential ecosystem service scores for the indicative river type, derived for surveyed length of Glenderaterra Beck

5.4.2 River Wharfe

The surveyed length of the River Wharfe measures 6-km from NGR SE0381160549 to NGR SE0585456748. The average channel width is between 28 and 37-m throughout the surveyed length, therefore the surveyed length has been divided into ten individual river reaches, each reach measuring 600-m in length (approximately, twenty times average channel width). Applying the criteria outlined in section 5.3.4, the indicative river type for each river reach has been classified as Type F.

River type F represents a partially confined river type with a straight / sinuous planform and an average alluvial bed material size class of gravel or cobble. The river corridor width is defined by the 1 in 100 year flood map for planning boundary. Typically, bedforms are expected to include pool and riffle sequences with oscillating point bars. These rivers typically exhibit moderate river width to floodplain width area ratios and thus have undergone widespread land use change to exploit the floodplain for agricultural and urban development.

Individual ecosystem service scores (Reach IESS) and total ecosystem service scores (Reach TESS) were derived for each 600m reach. The scores for each reach were amalgamated to provide reach scores for provisioning and regulating categories of services. The results are presented in Table 5-16 and Figure 5-22.

Reach IESS and Reach TESS for each river reach have been compared to the potential maximum scores, according to geomorphic river type (Table5-17and Figure 5-22). The minimum and maximum derived reach TESS along the surveyed length of river is 24.5 and 51, respectively. The maximum reach TESS for river type F is 88. All of the river reaches score significantly less than there potential maximum according to river type with moderate reach-to-reach variability.

Table 5-16 River Wharfe, individual and total ecosystem service scores per river reach

		Reach no. (indicative river type)									
Ecosystem service		1	2	3	4	5	6	7	8	9	10
Fisheries / BQ	Reach IESS	12	8	10	12	13	10	8	10	11	9
Agricultural crops		4	5	5	4	4	5	5	5	3	4
Timber production		0	0	0	1	0	0	0	0	0	0
Water Supply		1	0	0	0.5	1	0	0	0	1	0.5
HEP production		0	0	0	0	0	0	0	0	0	0
Water regulation		6	6	4	6	9	4	6	4	7	7
Carbon sequestration and other GHGs		4	3.5	1.5	4	7	1.5	3.5	1.5	5.5	5
Water quality		2	0	0	2	5	0	0	0	3.5	1
Erosion regulation		2	2	2	3	5	2	2	2	3	2
Microclimate regulation		4	2	2	4	7	2	2	2	5	3
Reach TESS		35	26.5	24.5	36.5	51	24.5	26.5	24.5	39	31.5
Provisioning (Reach PESS)		17	13	15	17.5	18	15	13	15	15	13.5
Regulating (Reach RESS)		18	13.5	9.5	19	33	9.5	13.5	9.5	24	18

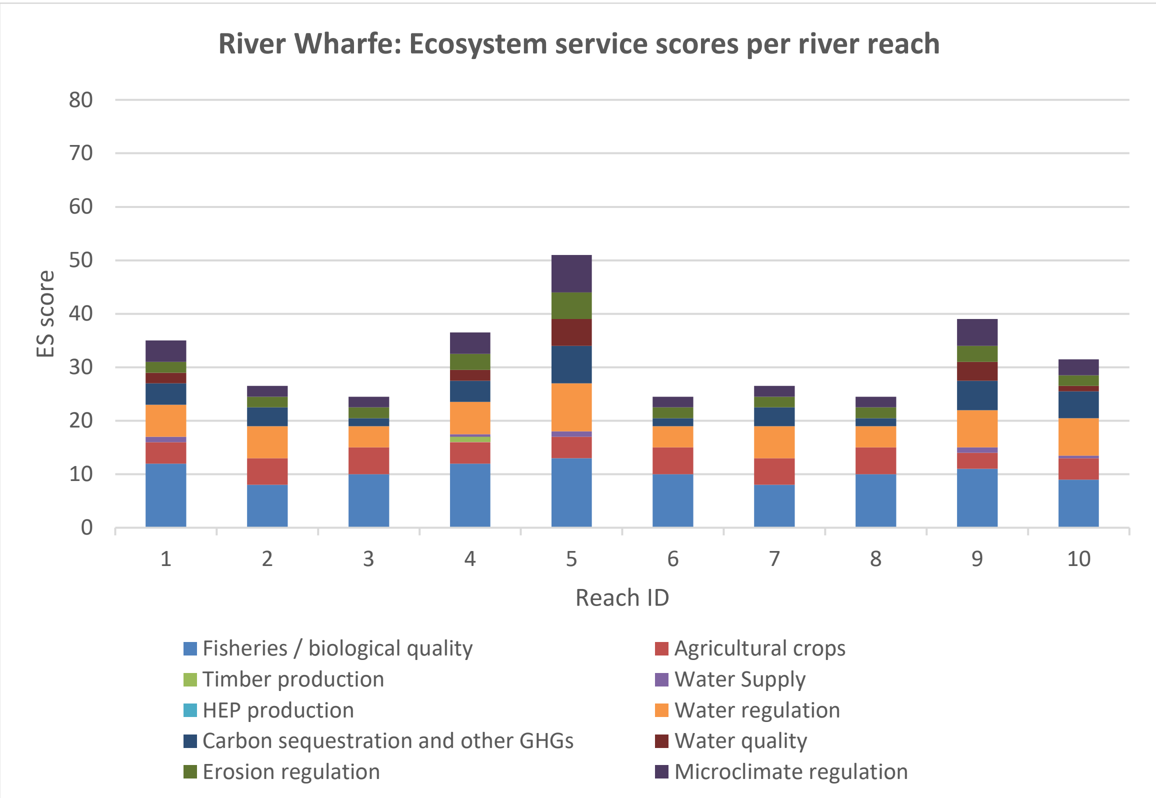


Figure 5-22 Graph showing individual and total ecosystem service scores per river reach, derived across the surveyed length of the River Wharfe

Table5-17 Maximum potential individual and total ecosystem service scores per river reach, for indicative river type F

Ecosystem service	River type F Reach IESS
Fisheries / biological quality	25
Agricultural crops	0
Timber production	0
Water Supply	5
HEP production	0
Water regulation	15
Carbon sequestration and other GHGs	13
Water quality	13
Erosion regulation	7
Microclimate regulation	10
Reach TESS	88

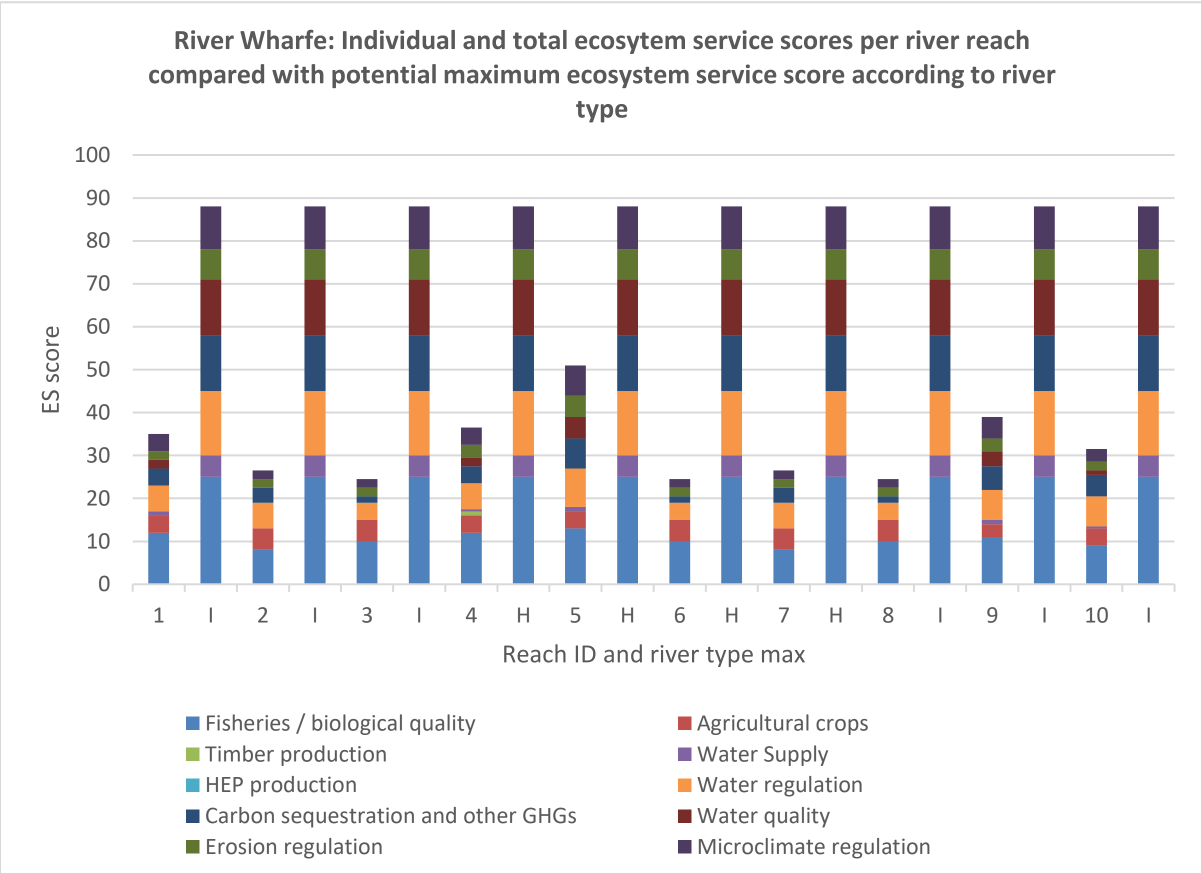


Figure 5-23 Individual and total ecosystem service scores per river reach plotted next to the maximum potential ecosystem service scores for the indicative river type, derived for surveyed length of River Wharfe

Reach 5 resulted in the highest ES score for the surveyed reach of 51. This is primarily attributed to reach 5 displayed an optimal riparian woodland buffer (scoring the maximum score of 5) whereas all other reaches where sub-optimal (scoring a 2 or 3 for this attribute). In turn, this attribute contributes to the provision of six of the ten ESs (fisheries and BQ; Water regulation; carbon sequestrations and other GHGs; water quality; erosion regulation and microclimate regulation) thus significantly increases the reach TESS. Regardless, the reach TESS remains considerably lower than its potential maximum for river type F but it does demonstrate the importance of riparian woodland buffers in raising ecosystem service provision.

Reaches 2, 3, 6, 7 and 8 resulted in the lowest overall reach TESS (between 24.5 and 26.5) which is partly attributed to a range of geomorphic complexity attributes and riparian woodland buffer scoring lower than other surveyed reaches. In addition, this reach scores highest for agricultural land, which reduces reach IESSs for water quality and carbon sequestration and other GHGs at the expense of agricultural crops, contributing to overall lower reach TESSs.

Restoration scenarios along the River Wharfe

In order to generate reach IESS and reach TESS for River Wharfe restoration scenario one (outlined in Section 5.3.5), reach IASs have been altered for *riparian woodland buffer* (reach IAS increased to ‘3’) and *woody material* (reach IAS increased to ‘2’). Reach IESS and reach TESS have been calculated based on the altered reach IASs and are presented in Table 5-18and Figure 5-24. The reach TESSs generated show a slight increase across ES provision for reach 2 compared with the baseline results, from 26.5 to 38. The reach IESSs benefitting from these measures include fisheries and BQ; water regulation; carbon sequestration and other GHGs; water quality; erosion regulation and microclimate regulation although all reach IESS remain below their potential max. Reach TESS for this scenario however, remains significantly lower than the potential maximum ES provision for river type F, which is calculated as 88. These results suggest that small scale interventions have some albeit limited benefit on increasing reach TESS to near its potential maximum.

In order to generate reach IESS and reach TESS for scenario two, reach IASs have been altered for *channelization / embankments* (reach IAS decreased to ‘2’ to represent 50% removal); *floodplain forest / mixed broadleaf woodland* (reach IAS increased to max ‘5’), *woody material* (reach IAS increased to max ‘2’), *bars* (reach IAS increased to max ‘2’) and *agricultural land* (reach IAS decreased to ‘0’). Reach IESS and reach TESS have been calculated based on the altered reach IASs and are presented in Table 5-18 and Figure 5-24. The reach TESS generated shows a significant increase compared with the baseline results, from 26.5 to 82.5, which is close to its potential maximum for river type F. These results support the findings of Addy and Wilkinson (2021) who undertook hydro-geomorphic monitoring of the lowering of a 70m long flood embankment on the upper River Dee, a medium sized gravel bed river in north-east Scotland to reconnect a backwater and floodplain

Comparisons between scenario one and two demonstrate that larger scale river restoration interventions which target both the river and floodplain are most effective at successfully raising reach IESS and reach TESS scores. This approach offers a simple but effective way of demonstrating and quantifying potential ecosystem service provision through implementing restoration interventions in a form accessible to river managers and other stakeholders.

Table 5-18 Comparison of reach IESS and reach TESS scores for baseline, restoration scenario one, restoration scenario two and river type potential maximum calculated for River Wharfe

Ecosystem service		Baseline	Restoration scenario 1	Restoration scenario 2	River type F Potential max
Fisheries / biological quality	Reach IESS	8	11	21	25
Agricultural crops		5	5	0	0
Timber production		0	0	0	0
Water Supply		0	0	2.5	5
HEP production		0	0	0	0
Water regulation		6	9	16	15
Carbon sequestration and other GHGs		3.5	4.5	14	13
Water quality		0	0.5	12	13
Erosion regulation		2	5	7	7
Microclimate regulation		2	3	10	10
Reach TESS		26.5	38	82.5	88

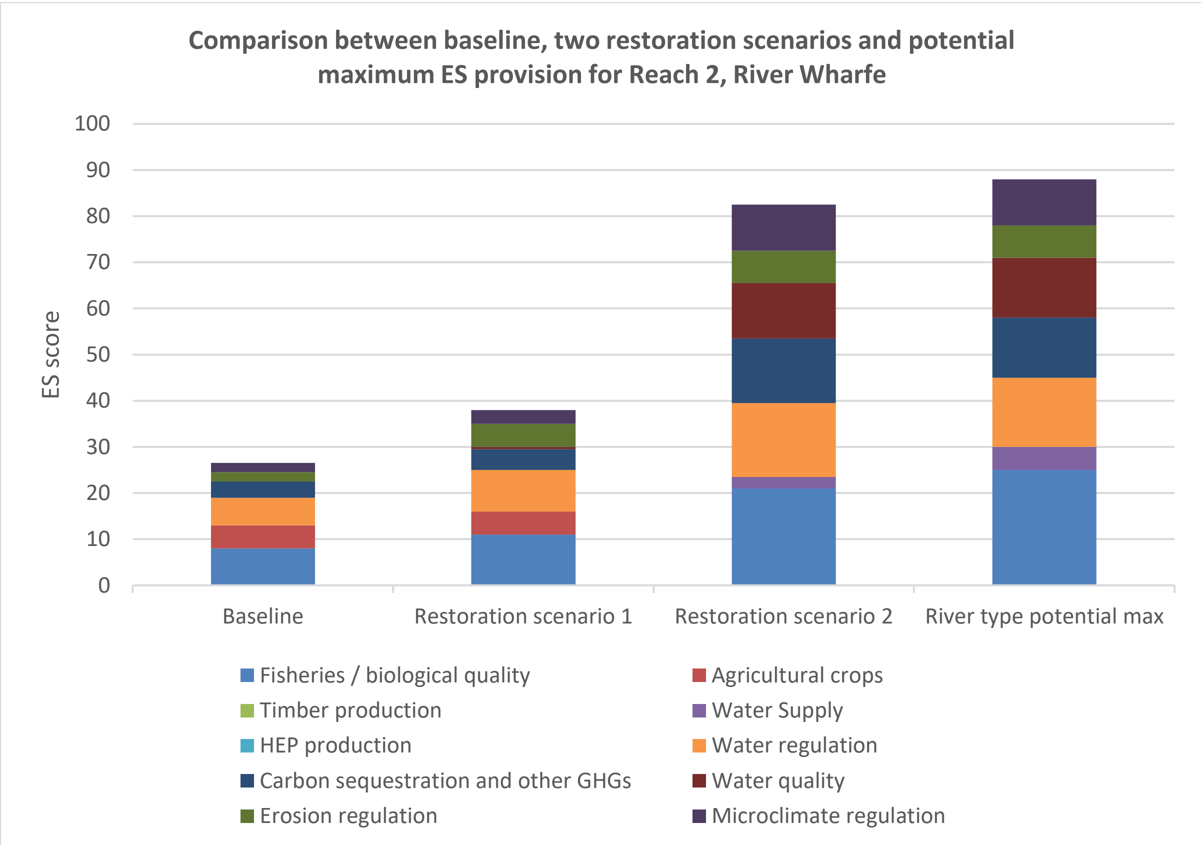


Figure 5-24 Comparison of reach IESS and reach TESS scores for baseline, restoration scenario one, restoration scenario two and river type potential maximum calculated for River Wharfe

5.4.3 River Bollin

The surveyed length of the River Bollin measures 2.4-km from NGR SJ8839979945 to NGR SJ8754180468. The average channel width is between 8 and 11-m throughout the surveyed length, therefore the surveyed length has been divided into ten individual river reaches, each reach measuring 200-m in length (approximately, twenty times average channel width). Applying the criteria outlined in section 5.3.4, the indicative river type for each reach has been classified as either Type H or Type I.

River type H and I represents partially confined river types with a straight / sinuous or meandering planform and an average alluvial bed material size class of sand with gravels representing the coarsest bed material size class. Typically, geomorphic complexity is high in these river types characterised by an array of bedforms associated with meander development and cut-off (bars, islands, pools and palaeochannels) creating a mosaic of wetland habitat. These rivers typically exhibit moderate river width to floodplain width area ratios. The river corridor width for the surveyed length is defined by the 1 in 100 year flood map for planning boundary.

Individual ecosystem service scores (Reach IESS) and total ecosystem service scores (Reach TESS) were derived for each 200m reach. The scores for each reach were amalgamated to provide reach scores for provisioning and regulating categories of services. The results are presented in Table5-19 and Figure 5-25.

Reach IESS and Reach TESS for each river reach have been compared to the potential maximum scores, according to geomorphic river type (Table5-20 and Figure 5-26). The minimum and maximum derived reach TESS along the surveyed length of river is 12 and 61.5, respectively. The maximum reach TESS for river type

H and I is 89 and 91, respectively. The results demonstrate high reach-to-reach variability with reaches one to five scoring consistently low and reaches six to ten scoring moderate to high (but not maximum).

Table5-19 River Bollin, individual and total ecosystem service scores per river reach

		Reach no. (indicative river type)									
Ecosystem service		1	2	3	4	5	6	7	8	9	10
Fisheries / BQ	Reach IESS	7	6	8	4	8	13	14	12	11	15
Agricultural crops		5	0	5	4	5	3	2	2	2	2
Timber production		0	0	0	0	0	0	0	0	0	0
Water Supply		0	0	0	0	0	1	1	0.5	0.5	1.5
HEP production		0	0	0	0	0	0	0	0	0	0
Water regulation		2	2	3	7	3	9	10	9	9	12
Carbon sequestration and other GHGs		0	2	0.5	5	0.5	7.5	9	7	8	11
Water quality		0	2	1.5	0	1.5	7.5	9	7	8	11
Erosion regulation		0	0	0	0	0	3	2	3	2	3
Microclimate regulation		0	0	0	0	0	5	4	3	3	6
Reach TESS		14	12	18	20	18	49	51	43.5	43.5	61.5
Provisioning (Reach PESS)		12	6	13	8	13	17	17	14.5	13.5	18.5
Regulating (Reach RESS)		2	6	5	12	5	32	34	29	30	43

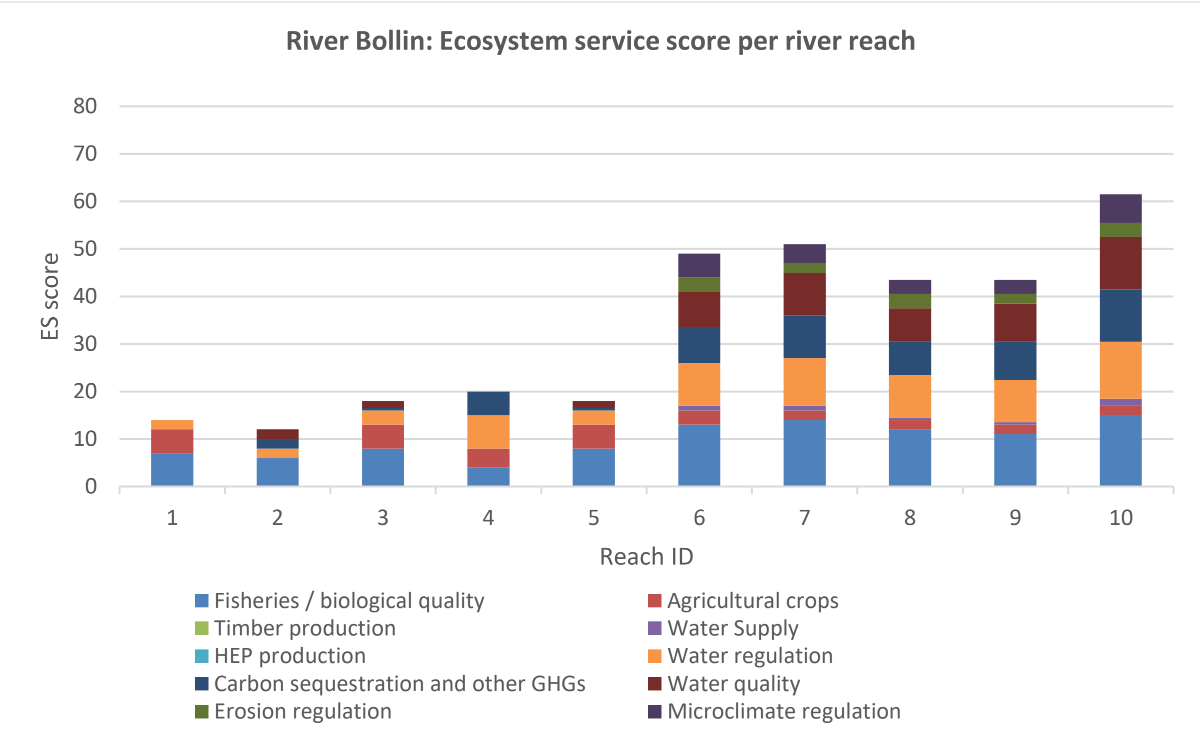


Figure 5-25 Graph showing individual and total ecosystem service scores per river reach, derived across the surveyed length of the River Bollin

Table5-20 Maximum potential individual and total ecosystem service scores per river reach, for indicative river types H and I

Ecosystem service		River type H	River type I
Fisheries / biological quality	Reach IESS	23	25
Agricultural crops		0	0
Timber production		0	0
Water Supply		5	5
HEP production		0	0
Water regulation		17	17
Carbon sequestration and other GHGs		15	15
Water quality		17	17
Erosion regulation		7	7
Microclimate regulation		5	5
Reach TESS		89	91

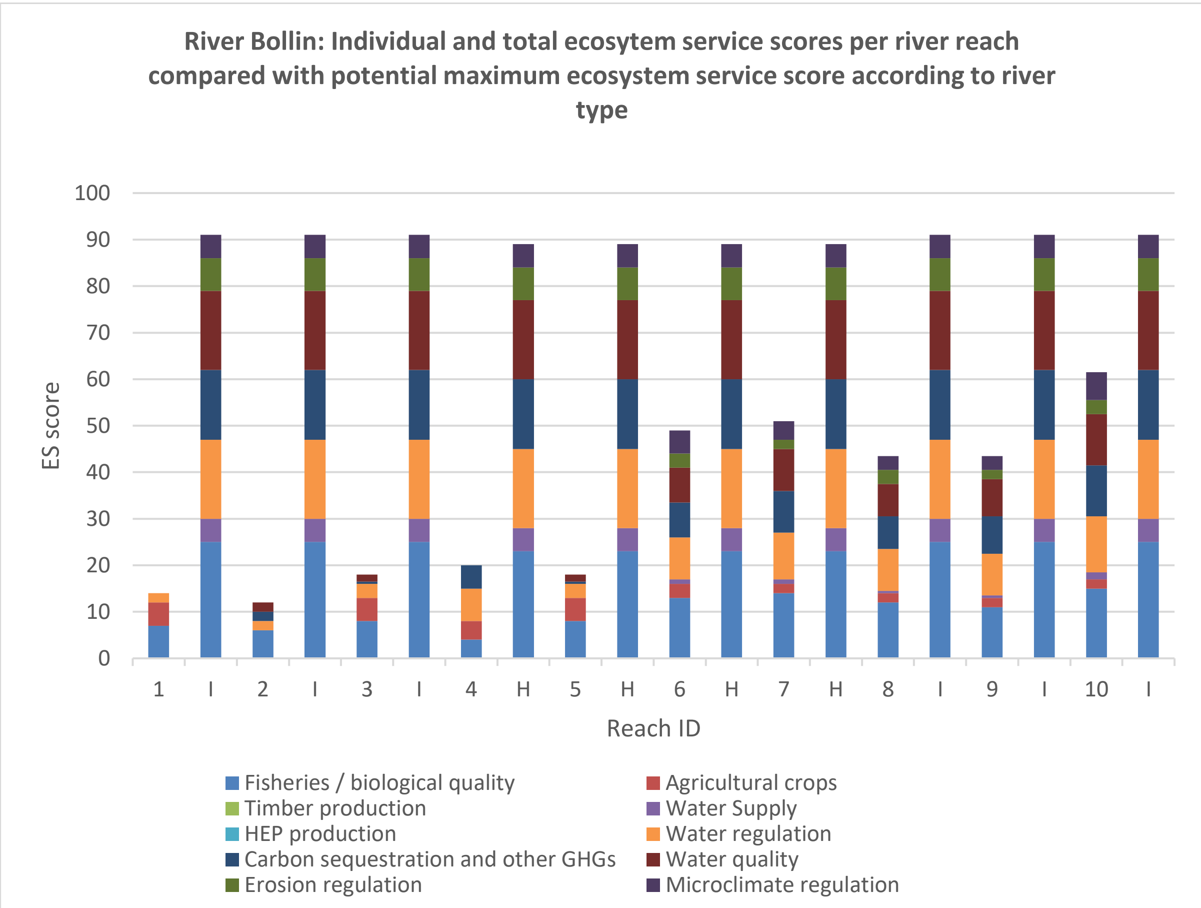


Figure 5-26 Individual and total ecosystem service scores per river reach plotted next to the maximum potential ecosystem service scores for the indicative river type, derived for surveyed length of River Bollin

The ES scores derived for reaches one to five suggest that these reaches are considerably degraded in terms of ES provision and it is clear that extensive channel and floodplain management has had an impact on natural ecological functions. On the other hand, ES scores derived for reaches six to ten are considerably higher suggesting that natural ecological functions are considerably higher. Reaches six to ten sit within the Bollin valley, Wilmslow park to Mottram Bridge local wildlife site (LWS) (Figure 5-27) which is acknowledged for its "rich ecological character with a floodplain grazing marsh, species rich hedgerows, marshy remnants of oxbow lakes and gravel and sand beds within the river" (Wilmslow Neighbourhood Plan, Wilmslow's Countryside: A landscape character assessment). This demonstrates that protecting sites for wildlife and biodiversity can also raise ecosystem service provision.

Figure 5-27 Surveyed river reaches on the River Bollin indicating the LNR boundary (orange dashed line).

5.4.4 River Stour

The surveyed length of the River Stour measures 6-km from NGR SZ0162099209to NGR SZ0498497842. The average channel width is between 20-m and 34-m throughout the surveyed length The surveyed length has been divided into ten individual river reaches, each reach measuring 600-m in length (approximately, twenty times average channel width). Applying the criteria outlined in section 5.3.4, the indicative river type for each reach has been classified as Type K or Type L.

River type K and L represent unconfined river types with a straight / sinuous or meandering planform and an average alluvial bed material size class of silt/clay with sand representing the coarsest bed material size class. Typically, geomorphic complexity is limited to pools and glides in these river types with the potential for an abundance of aquatic vegetation. These rivers typically exhibit high river width to floodplain width area ratios. The river corridor width for the surveyed length is defined by the 1 in 100 year flood map for planning boundary.

Individual ecosystem service scores (Reach IESS) and total ecosystem service scores (Reach TESS) were derived for each 600m reach. The scores for each reach were amalgamated to provide reach scores for provisioning and regulating categories of services. The results are presented in Table 5-21 and Figure 5-28.

Reach IESS and Reach TESS for each river reach have been compared to the potential maximum scores, according to geomorphic river type (Table 5-22 and Figure 5-29). The minimum and maximum derived reach TESS along the surveyed length of river is 31 and 53.5, respectively. The maximum reach TESS for river type K and L is 87. The results demonstrate moderate reach-to-reach variability in reach TESS with reach four representing the highest reach TESS and reach ten providing the lowest reach TESS. However, all reaches score considerably lower ES scores than expected for the indicative river type.

Table 5-21 River Stour, individual and total ecosystem service scores per river reach

		Reach no. (indicative river type)									
Ecosystem service		1	2	3	4	5	6	7	8	9	10
Fisheries / BQ	Reach IESS	7	8	10	12	7	8	9	7	9	8
Agricultural crops		1	3	2	1	3	4	0	3	3	5
Timber production		0	0	0	0	0	0	0	0	0	0
Water Supply		0.5	0.5	0.5	0.5	0	0	0	0	0.5	0
HEP production		0	0	0	0	0	0	0	0	0	0
Water regulation		10	11	11	12	10	9	11	11	12	7
Carbon sequestration and other GHGs		9.5	9.5	10	11.5	8.5	7	11	9.5	10.5	4.5
Water quality		4.5	4.5	6	9.5	6.5	5	9	5.5	7.5	2.5
Erosion regulation		2	2	3	3	2	3	3	3	3	2
Microclimate regulation		3	3	4	4	2	3	3	3	4	2
Reach TESS		37.5	41.5	46.5	53.5	39	39	46	42	49.5	31
Provisioning (Reach PESS)		8.5	11.5	12.5	13.5	10	12	9	10	12.5	13
Regulating (Reach RESS)		29	30	34	40	29	27	37	32	37	18

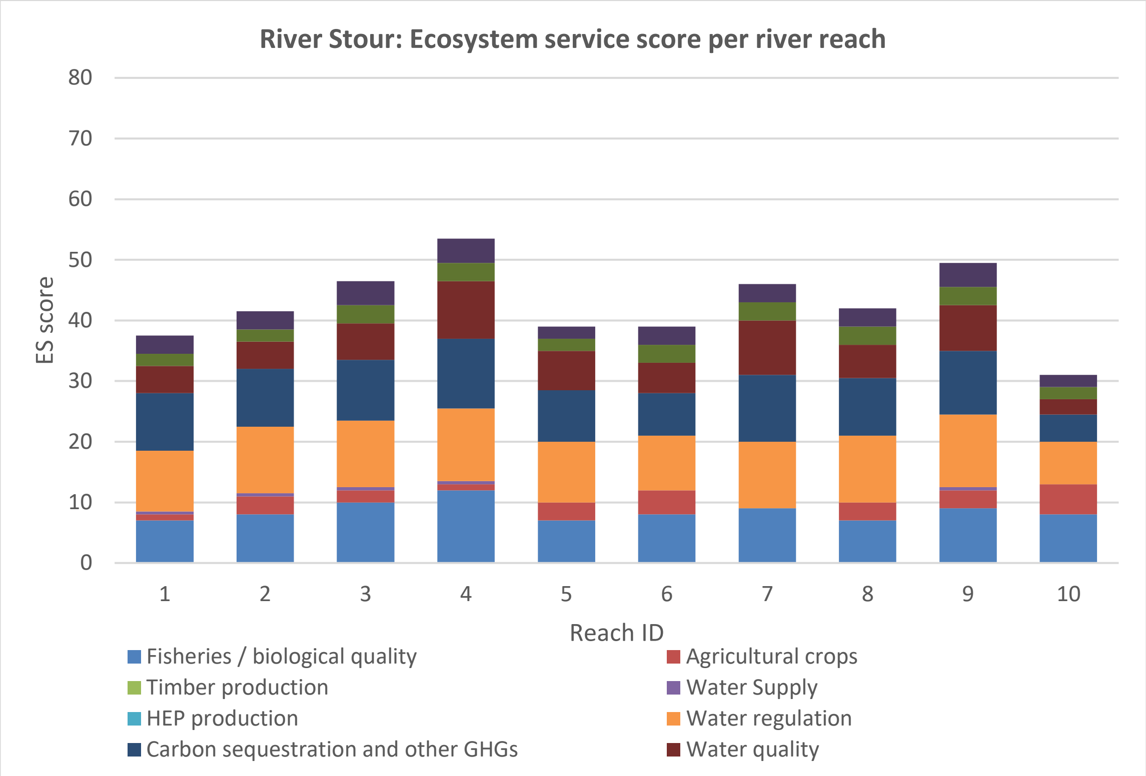


Figure 5-28 Graph showing individual and total ecosystem service scores per river reach, derived across the surveyed length of the River Stour

Table 5-22 Maximum potential individual and total ecosystem service scores per river reach, for indicative river types K and L

Ecosystem service		River type K	River type L
Fisheries / biological quality	Reach IESS	20	20
Agricultural crops		0	0
Timber production		0	0
Water Supply		5	5
HEP production		0	0
Water regulation		17	17
Carbon sequestration and other GHGs		15	15
Water quality		18	18
Erosion regulation		7	7
Microclimate regulation		5	5
Reach TESS		87	87

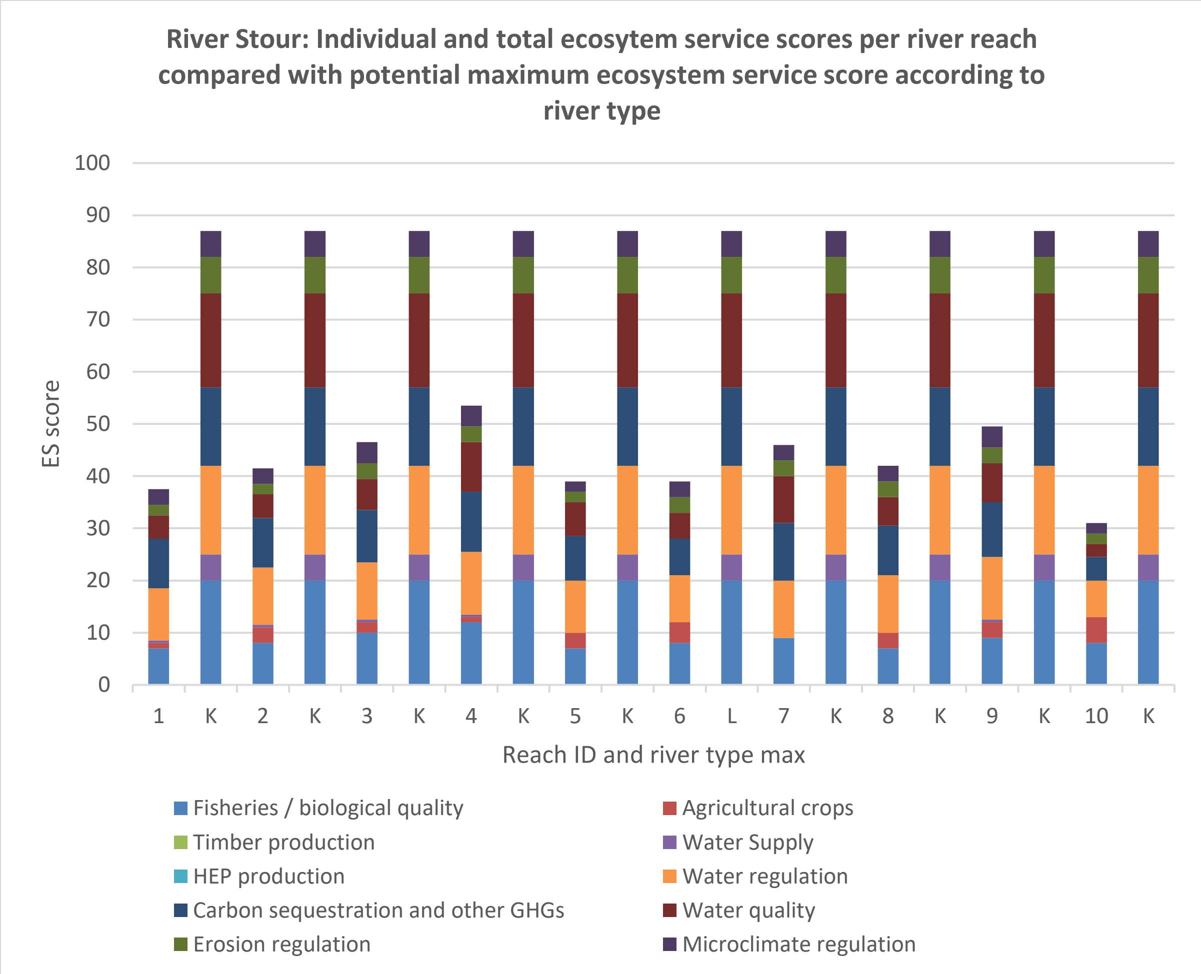


Figure 5-29 Individual and total ecosystem service scores per river reach plotted next to the maximum potential ecosystem service scores for the indicative river type, derived for surveyed length of River Stour

It is difficult to generalise the reasons for higher reach TESS as it varies between reaches. In some instance, reaches with higher reach TESS scores are a result reach IASs being lower for agricultural land and higher for lowland wetlands and aquatic vegetation (such as reaches 4 and 7) whereas in other reaches the increase in reach TESS is due to higher reach IASs being derived for riparian woodland buffers. The reaches scoring lowest generally score higher reach IASs for agricultural land and lower for lowland wetlands (such as reaches 6 and 10), compared to other surveyed river reaches.

Large areas of the floodplain throughout the surveyed length of the River Stour are classified as existing wetlands and the majority of the remaining floodplain is classified as potential for future wetlands (according to the wetlands vision layer), characteristic of river types K and L when functioning 'naturally' The results indicate that the presence of lowland wetlands raises ecosystem service provision. Conversely, agricultural land can lower ecosystem service provision of several ecosystem services as a trade-off for agricultural services.

Approximately 50% of the floodplain is classified as existing wetlands, according to the Wetlands Vision layer however, the aerial imagery suggests that less than 20% of this is currently functioning as lowland wetland habitat with evidence of agriculture land management practices present (Figure 5-15).

Restoring lowland wetland ESs along the River Stour

Baseline scores for lowland wetlands vary between 1 and 3, although aerial imagery analysis suggests that existing wetlands are likely to be under-performing due to historic modifications (embankments) and land use practices. In order to generate ES scores for the hypothetical restoration scenario, reach IASs have been altered for *channelization / embankments* (reach IAS decreased to '0'); *aquatic vegetation* (reach IAS increased to near max '4'), *lowland wetlands* (reach IAS increased to max '5') and *agricultural land* (reach IAS decreased to '0'). Reach IESS and reach TESS have been calculated based on the altered reach IASs and are presented in Figure 5-23 and Figure 5-30. The reach TESSs generated show a moderate increase across reaches 5-8 compared with the baseline results demonstrating the potential benefits for ES provision under the simulated restoration scenario. Reach TESS across all 4 ‘restored’ reaches included in the scenario however, remain below the potential maximum for river types K and L suggesting lowland wetland creation alone can significantly raise ES provision but additional interventions may also be needed to achieve potential maximum ES provision.

Table 5-23 Comparison of individual and total ecosystem service scores for reaches 5-8 of the River Stour under three scenarios: baseline; lowland wetland restoration and river type potential maximum.

	Reach no.											
Ecosystem service	Reach 5 baseline	Reach 5 wetland restoration	Reach 5 potential max	Reach 6 baseline	Reach 6 wetland restoration	Reach 6 potential max	Reach 7 baseline	Reach 7 wetland restoration	Reach 7 potential max	Reach 8 baseline	Reach 8 wetland restoration	Reach 8 potential max
Fisheries / BQ	7	13	20	8	14	20	9	15	20	7	15	20
Agricultural crops	3	0	0	4	0	0	0	0	0	3	0	0
Timber production	0	0	0	0	0	0	0	0	0	0	0	0
Water Supply	0	0	5	0	0	5	0	0	5	0	0	5
HEP production	0	0	0	0	0	0	0	0	0	0	0	0
Water regulation	10	12	17	9	13	17	11	13	17	11	13	17
Carbon sequestration and other GHGs	8.5	12	15	7	13	15	11	13	15	9.5	13	15
Water quality	6.5	16	18	5	17	18	9	17	18	5.5	17	18
Erosion regulation	2	2	7	3	3	7	3	3	7	3	3	7
Microclimate regulation	2	2	5	3	3	5	3	3	5	3	3	5
Reach TESS	39	57	87	39	63	87	46	64	87	42	64	87

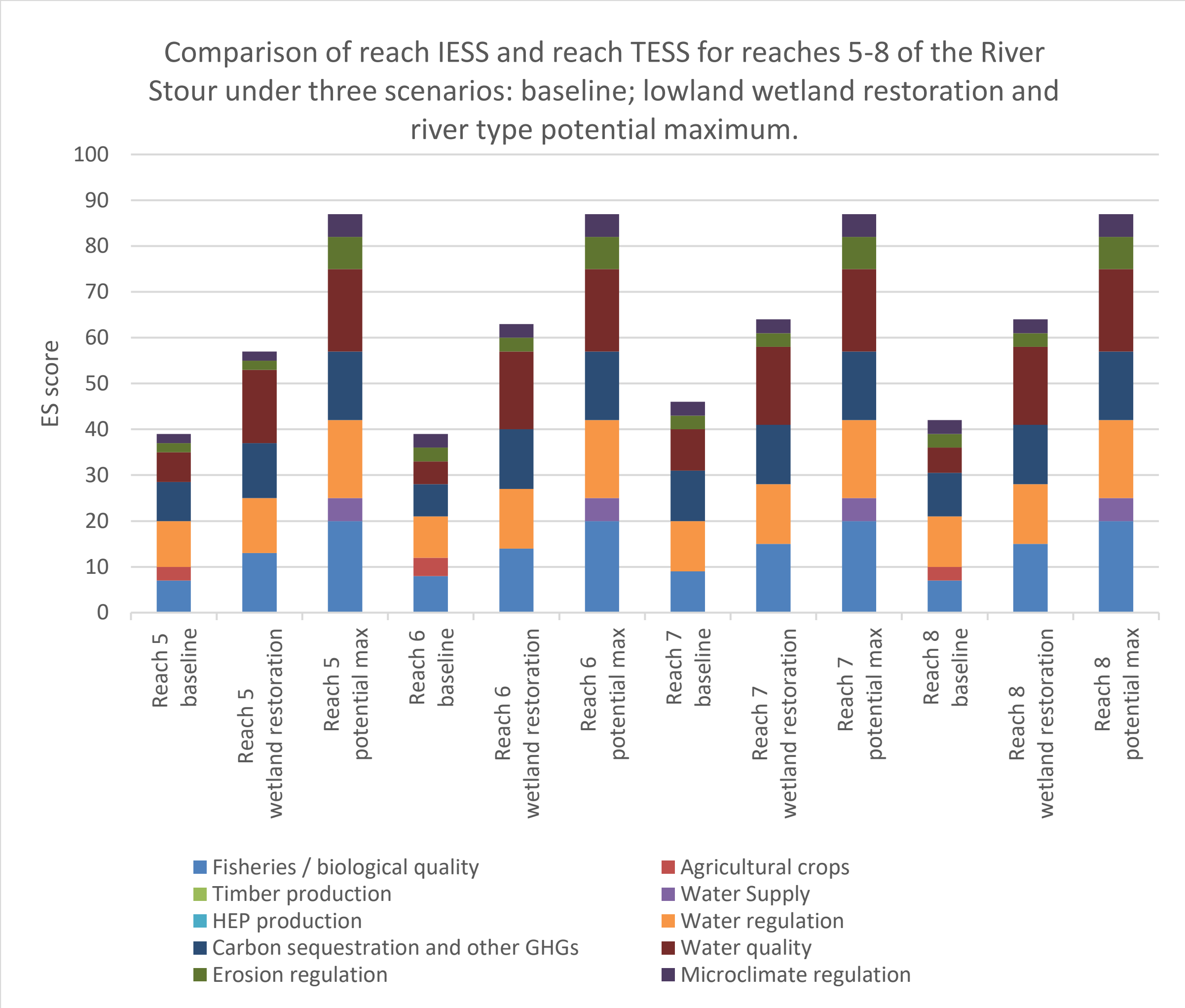


Figure 5-30 Comparison of individual and total ecosystem service scores for reaches 5-8 of the River Stour under three scenarios: baseline; lowland wetland restoration and river type potential maximum.

5.5 **Discussion**

5.5.1 Appraisal of the utility of the approach

This study has demonstrated the successful application of a bespoke approach to river ecosystem service assessment of English river types. The approach outlined represents a significant advancement to the Large and Gilvear (2015) approach by proposing significant improvements in the procedure for river ecosystem service assessment and integration of a geomorphic river typing classification representing rivers found in England. Heuristic improvements in the methods for delineating and scoring riverscape attributes and the procedures for deriving river indices are set out based on the evidence based linkage matrix using confidence descriptors based on the uncertainty 4-box model (Figure 5-7) and the RESCaM framework (Figure 5-1), advancing the methodology beyond theory. Furthermore, the methodology can be easily deployed and does not require specialist skills. It is likely also to be applicable to many other countries with limited adaption needed. In the case of England all the information for undertaking the assessment is widely accessible from GE™ aerial imagery and from national hydrological and asset datasets available through the DEFRA data services platform which provide national coverage (as outlined in Table 5-5). The use of national datasets provides ease of identification of several riverscape connectivity attributes and land cover types, facilitating consistent results and reducing subjectivity of the “non-specialist user” therefore increasing the robustness of the methodology. Geomorphic complexity attributes are aided by pictorial examples again, minimising the need for interpretation of these attributes by trained specialists. The simple scoring system provides easy uptake and is bespoke to English river types. Furthermore, the approach described here incorporates indicative geomorphic river typing within the procedure allowing appropriate consideration to be given to ES provision across the thirteen identified English river types. This addresses previous failings of ecosystem service approaches by acknowledging the biophysical structure associated with each of the thirteen geomorphic river types where ecosystem services are generated. The value of river restoration is also explored in the context of maximising ES provision and targeting restoration interventions that are compatible with the geomorphic characteristics of a given river type. The methodology has proven to be equally applicable across all four surveyed river lengths which encompass 7 of the 13 river types found in England. Although the testing is limited to ten river reaches of each study site, it can be applied to individual river reaches, entire rivers from source to mouth or across whole river networks allowing identification of “hotspots” and areas devoid of ecosystem services from river reach to river network scales. The methodology facilitates the assessment and quantification of ES provision across individual river reaches and across entire river networks, whether for an individual ecosystem service (reach and river IESS) value or across all ten ecosystem services considered (reach and river TESS). The methodology also allows for comparison of individual river reaches assigned the same indicative geomorphic river type both within the same river network and across catchment boundaries. The approach is valuable to catchment managers and planners, as reaches with lower ES provision scores can be examined to determine whether this is expected for the given river type or whether this provides an indication of environmental degradation.

5.5.2 Challenges and opportunities

The method described here provides a scientifically robust but pragmatic basis for river ecosystem service assessment of English river types, emphasising that hydro-geomorphic interactions occurring within and between the river and floodplain form the physical template upon which ecological processes operate (Mertes, 2000, Petts, 2000, Hancock *et al*., 2005, Malard *et al*., 2006; Thorp *et al.,* 2006; 2010) and where ES interactions occur (Tomscha *et al.,* 2017). Riverscape connectivity attributes, geomorphic complexity attributes and land cover types have been selected to represent those commonly found across English river types with suitable evidence (outlined in the linkage matrix) to support a positive or negative linkage between individual attributes and ecosystem service provision They are assessed at the reach-scale and their potential maximum scores are given according to their assigned geomorphic river type. The method is developed for bespoke application to English river types and thus would need to be refined for application elsewhere in the world.

The riverscape attributes and land cover types and ESs included were deemed the best selection based on the available evidence in the linkage matrix and with a view to offering ease of identification from GE^{TM} aerial imagery and hydrological and asset datasets available for England. The methodology is expected to progress naturally as the nature of the linkages between riverscape attributes and land-cover types and ecosystem services become more firmly established in the scientific literature. The linkage matrix itself uses levels of confidence and therefore highlights linkages which are poorly established or where linkages are thought probable but lack sufficient evidence to support them, thus providing a basis for which to target future research efforts and refinement.

Accounting for the provision of ecosystem services in headwater streams has been overlooked in previous studies assessing riverine ecosystem service provision (e.g. Large and Gilvear, 2015; Keele *et al*., 2019) despite the fact that upland rivers make up the bulk of the river network. These studies applied a consistent reach scale of 500m (minimum) which is deemed too coarse for application to English rivers. To resolve this, the bespoke methodology presented here adopts a varying reach length scale, calculated as twenty times average channel width, providing "a useful scale over which to relate stream morphology to channel processes, response potential, and habitat characteristics" (Montgomery and Buffington, 1997; Milner, 2010; Gurnell *et al*., 2016). This allows for comparison of river reaches exhibiting similar scales and geomorphic river type, both within and between river catchments and prevents disproportionately long reach lengths on smaller, upland streams, in particular. It should be acknowledged that a varying reach length impedes direct comparison between river reaches of differing scales.

Despite GE™ showing clear potential, it is acknowledged that image and data quality is not consistently good and as such has been reported to cause problems in some areas in terms of riverscape attribute recognition and measurement, most prominent on headwater streams (Large and Gilvear, 2015). The method has tested on a small, headwater stream, Glenderaterra Beck, which has an average with of ~9-m and proved to be effective in this case, although it is recognised that this may not be the case for other headwater streams. However, the inclusion of hydrological and asset datasets will reduce the need to rely on aerial imagery via GE™ to assess riverscape connectivity attributes and land cover types but will not completely resolve the issue for geomorphic complexity attributes. That said, assigning a geomorphic river type allows assumptions to be made on the potential for a reach to exhibit geomorphic complexity attributes which may be sufficient for some uses of the methodology regardless of image quality. The second issue with relying solely on GE™ is determining the river corridor width. To resolve this, an alternative approach using flood inundation mapping (1 in 100 year flood map for England) is used for partially and unconfined river valleys and a manual approach is proposed for confined river types. Kail *et al.* (2009) used a similar approach when defining river corridors for two German streams and Keele *et al.* (2019) used a similar approach for assessing river ESs on Scottish rivers.

The approach here predominantly focuses on assessing ecological aspects of river ecosystem services by attempting to quantify the capacity of riverscape attributes and land cover types to facilitate natural ecosystem functions which ultimately provide provisioning and regulating ecosystem services resulting from interactions between various geomorphological, hydrological and ecological processes (Thorp *et al.,* 2006, 2008; Large and Gilvear, 2015), set out in the RESCaM framework. The approach considers anthropogenic modification of the river and surrounding land use in terms of their ecological implications, by recognising both positive and negative linkages and scoring them based on the evidence provided in the linkage matrix. For example, the available evidence confirms with a high degree of confidence that agricultural land can negatively impact water quality and carbon sequestration. According to a review of 86 studies by Ekka *et al*., (2020), "almost all anthropogenic modifications have a positive impact on economic value of ESs but ecological and socio-cultural values are negatively impacted by anthropogenic modifications". The proposed approach herein however, does not consider economic valuation of ESs or trade-offs between ESs as this requires detailed economic evaluation and consideration of regional or local decision making frameworks (Burkhard, 2009), which is beyond the scope of this research. Instead, equal weighting is applied to all ten provisioning and regulating ecosystem services with the prospect that this could be refined through further development. The critical challenge remaining is recognition of economic and socio-cultural values of ecosystem services (Dunham *et al.,* 2018; De Groot *et al.,* 2010) which must recognise both national government policies and frameworks and local planning authority requirements for sustainable ecosystem management.

Furthermore, the inclusion of hydrological and asset spatial datasets increases the consistency and accuracy of applying the methodology across entire river networks and offers an opportunity to develop (semi-)automated approaches to extracting the information required from the datasets (for example, through a GIS tool) to facilitate rapid deployment of the methodology.

5.6 **Conclusions**

This chapter presents a bespoke desk-based riverine ecosystem service assessment methodology for application across English river networks. The assessment uses current scientific knowledge of river ecosystem functioning as captured in the evidence-based linkage matrix to establish confidence levels for linkages between twenty-four riverscape attributes and land cover types and ten ecosystem services. It is accepted that the linkage matrix will evolve as linkages become more established through further research. The linkages are set within the RESCaM framework (Figure 5-1), adapted from the cascade model of Potschin and Haines-Young, (2011) to allow assessment of river ecosystem service provision from source to mouth. The RESCaM framework integrates eco-hydromorphological principles and concepts and a geomorphic river typing classification, whereby river reaches are assigned one of thirteen indicative river types that may be found across England based on Gurnell *et al*., (2020), (Figure 2-10; Section 2.4.3). This provides a suitable template for which to evaluate ecosystem service ‘performance’ at the reach-scale. which is most appropriate for river management (Thorp *et al*., 2008). In addition, the methodology uses readily available GE^{TM} imagery and additional hydrological and asset spatial datasets to extract information on riverscape attributes and land cover types. The rules-based ecosystem service scoring approach has been developed for bespoke application to the thirteen geomorphic river types commonly found in England.

The assessment has been tested on four study sites which includes seven different geomorphic river types commonly found in England, representing the full spectrum from confined upland rivers to unconfined lowland rivers showing varying degrees of human modification and land uses. The exercise showed the tool to be equally applicable across all seven geomorphic river types and it is expected to be equally applicable to the further six geomorphic river types. The methodology presented here has a range of applications from assessing the current ecosystem service value of English rivers to identifying where river management interventions may be beneficial for raising ecosystem service provision. Furthermore, geomorphic river typing offers a way of guiding river restoration towards achieving maximum-attainable ecosystem service provision for a given river type, ensuring restoration efforts work with natural ecosystem functioning to ensure river management is sustainable. This has been demonstrated through hypothetical restoration scenario-testing on the River Wharfe and River Stour whereby interventions deemed compatible with the geomorphic river type were assessed. The assessment methodology could be deployed across a range of pilot sites to validate its robustness further.

6 Conclusions

6.1 Introduction

This section reviews the research presented in Chapters 3-5, summarising the main findings and discusses them in relation to the common themes within this thesis. A detailed discussion of the results from the individual experiments are provided in each experimental chapter. An overview of the strengths of the approach used in this thesis, alongside the possible caveats are also presented. Finally, an assessment of the challenges and uncertainties identified in this thesis that need to be addressed by future research is also provided.

6.2 Rationale

Riverine ecosystems are hotspots for many ecosystem services (Tomscha *et al*., 2017). R*iverine ecosystem services* and can be broadly defined as those "provided by rivers and the broader river-dependent landscapes that are hydrologically connected to rivers" (Hanna *et al*., 2018; Thorp *et al*., 2006). However, it is widely acknowledged that anthropogenic modification of rivers globally, has resulted in partial or full disconnection of river channels from their floodplains and adjacent hillslopes, and a breakdown in the flow of ecological, social and economic benefits (UKNEA, 2011; Everard, 1997a, b). Research shows that riverine ecosystems are both "disproportionately important for livelihoods and disproportionately threatened" (Tockner *et al*., 2002; Vörösmarty *et al*., 2010), emphasising the need for better informed river management. Increasing intensification of land use change and other associated human activities to rivers globally has resulted in a shift in structure and natural ecosystem functions needed to sustain the provision of ecosystem services throughout river landscapes (Bock, 2018; Burkhard *et al.,* 2009).

To date, ecosystem service research has failed to recognise the biophysical structure of riverine ecosystems (Ekka *et al*., 2020; Tomscha *et al*., 2017), despite accelerating progression in developing approaches for the valuation of ecosystem goods and services. To improve our understanding of the biophysical structure of riverine ecosystems and its importance for generating ecosystem services, we must better integrate concepts from the fields of ecology, geomorphology and hydrology to improve our understanding of river ecosystem service provision throughout river networks. This gap in the field of riverine ecosystem services has underpinned the work undertaken in this thesis.

The work of Large and Gilvear (2015), which was used as a starting point for this research, uses the Thorp *et al*. (2006) riverine ecosystem synthesis to "develop theoretical linkages between fluvial features, attributes and land cover types, natural ecosystem functions and river ecosystem service delivery whereby attributes of rivers that positively enhance heterogeneity, connectivity and fluvial dynamics within river corridors positively enhance ecosystem service provision". While this work recognised the importance of linking natural ecosystem functions with the provision of ecosystem services, it was viewed as "providing a foundation upon which heuristic improvement and refinement is needed." This research has aimed to do exactly that in order to provide a robust and bespoke riverine ecosystem service assessment methodology for application across English river networks.

Specifically, earlier chapters identified the need to expand and quantify the linkages between riverscape attributes and ecosystem services, refine the methods for extracting and scoring riverscape attributes that are pertinent to English river types and to validate the methodology through field testing.

Furthermore, evaluation of ecosystem services by using various techniques of river typing has previously been suggested (Thorp *et al*., 2010) whereby knowledge of the broad geomorphic river type provides a useful template for defining the biophysical structure and associated ecosystem functionality of the given river type when it is functioning naturally (Gurnell *et al*., 2020). Therefore, a geomorphic river typing classification (adapted from Gurnell *et al*., 2020) which identifies thirteen river types found in England is incorporated into a RESCaM framework which is used to evaluate ecosystem service provision. There are currently no published river ecosystem service assessment methods which recognise the geomorphic river type. Therefore, an opportunity was identified to investigate whether geomorphic river typing provided a suitable means of linking the biophysical structure of riverine ecosystems with ecosystem service provision.

6.3 **Synthesis of findings**

The main aim of this thesis was to develop a bespoke riverine ecosystem service assessment methodology for English river types underpinned by current understanding of how ecological, geomorphological and hydrological processes (eco-hydromorphological) and natural ecosystem functions shape and sustain river ecosystem service provision and assess its performance. The findings from each chapter are summarised in the proceeding sections.

6.3.1 A critical review of Large and Gilvear's (2015) reach-based riverine ecosystem service assessment methodology

The overarching aim of chapter 3 was to synthesise and then critically review the L&G2015 reach-based riverine ecosystem service assessment methodology using the GE^{TM} platform, considering the suitability of the approach to English river networks. To do this, the methodology was applied to two contrasting rivers in England, River Lyd, Devon and River Wharfe, North Yorkshire. Whilst L&G2015 demonstrate that their application of the methodology showed equal applicability to the three rivers they applied it too, the critique herein revealed numerous theoretical and practical limitations when applying the methodology to two contrasting rivers in England leading to the conclusion that the methodology is unsuitable for application across English river networks. The main limitations identified are: a lack of evidence and low confidence to support the linkages identified in L&G2015 between eighteen riverscape attributes and eight ecosystem services; insufficient testing on low order headwaters streams and a variety of geomorphic river types commonly found in England; a lack of validation of GE^{TM} extracted data, particularly riverscape attributes which rely on GE^{TM} elevation data (slope; river floodplain width ratio) and where riverscape attributes are obscured from view (due to tree cover or poor resolution imagery); inappropriate scoring criterion for English river types which typically exhibit low geomorphic and floodplain complexity. These limitations justified the need to undertake further testing and field validation to thoroughly evaluate the transferability of the approach for application across entire English river networks.

6.3.2 Further testing and field validation of the L&G2015 method as applied to English rivers

The main aim of Chapter 4 was to further explore the limitations identified in Chapter 3 through undertaking extensive testing of the L&G2015 methodology across a selection of lower-order headwaters streams and a range of geomorphic river types commonly found across England. Several control sites representing main stem rivers were also assessed for comparative purposes. Further to this, the secondary aim was to validate the assessment procedure through field work, whereby field-based data collected for riverscape attributes and land cover types has been compared with the desk-based data collected using GE^{TM} and ecosystem service scores generated from both methods have been evaluated.

Firstly, the results demonstrated that information extracted for some riverscape attributes, in particular, active channel complexity, secondary channels or braiding, palaeochannels and wetlands, which are typically formed in response to dynamic river processes and lateral river-floodplain interactions, yield consistently low scores across all study sites tested in England. On a global scale, for which the methodology is intended to be applicable to, scores for these attributes can be highly variable representing the varying scales and high degree of dynamism characterising global rivers. However, rivers in England are typically small in comparison with low degrees of dynamism resulting in stable or incising, single thread channels (Gurnell *et al*., 2020) characterised by low geomorphic complexity and floodplain diversity due to the extensive anthropogenic modifications which have led to their degradation since the Bronze age (Entwistle *et al.,* 2019).

It was therefore concluded that to develop a robust riverine ecosystem service assessment for application across English river networks a revised suite of the riverscape attributes representative of the river types found in England and a revised scoring criteria to reflect the degree to which riverscape attributes vary across English rivers is needed. To address this, it was proposed that an evidence-based linkage matrix with assigned confidence levels was developed to identify riverscape attributes and land cover types which reflect the character of different geomorphic river types common in England and a subsequent scoring criterion was developed to reflect this. In addition, it was proposed that a geomorphic river typing classification could be incorporated into the RESCaM framework to recognise the biophysical template from which to link riverscape attributes and land cover types to ecosystem service provision, recognising that different river types are associated with different ecosystem processes and natural ecosystem functions to ultimately provide different 'amounts' of ecosystem services.

Furthermore, comparison of desk-based and field-based derived data revealed differences between the scores generated as a result of the different data collection methods, demonstrating a degree uncertainty in results generated from GE™ extracted data. Over-estimation and under-estimation of scores were greatest for river / river corridor ratio width and valleyside connectivity. We argue that river / river corridor width and the degree of valleyside connectivity is crucial for recognising the river-floodplain interactions which contribute to some ESs and thus providing a robust, consistent and accurate method for their delineation and attribution to ES provision is crucial. It was therefore proposed that existing hydrological and asset datasets available for England could be utilised to delineate and extract information on those riverscape attributes to improve the reliability and ensure consistent results are generated without relying on field validation.

6.3.3 Development and testing of a bespoke riverine ecosystem service assessment for English river types

Chapter 5 developed a bespoke riverine ecosystem service assessment methodology and RESCaM framework for English river types taking account of the limitations and gaps identified and recommendations given in Chapters 3 and 4. Firstly, an evidence-based linkage matrix was developed which established linkages between twenty-seven riverscape attributes and land cover types and ten provisioning and regulating ecosystem services which were identified as being pertinent to English rivers. The twenty-seven attributes were selected to represent the biophysical template of English river types using scientific evidence to underpin their geomorphological, ecological and hydrological importance as demonstrated in the RESCaM framework. The attributes are sub-divided into riverscape connectivity attributes, geomorphic complexity attributes and land cover type categories. In total, over 280 scientific journals were reviewed and each individual linkage identified was assigned an individual confidence score (ICS) based on a set criterion. Each linkage was then assigned an overall confidence score (OCS) according to a criterion designed to assess the overall level of confidence in the linkage identified This is presented in a simple but effective linkage matrix whereby a total of forty-six linkages, between twenty-three riverscape attributes and ten ecosystem services were successfully established with a high degree of confidence. An additional twelve linkages were identified but subsequently excluded due to low levels of confidence, providing a basis for which to target future research efforts. The linkage matrix provided an evidence basis for which to develop appropriate methods for extracting and scoring riverscape attributes and ecosystem service provision, reflective of the confidence in the linkages. Methods for extracting and scoring riverscape attributes and land cover types have been developed to utilise a range of data sources including GE™ aerial imagery, 1 in 100 year flood maps for England, EA asset datasets and wetland vision data, the latter three of which are available as GIS layers for the whole of England. This has resulted in a significant advance of the L&G2015 methodology, providing more robust and consistent methods for extracting data and relevant scoring criteria that is bespoke for assessing ecosystem service provision of English river networks. Furthermore, integration of a geomorphic river typing classification (as suggested by Thorp *et al*., 2008) within the RESCaM framework has been proposed, whereby thirteen indicative geomorphic river types commonly found in England, based on Gurnell *et al*., (2020), are assessed. This has been proposed to provide a template for defining the biophysical habitat that each geomorphic river type may display when it is functioning naturally and is seen as a major development in the riverine ecosystem service assessment methodology. This provides a new and unique perspective for comparing observed biophysical habitats associated within a study area with those that are "expected" for the assigned indicative geomorphic river type at the reach scale, enabling informed river management decisions to be made accordingly.

The proposed methodology has been tested on four study sites representing seven different geomorphic river types. The methodology showed equal applicability to all seven geomorphic river types. The results demonstrated that all river reaches were under-performing compared to their expected condition for their indicative river type when functioning naturally, although it is important to recognise, that ecologically degraded rivers may have acquired social value (e.g., Adams, 1997; Junker *et al*., 2007) which is not explicitly accounted for within the methodology. Nonetheless, comparison of observed ESs and maximum potential ES provision for the given geomorphic river type provides ease of identification of individual river reaches which are ecologically degraded (condition is below "expected" for the given river type) which can then scrutinised further and used as a basis to develop river restoration interventions that can maximise ES provision, as demonstrated through testing of hypothetical restoration scenarios. To implement this successfully, further consideration of the different stakeholders needs must be considered on a case-by-case basis to develop social-ecological understanding, integrating society's needs with that of nature. It is therefore proposed that the methodology is integrated into a wider natural capital approach whereby river managers and policy makers must consider the beneficiaries, trade-offs and synergies when looking to optimise ES provision to for sustainable river management.

6.4 **Strengths of the approach**

This research has addressed several gaps identified in previous chapters. The main contributions of this research are discussed in this section.

Firstly, the research has established an evidence base for the linkages between twenty-seven riverscape attributes, ecosystem processes, natural ecosystem functions and ten provisioning and regulating ecosystem services provided by riverine ecosystems, with a specific focus on geomorphic river types commonly found in England. Nonetheless, the linkages have global significance, using available evidence published throughout the world and thus could be adopted and refined to suit the region in which they are utilised. Linkages have been assigned confidence scores to reflect the available evidence and to direct future research efforts which should seek to establish greater confidence in poorly established linkages. This research puts equal emphasis on five provisioning and five regulating services, acknowledging the biophysical structure of English riverscapes where ecosystem services are generated. The rationale for scoring is based on a weight of evidence approach using the confidence scores assigned in the linkage matrix. This sets the basis for which adjustments to the weighting can be made, to account for local decisions and stakeholder preference, meaning the approach can be adapted for making informed management decisions across different regions.

Secondly, the approach has been developed to account for the provision of ecosystem services in lower order / headwater streams as well as main stem rivers to facilitate an understanding of ecosystem service provision across whole river networks, something which has previously been overlooked (e.g. Large and Gilvear, 2015; Keele *et al*., 2019). The methodology adopts a variable reach length scale, which is deemed the most appropriate scale for river management (Montgomery and Buffington, 1997; Milner, 2010; Gurnell *et al*., 2016) and allows for comparison of river reaches exhibiting similar scales and geomorphic river type, both within and between river catchments.

Finally, the proposed methodology includes full integration of a geomorphic river typing framework, demonstrating its potential as a means of comparing observed riverscape attributes and land cover types and ES scores generated for a given river reach with those that are expected for its indicative geomorphic river type. For partly confined and unconfined river types, the approach utilises the 1 in 100 year flood map available for the whole of England to provide the river and floodplain template, recognising the importance of hydrological and sedimentological connectivity between river channels and their floodplains which affects the of a range of ecosystem services e.g. fisheries and biological quality, water supply and flood regulation services (Tockner and Stanford, 2002). For confined river valleys, a manual method to delineate an ecologically meaningful river corridor template is proposed, recognising that confined river valleys do not typically have a 'functional floodplain' but do have a riparian corridor which contributes towards the provision of some ecosystem services e.g. water quality, fisheries and biological quality and erosion regulation. Assessing ecosystem service provision using a geomorphic river typing framework has been shown to be suitable across the full spectrum of English river types providing an improved understanding of the biophysical template upon which ESs are generated and facilitating the identification of the most effective interventions which are appropriate for the given river type, thus informing sustainable catchment management.

6.5 **Significance for policy and management**

The wide-spread degradation and destruction of ecosystems has resulted in ecological restoration being implemented worldwide, offering potential synergies with improving population health, socioeconomic well-being, and the integrity of diverse national and ethnic cultures (Aronson *et al*., 2020). Ecological restoration is high on both national and international political agendas. As part of the 2030 agenda for sustainable development[19], 17 sustainable development goals were adopted by all UN Member States in 2015 which include, amongst others, good health and well-being, clean water and sanitation, climate action and life below water. More recently, the UN declared "2021-2030 the Decade on Ecosystem Restoration (UN-DER), for preventing, halting and reversing degradation of ecosystems worldwide" with the aim

[19] https://www.un.org/sustainabledevelopment/development-agenda/ - accessed on 02.03.2022

to "massively scale up the restoration of degraded and destroyed ecosystems" (Abhilash., 2021). In addition, legislation across the EU such as the EU's Biodiversity Strategy (COM/2011/0244), Regulation on Invasive Alien Species (REGULATION (EU) No 1143/2014) and Directive for Environmental Liability (2004/35/CE) recognises the importance of managing ecosystem services effectively (Broszeit *et al*., 2019). Clearly then, there is a growing global political interest which has accelerated within the last decade to restore a range of ecosystems and the services they provide to society.

At a national level, Defra (UK Department for Environment, Food and Rural Affairs) published its ‘25 Year Environment Plan’ (25 YEP) in January 2018 (Defra 2018a), which sets out the Government’s goals for improving the environment with the ambition to leave a better environment for the next generation. Specifically, it aims to:

> *"…deliver cleaner air and water; thriving plants and wildlife; reduced risk of harm from floods and drought; to use resources more sustainably and efficiently; and to enhance beauty, heritage and engagement with the natural environment. It calls for an approach to agriculture, forestry, land use and fishing that puts the environment first."*

Taking a natural capital approach is at the heart of the 25 YEP whereby natural capital is described as our stock of natural assets (including recognition of ecosystem functions and processes amongst other things) which provide a flow of ecosystem services that benefit people in a wide variety of ways which can be valued in monetary and non-monetary terms.

This research proposes a bespoke riverine ecosystem services assessment methodology set within a RESCaM framework which ultimately assesses the capacity of riverine ecosystem to provide natural ecosystem functions and a flow of ecosystem services across English river catchments. It is underpinned by scientific understanding of the biophysical template upon which ES interactions occur recognising that different geomorphic river types provide different levels of ecosystem services and should be managed accordingly. Therefore, this research has significance for the UK government and could contribute towards delivering the ambitions of the 25 YEP by embedding riverine ESs assessments within the natural capital approach. It provides a means of bringing nature into economic decision making by providing a non-monetary valuation of the state of riverine ecosystems that can facilitate future ecological restoration for enhancing ES provision.

To support the rural economy whilst simultaneously achieving the goals of the 25YEP, DEFRA are also in the process of rolling out three new environmental land management schemes (ELMs): sustainable farming incentive scheme, local nature recovery scheme and landscape recovery scheme[20]. These schemes will allow farmers and other land managers to enter into agreements to be paid for delivering environmental improvements such as ‘clean and plentiful water’, ‘thriving plants and wildlife’ and ‘reduction of and adaption to climate change’, amongst others. These schemes are currently being piloted or will begin to be piloted in the coming year and further demonstrates the governments ambitions to protect and enhance the ecosystem services our natural environment provides.

Furthermore, as discussed in Section 5.3.5, the Rural Payments Agency and Natural England’s ‘Making space for water’ incentive[21] remains available to land owners

[20] Information is available at: https://www.gov.uk/government/publications/environmental-land-management-schemes-overview/environmental-land-management-scheme-overview - accessed on 03.03.2022
[21] Available at https://www.gov.uk/countryside-stewardship-grants/making-space-for-water-sw12 22.07.21

across England to improve the management of whole or part parcels of arable, temporary grassland or improved permanent grassland by allowing increased frequency of inundation to the land with the aim of restoring river and wetland habitats. This incentive offers payments which lasts for 20 years, demonstrating the longer-term aspirations to restore ecological functionality of England's river-floodplain ecosystems.

In addition, the Environment Agency's[22] Flood and Coastal Erosion Risk Management (FCERM) Research and Development Programme published the evidence base for 'Working with Natural Processes (WwNP) to reduce flood risk'[23]. It includes a suite of reports and evidence directory to aid flood risk managers with understanding the potential FCERM benefits and multiple benefits from WWnP. Simultaneously, they published the 'Natural Flood Management (NFM) manual'[24] which provides design and management guidance to help practitioners with NFM. Both of these approaches to flood risk management appear throughout the most recent Flood and Coastal Erosion Risk Management Policy Statement (DEFRA., 2020[25]), published in July 2020, setting out the Governments ambition to "create a nation more resilient to future flood and coastal erosion risk", captured in five key policies. Specifically, one of the five key policies states that we must "Harness the power of nature to reduce flood and coastal erosion risk and achieve multiple benefits". It is stated that this will be achieved through "increased emphasis on nature-based solutions to support reduction in flood and coastal risk, including

[22] Environment Agency is a non-departmental government regulatory body with responsibilities relating to the protection and enhancement of the environment in England
[23] Available at: Working with natural processes to reduce flood risk - GOV.UK (www.gov.uk)
[24] Available at: The Natural Flood Management (NFM) manual - GOV.UK (www.gov.uk)
[25] Available at: https://www.gov.uk/government/publications/flood-and-coastal-erosion-risk-management-policy-statement

natural flood management, use of flood plains and opportunities for temporary or permanent water storage to manage peak flows".

The proposed riverine ecosystem service methodology for English river networks demonstrates the multiple benefits (in the form of final provisioning and regulating ecosystem services) that different geomorphic river types throughout English river catchments can provide. It emphasises the importance of hydrological connectivity between river and floodplain facilitating the exchanges of water, sediment, nutrients and biota, and the importance of riparian woodlands and natural / semi-natural habitats which is in line with the EAs ambitions of working with natural processes and natural flood management to provide multiple benefits. Ultimately, the ecosystem service approach, provides a means of assessing and valuing the power of nature, providing a holistic way of delivering these ambitions and is likely to offer an effective means of optimising ES provision in the future, benefiting flood and coastal erosion risk management as well as ecosystem resilience to pressures such as climate change and population growth.

6.6 Future work and recommendations

The proposed riverine ecosystem service assessment methodology presented in this thesis focuses on the **capacity** of English river ecosystems to provide five provisioning and five regulating ecosystem services based on biophysical properties and natural functions. Other aspects of a service can be measured, including **flow**, defined as "the actual production or use of the service," and **demand**, defined as “the amount of a service required or desired by society" (after Villamagna *et al*., 2013). Understanding the capacity or potential of a river ecosystem to deliver services is an important starting point for informing river management decisions. However, to inform sustainable management of ecosystem service provision across space and through time, understanding the actual flow and demand of ecosystem services is required. It is therefore, recommended that further work considers both the flow and demand of riverine ecosystem services across England.

Secondly, cultural ecosystem services (CES) have been ignored in the proposed methodology, with approaches to informing understanding of CES remaining the subject of on-going debate (Fish *et al*., 2016). Whilst it remains challenging for CES to be fully integrated into a field where the quantitative measurement of ecosystem services is considered central to their visibility within decision making (Tratalos *et al*., 2016), methodologies using qualitative methods are beginning to emerge. For example, the method proposed by Keele *et al*., (2019) used the responses from a public questionnaire to identify a range of cultural services for Scottish paired rivers. It is recommended that this approach or similar could be adopted for English rivers and included within the assessment framework. It is therefore, recommended that methods for assessing cultural ecosystem services (CES), such as the method proposed by Keele *et al*., (2019) are considered for adaption and integration within the proposed methodology for English rivers.

Finally, it is recommended that opportunities for automating the extraction and scoring of some riverscape attributes using a GIS or similar are explored and developed accordingly. This could significantly improve the processing time involved with undertaking the assessment and increase the consistency and repeatability of the methodology.

6.7 **Final remarks**

Over the next few decades, the nature of our river corridors are likely to change immensely in response to pressures such as **climate change** and **population growth**. An increasing demand for water due to population growth is putting immense pressure on river ecosystems,(Johnson *et al*., 2009) whilst climate change is altering the thermal regimes of rivers (Garner *et al*., 2017a, Garner *et al*., 2017b, Reid *et al*., 2019, van Vliet *et al*., 2013; Wilby and Johnson., 2020), reducing water quality (Whitehead *et al*., 2009), increasing eutrophication (Charlton *et al*., 2018) and reducing the reliability of supply sources (Arnell and Delaney., 2006).

In the UK, river management is **adapting** in response to a changing climate, population growth and the biodiversity crisis (Newson *et al*., 2021). November 2021 saw the passing of the Environment Act (Environment Act 2021) which has been described as a **turning point for nature** allowing the UK to enshrine better environmental protection into law. The Act has the potential to change the context in which the UK manages our natural environment and means the ambitions outlined in the 25 YEP can become a reality.

Taking a natural capital approach is at the heart of the 25 YEP which recognises that "stocks of natural capital provide flows of ecosystem services over time, which often in combination with other forms of capital (human, produced and social) produce a wide range of benefits for society". An **ecosystems service framework** is now widely accepted for helping understand the societal impacts of management decisions and focusing management efforts to preserve and restore ecosystems

(Daily *et al*., 2009; Börger *et al*., 2014; Cavanagh *et al*., 2016; Looy *et al*., 2017; Broszeit *et al*., 2019).

Ultimately for **sustainable** river management, humans must also be treated as part of riverine ecosystems (Newson and Large., 2006) which are becoming increasingly viewed as coupled and complex **social-ecological systems** (SES) (Dunham *et al.*, 2018; Berkes *et al*., 2008).

The RESCaM framework presented in this thesis is underpinned by current understanding of how ecological, geomorphological and hydrological processes (eco-hydromorphological) and natural ecosystem functions shape and sustain river ecosystem service provision across river networks throughout England. It provides a means for assessing ecosystem service capacity across English river networks and evaluating river management interventions which could be implemented to maximise ecosystem service provision. It could be a central part of the move towards green recovery and nature-based solutions as advocated in the 25 YEP (DEFRA., 2018).

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8 Appendices

A.1 Appendix 1 Supplementary material for Chapter 3

A 1.1 Table 8-1 Individual and total feature scores for River Wharfe surveyed reaches

A 1.2 Table 8-2 Individual and total ecosystem service score for River Wharfe surveyed length

A 1.3 Table 8-3 Individual and total feature scores for River Lyd surveyed reaches

A 1.4 Table 8-4 Individual and total ecosystem service score for River Lyd surveyed length

Table 8-1 Individual and total feature scores for River Wharfe surveyed reaches

	Fluvial features, attributes and land cover types																		
	Sinuosity	Secondary channels/braiding	No of tributaries	Active channel/hydraulic complexity	Slope	Valley side connectivity with river	River/river corridor width ratio	Riparian/river bank woodland	Floodplain physical habitat mosaic	Palaeochannels	Wetlands	Floodplain forest	Floodplain lakes	Agriculture	Woodland plantation	Urban areas	Embankments / clearly incised	Channel instability/naturalness	Total
Reach ID																			
1	1	1	1	2	3		2	0	1	0	0	0	0	3	0	1	2	1	18
2	1	1	2	2	3		1	0	1	0	0	0	0	3	0	1	2	1	18
3	1	1	0	2	3		2	0	2	0	0	0	0	3	0	1	2	1	18
4	1	1	1	1	3		3	0	2	1	0	0	0	3	0	1	2	1	20
5	1	1	1	2	3		1	0	2	0	0	0	0	3	0	1	3	1	19
6	1	1	0	0	3		1	0	2	0	0	0	0	3	0	1	2	1	15
7	1	1	1	0	3		2	0	2	0	0	0	0	3	0	1	2	1	17
8	0	1	1	1	3		3	1	2	0	0	0	0	3	0	0	2	1	18
9	1	1	0	1	3		2	1	2	0	0	0	0	3	0	1	2	1	18
10	1	1	3	1	3		1	1	2	1	0	0	0	3	0	1	2	1	21
11	1	1	1	2	3		2	1	2	1	0	0	0	3	0	1	1	1	20
12	1	1	1	2	3		1	1	2	0	0	0	0	3	0	2	2	1	20
13	1	1	0	1	3		2	2	1	0	0	0	0	3	0	1	1	1	17
14	1	1	1	3	3		1	2	1	0	0	0	0	3	0	1	1	1	19
15	1	1	1	2	3		3	2	1	2	0	0	0	3	0	0	2	1	22
16	1	1	0	2	3		3	2	1	0	0	0	0	3	0	1	2	1	20
17	1	1	1	2	3		3	2	1	0	0	0	0	3	0	0	2	1	20
18	1	1	0	3	3		3	1	1	1	0	0	0	3	0	0	2	1	20
19	1	1	0	3	3		3	1	1	1	0	0	0	3	0	1	2	2	22
20	1	1	0	3	3		3	1	1	0	0	0	0	3	0	1	1	2	20
21	1	1	1	3	3		3	1	1	1	0	0	0	3	0	1	2	1	22
22	1	1	0	3	3		3	0	1	2	0	0	0	3	0	1	2	1	21

23	1	1	1	2	3		3	0	1	1	0	0	0	3	0	0	2	1	19
24	1	1	2	0	3		2	2	1	0	0	0	0	3	0	0	2	1	18
25	1	1	0	2	3		3	2	1	2	0	0	0	3	0	0	1	2	21
26	2	1	0	2	3		2	0	1	1	0	0	0	3	0	1	2	2	20
27	2	1	1	2	3		3	0	1	1	0	0	0	3	0	0	1	2	20
28	1	1	0	2	3		3	2	1	0	0	0	0	3	0	0	1	2	19
29	1	1	0	1	3		3	0	1	1	0	0	0	3	0	0	1	2	17
30	1	1	1	0	3		3	2	1	0	0	0	0	3	0	0	2	1	18
31	1	1	1	2	3		0	1	1	0	0	0	0	3	0	2	3	1	19
32	1	1	0	0	3		1	3	1	0	0	0	0	3	0	1	2	1	17
33	1	1	0	2	3		1	3	1	0	0	0	0	3	0	1	2	1	19
34	1	1	0	1	3		3	3	1	1	0	0	0	3	0	1	2	1	21
35	1	1	0	0	3		2	3	1	0	0	0	0	3	0	0	2	1	17
36	1	1	1	2	3		3	2	1	0	0	1	0	3	0	0	2	1	21
37	1	1	0	1	3		3	2	1	0	0	0	0	3	0	1	2	1	19
38	1	1	1	3	3		3	2	1	0	0	0	0	3	0	1	2	1	22
39	1	1	1	3	3		2	2	1	0	0	1	1	3	0	0	2	1	22
40	1	1	0	0	3		3	2	1	0	0	1	1	3	0	0	2	1	19
41	1	1	0	3	3		3	0	1	0	0	0	0	3	0	2	2	1	20
42	1	1	0	2	3		2	1	1	0	0	0	1	3	0	1	1	1	18
43	1	1	0	2	3		2	3	2	0	0	0	1	3	0	1	1	2	22
44	1	1	2	3	3		2	2	1	0	0	0	0	3	0	1	1	2	22
45	1	1	0	2	3		1	2	1	0	0	1	0	3	0	0	1	2	18
46	1	1	0	1	3		2	1	1	0	0	1	0	3	0	0	2	1	17
47	1	1	1	3	3		1	0	2	1	0	0	0	3	0	1	2	1	20
48	1	1	1	2	3		2	3	2	0	0	3	0	0	0	1	1	1	21
49	1	1	0	0	3		2	2	1	0	0	3	0	3	0	1	0	2	19
50	1	1	0	3	3		3	1	1	0	0	0	0	3	0	2	1	2	21
51	1	1	0	1	3		2	1	1	1	0	0	0	3	0	1	1	2	18
52	1	1	0	0	3		2	2	1	0	0	2	0	3	0	2	1	1	19
53	1	1	0	0	3		1	2	1	0	0	0	0	3	0	1	1	1	15
54	1	1	1	1	3		1	2	1	0	0	0	0	3	0	2	1	1	18
55	1	1	0	1	3		2	2	1	0	2	0	0	3	0	2	2	1	21
56	1	1	1	1	3		2	3	2	0	1	1	0	3	0	1	1	2	23
57	1	1	0	1	3		2	2	1	0	0	1	0	3	0	1	1	2	19

58	1	1	0	1	3		1	1	1	0	0	0	0	3	0	0	1	2	15
59	1	1	0	0	3		1	2	1	0	1	1	0	3	0	0	1	1	16
60	1	1	1	0	3		2	2	1	0	1	1	0	3	0	1	1	1	19
61	1	1	0	1	3		2	2	1	0	0	1	0	3	0	1	1	2	19
62	1	1	0	1	3		1	2	1	0	1	1	0	3	0	2	1	2	20
63	1	1	0	2	3		1	1	1	0	0	0	0	3	0	2	2	1	18
64	1	1	1	2	3		2	1	1	0	0	0	0	3	0	1	2	1	19
65	1	1	1	1	3		2	2	1	0	0	0	0	3	0	0	0	2	17
66	1	1	0	2	3		2	3	1	0	0	2	0	3	0	0	0	2	20
67	1	1	0	2	3		3	2	1	0	0	1	0	3	0	1	0	2	20
68	1	1	0	2	3		1	3	1	0	1	0	1	3	0	1	0	2	20
69	1	1	0	2	3		2	1	1	0	1	0	0	3	0	0	0	2	17
70	1	1	0	2	3		1	3	2	0	0	3	0	2	0	0	0	2	20
71	1	1	1	1	3		2	3	1	0	0	1	0	3	0	1	2	2	22
72	0	1	0	0	3		2	1	1	1	0	0	0	3	0	1	0	2	15
73	1	1	1	1	3		2	1	1	0	0	0	0	3	0	0	0	2	16
74	1	1	0	2	3		2	2	1	1	0	1	0	3	0	1	0	2	20
75	1	1	0	0	3		1	3	1	0	0	2	0	3	0	1	1	1	18
76	1	1	0	1	3		2	2	1	2	0	1	1	3	0	1	0	2	21
77	1	1	0	0	3		2	2	1	1	0	2	0	3	0	1	1	1	19
78	1	1	0	0	3		2	3	1	0	0	3	0	2	0	0	0	2	18
79	1	1	0	0	3		2	3	2	0	0	3	0	1	2	0	0	2	20
80	1	1	0	1	3		1	3	2	0	0	3	0	1	0	0	0	2	18
81	1	1	0	0	3		2	3	2	0	0	3	0	1	0	1	0	2	19
82	1	1	0	1	3		1	3	2	0	0	3	0	1	0	1	1	1	19
83	1	1	0	0	3		1	2	1	0	0	2	0	3	0	1	1	2	18
84	1	1	0	1	3		2	3	1	0	0	3	0	3	0	1	1	2	22
85	2	1	0	3	3		1	2	1	0	0	1	0	3	0	2	1	2	22
86	1	1	0	3	3		2	2	1	0	0	2	0	3	0	2	0	1	21
87	1	1	0	1	3		2	0	1	0	0	0	0	3	0	1	1	2	16
88	1	1	0	2	3		3	2	1	0	0	0	0	3	0	1	0	2	19
89	1	1	0	0	3		3	3	1	0	0	1	0	3	0	1	1	1	19
90	1	1	0	0	3		3	3	1	0	0	3	0	3	0	0	2	2	22
91	1	1	0	0	3		2	2	1	0	0	2	0	3	0	2	1	1	19
92	1	1	0	0	3		2	3	1	0	0	1	0	3	0	1	0	2	18

93	1	1	0	0	3		2	3	1	0	0	1	0	3	0	1	0	1	17
94	1	1	0	0	3		2	3	1	0	0	1	0	3	0	1	0	1	17
95	1	1	0	1	3		1	3	1	0	0	0	0	3	0	2	1	1	18
96	1	1	0	1	3		2	3	1	0	0	0	0	3	0	3	0	1	19
97	1	1	0	1	3		2	2	1	0	0	1	0	3	0	2	0	1	18
98	1	1	0	0	3		2	3	1	0	0	1	0	3	0	2	1	1	19
99	1	1	0	0	3		2	3	2	0	0	1	0	1	0	1	1	2	18

Table 8-2 Individual and total ecosystem service scores for River Wharfe surveyed reaches

	Ecosystem services									ES category		
Reach ID	Fisheries (P)	Water Supply [P]	Flood mitigation [R]	Carbon Sequestration [R]	Biodiversity [C]	Water quality [R]	Timber [P]	Agricultural crops [P]	TOTAL	Provisioning	Regulating	Supporting
1	4	1	9	0	8	6	0	3	31	8	15	8
2	4	2	8	0	9	5	0	3	31	9	13	9
3	4	0	9	0	9	6	0	3	31	7	15	9
4	3	1	9	1	11	8	0	3	36	7	18	11
5	4	1	8	0	9	5	0	3	30	8	13	9
6	2	0	6	0	6	5	0	3	22	5	11	6
7	2	1	7	0	8	6	0	3	27	6	13	8
8	3	1	8	0	10	7	0	3	32	7	15	10
9	4	0	8	0	9	6	0	3	30	7	14	9
10	4	3	7	1	12	6	0	3	36	10	14	12
11	5	1	9	1	12	7	0	3	38	9	17	12
12	5	1	8	0	10	5	0	3	32	9	13	10
13	5	0	8	0	9	6	0	3	31	8	14	9
14	7	1	9	0	11	5	0	3	36	11	14	11
15	6	1	10	0	14	9	0	3	43	10	19	14
16	6	0	10	0	11	7	0	3	37	9	17	11
17	6	1	10	0	12	7	0	3	39	10	17	12
18	6	0	11	0	12	8	0	3	40	9	19	12
19	6	0	11	0	13	9	0	3	42	9	20	13
20	6	0	11	0	12	8	0	3	40	9	19	12
21	6	1	11	0	13	8	0	3	42	10	19	13
22	5	0	11	0	12	9	0	3	40	8	20	12
23	4	1	10	0	11	8	0	3	37	8	18	11
24	4	2	7	0	10	6	0	3	32	9	13	10
25	6	0	10	0	14	10	0	3	43	9	20	14
26	5	0	10	0	11	8	0	3	37	8	18	11

27	5	1	11	0	13	9	0	3	42	9	20	13
28	6	0	10	0	12	8	0	3	39	9	18	12
29	3	0	9	0	10	9	0	3	34	6	18	10
30	4	1	8	0	10	7	0	3	33	8	15	10
31	5	1	7	0	8	4	0	3	28	9	11	8
32	5	0	6	0	8	5	0	3	27	8	11	8
33	7	0	8	0	10	5	0	3	33	10	13	10
34	6	0	9	0	12	8	0	3	38	9	17	12
35	5	0	7	0	9	6	0	3	30	8	13	9
36	7	1	11	1	13	8	0	3	44	11	20	13
37	5	0	9	0	10	7	0	3	34	8	16	10
38	7	1	11	0	13	7	0	3	42	11	18	13
39	9	2	11	2	14	8	0	3	49	14	21	14
40	6	1	9	2	11	9	0	3	41	10	20	11
41	5	0	11	0	10	7	0	3	36	8	18	10
42	6	1	9	1	10	7	0	3	37	10	17	10
43	8	1	9	1	14	8	0	3	44	12	18	14
44	7	2	10	0	14	7	0	3	43	12	17	14
45	7	0	9	1	11	7	0	3	38	10	17	11
46	5	0	9	1	9	7	0	3	34	8	17	9
47	5	1	9	0	11	6	0	3	35	9	15	11
48	10	1	12	3	16	9	0	0	51	11	24	16
49	7	0	10	3	12	10	0	3	45	10	23	12
50	6	0	11	0	12	8	0	3	40	9	19	12
51	4	0	8	0	10	8	0	3	33	7	16	10
52	6	0	9	2	10	8	0	3	38	9	19	10
53	4	0	6	0	7	5	0	3	25	7	11	7
54	5	1	7	0	9	5	0	3	30	9	12	9
55	5	2	8	0	11	8	0	3	37	10	16	11
56	7	2	9	1	15	9	0	3	46	12	19	15
57	6	0	9	1	11	8	0	3	38	9	18	11
58	4	0	7	0	8	6	0	3	28	7	13	8
59	5	1	7	1	9	7	0	3	33	9	15	9
60	5	2	8	1	11	8	0	3	38	10	17	11
61	6	0	9	1	11	8	0	3	38	9	18	11

62	6	1	8	1	11	8	0	3	38	10	17	11
63	5	0	8	0	8	5	0	3	29	8	13	8
64	5	1	9	0	10	6	0	3	34	9	15	10
65	5	1	8	0	11	7	0	3	35	9	15	11
66	9	0	11	2	14	9	0	3	48	12	22	14
67	7	0	11	1	13	9	0	3	44	10	21	13
68	8	2	8	1	13	8	0	3	43	13	17	13
69	5	1	9	0	11	8	0	3	37	9	17	11
70	10	0	11	3	15	9	0	2	50	12	23	15
71	7	1	9	1	13	8	0	3	42	11	18	13
72	2	0	6	0	8	8	0	3	27	5	14	8
73	4	1	8	0	10	7	0	3	33	8	15	10
74	7	0	10	1	13	9	0	3	43	10	20	13
75	7	0	8	2	10	7	0	3	37	10	17	10
76	7	1	9	2	14	11	0	3	47	11	22	14
77	6	0	9	2	11	9	0	3	40	9	20	11
78	8	0	10	3	13	10	0	2	46	10	23	13
79	8	0	12	3	14	10	2	1	50	11	25	14
80	9	0	10	3	14	9	0	1	46	10	22	14
81	8	0	10	3	14	10	0	1	46	9	23	14
82	9	0	10	3	13	8	0	1	44	10	21	13
83	6	0	8	2	10	8	0	3	37	9	18	10
84	9	0	11	3	14	10	0	3	50	12	24	14
85	9	0	11	1	13	7	0	3	44	12	19	13
86	9	0	12	2	13	8	0	3	47	12	22	13
87	3	0	8	0	8	7	0	3	29	6	15	8
88	6	0	10	0	12	8	0	3	39	9	18	12
89	6	0	9	1	11	8	0	3	38	9	18	11
90	8	0	11	3	14	11	0	3	50	11	25	14
91	6	0	9	2	10	8	0	3	38	9	19	10
92	6	0	8	1	11	8	0	3	37	9	17	11
93	6	0	8	1	10	7	0	3	35	9	16	10
94	6	0	8	1	10	7	0	3	35	9	16	10
95	6	0	7	0	9	5	0	3	30	9	12	9
96	6	0	8	0	10	6	0	3	33	9	14	10

97	6	0	9	1	10	7	0	3	36	9	17	10
98	6	0	8	1	10	7	0	3	35	9	16	10
99	6	0	8	1	12	8	0	1	36	7	17	12

Table 8-3 Individual and total feature scores derived for the River Lyd

	Fluvial features, attributes and land cover types																	
	Sinuosity	Secondary channels/braiding	No of tributaries	Active channel/hydraulic complexity	Slope	Valley side connectivity with river	River/river corridor width ratio	Riparian/river bank woodland	Floodplain physical habitat mosaic	Palaeochannels	Wetlands	Floodplain forest	Floodplain lakes	Agriculture	Woodland plantation	Urban areas	Embankments / clearly incised	Channel instability/naturalness	Total
Reach ID																			
1	1	1	1	1	3	0	3	0	1	1	0	0	0	3	0	0	0	3	18
2	1	1	0	1	3	0	3	0	0	0	0	0	0	3	0	0	0	3	15
3	1	1	0	1	3	2	3	0	1	0	0	0	0	3	0	0	0	3	18
4	1	1	1	0	3	3	3	0	1	0	0	0	0	3	0	0	0	3	19
5	1	1	0	0	3	3	3	0	1	0	0	0	0	3	0	0	0	3	18
6	1	1	0	0	3	3	3	0	1	0	0	0	0	3	0	0	0	3	18
7	1	1	0	0	3	3	3	0	1	1	0	0	0	3	0	0	0	2	18
8	1	1	0	1	3	3	3	0	1	0	0	0	0	3	0	0	0	3	19
9	1	1	0	1	3	2	3	0	1	2	1	0	0	3	0	0	0	2	20
10	1	1	1	0	3	3	3	0	1	2	0	2	0	3	0	0	0	2	22
11	1	0	0	0	3	3	3	0	1	0	0	3	0	2	0	1	0	2	19
12	1	0	0	0	3	3	2	3	1	0	1	1	0	2	0	2	0	2	21
13	1	0	1	0	3	3	0	3	1	0	0	3	0	3	0	2	0	2	22
14	1	1	0	0	3	3	0	3	1	0	0	3	0	1	0	1	0	2	19
15	1	0	0	0	3	3	2	3	1	0	0	3	0	0	0	0	0	3	19
16	1	0	0	0	3	3	1	3	1	0	0	3	0	0	0	0	0	3	18
17	1	0	0	0	3	3	1	3	1	0	0	3	0	0	0	0	0	3	18
18	1	1	0	2	3	2	2	3	2	0	0	3	0	1	1	0	0	2	23
19	1	0	0	0	3	3	1	3	2	0	0	3	0	0	2	0	0	2	20
20	1	0	0	0	3	2	1	3	2	0	0	3	0	0	3	0	0	2	20
21	1	0	0	0	3	1	1	3	2	0	1	3	0	2	1	1	0	2	21
22	1	0	0	0	3	1	2	3	1	0	0	1	1	3	0	1	0	1	18

23	1	0	0	0	3	1	3	3	1	0	0	3	0	3	0	0	0	2	20
24	1	0	0	0	3	0	3	3	0	0	0	1	0	3	0	1	0	1	16
25	1	0	1	0	3	0	3	3	0	0	0	0	0	3	0	0	0	2	16
26	1	0	0	0	3	0	3	3	0	0	0	0	0	3	0	0	0	2	15
27	1	0	0	0	3	0	3	3	0	0	0	0	0	3	0	0	0	2	15
28	1	1	1	1	3	0	3	3	1	0	0	2	0	3	0	1	0	2	22
29	1	0	0	0	3	0	3	3	1	0	0	2	0	3	0	0	0	2	18
30	1	1	0	0	3	0	3	3	1	0	0	2	0	3	0	0	0	2	19
31	1	1	0	0	3	0	3	3	0	0	0	0	1	3	0	2	0	1	18
32	1	1	0	0	3	0	2	3	1	0	0	2	0	2	0	2	0	1	18
33	1	0	0	0	3	0	1	3	2	1	1	3	0	3	0	0	0	2	20
34	1	1	0	1	3	0	2	3	2	0	1	3	0	2	0	0	0	2	21
35	1	1	1	0	3	0	3	3	2	0	2	2	0	3	0	0	0	1	22
36	1	0	0	0	3	0	2	3	2	0	1	3	0	2	0	0	0	2	19
37	1	0	0	0	3	0	3	3	0	0	0	0	0	3	0	1	0	2	16
38	1	0	0	0	3	0	3	3	1	0	0	0	0	3	0	2	0	1	17
39	1	0	0	0	3	0	2	3	1	0	0	1	0	1	0	3	0	1	16
40	1	0	3	0	3	0	3	3	1	2	0	2	0	2	0	2	0	1	23
41	1	0	0	0	3	0	3	3	1	0	0	1	0	3	0	2	0	1	18
42	1	1	0	0	3	0	3	3	1	3	0	0	0	3	0	1	0	2	21
43	1	0	0	0	3	0	3	3	1	0	0	2	0	3	1	0	0	2	19
44	1	0	0	0	3	0	3	3	1	0	0	1	0	3	1	0	0	2	18

Table 8-4 Individual and total ES scores derived for the River Lyd

	Ecosystem services									ES category		
Reach ID	Fisheries (P)	Water Supply [P]	Flood mitigation [R]	Carbon Sequestration [R]	Biodiversity [C]	Water quality [R]	Timber [P]	Agricultural crops [P]	TOTAL	Provisioning	Regulating	Supporting
1	3	1	9	1	9	10	0	3	33	7	20	9
2	3	0	9	0	9	9	0	3	30	6	18	9
3	3	0	9	0	12	9	0	3	33	6	18	12
4	2	1	8	0	13	9	0	3	34	6	17	13
5	2	0	8	0	12	9	0	3	32	5	17	12
6	2	0	8	0	12	9	0	3	32	5	17	12
7	2	0	8	1	12	9	0	3	33	5	18	12
8	3	0	9	0	13	9	0	3	34	6	18	13
9	3	1	9	3	14	11	0	3	41	7	23	14
10	4	1	10	4	16	12	0	3	46	8	26	16
11	4	0	10	3	13	11	0	2	39	6	24	13
12	5	1	7	2	14	9	0	2	35	8	18	14
13	7	1	7	3	14	8	0	3	36	11	18	14
14	8	0	8	3	14	8	0	1	34	9	19	14
15	7	0	9	3	16	11	0	0	39	7	23	16
16	7	0	8	3	15	10	0	0	36	7	21	15
17	7	0	8	3	15	10	0	0	36	7	21	15
18	10	0	13	3	18	10	1	1	46	12	26	18
19	7	0	10	3	15	9	2	0	39	9	22	15
20	7	0	11	3	14	9	3	0	40	10	23	14
21	7	1	9	3	14	10	1	2	40	11	22	14
22	6	1	7	2	11	8	0	3	32	10	17	11
23	7	0	10	3	14	11	0	3	41	10	24	14
24	5	0	8	1	9	8	0	3	29	8	17	9
25	4	1	7	0	10	8	0	3	29	8	15	10
26	4	0	7	0	9	8	0	3	27	7	15	9

27	4	0	7	0	9	8	0	3	27	7	15	9
28	8	1	11	2	15	10	0	3	42	12	23	15
29	6	0	9	2	12	10	0	3	36	9	21	12
30	7	0	10	2	13	10	0	3	38	10	22	13
31	6	1	8	1	10	8	0	3	31	10	17	10
32	7	0	9	2	11	8	0	2	32	9	19	11
33	7	1	8	3	14	11	0	3	40	11	22	14
34	9	1	11	3	16	11	0	2	44	12	25	16
35	7	3	10	2	16	11	0	3	45	13	23	16
36	7	1	9	3	14	11	0	2	40	10	23	14
37	4	0	7	0	9	8	0	3	27	7	15	9
38	4	0	7	0	9	7	0	3	26	7	14	9
39	5	0	7	1	9	7	0	1	25	6	15	9
40	6	3	9	2	16	11	0	2	43	11	22	16
41	5	0	8	1	10	8	0	3	30	8	17	10
42	5	0	8	0	14	11	0	3	36	8	19	14
43	6	0	10	2	12	10	1	3	38	10	22	12
44	5	0	9	1	11	9	1	3	34	9	19	11

A.1 Appendix 2 Supplementary material for Chapter 4

A 2.1 Figure 8-1 FIELD DATA RECORD SHEET adapted from L&G2015, for extracting information of fluvial features, attributes and land cover types through field measurement

A.2.2 Excel spreadsheet containing field and desk based collected data, ES scores derived, and river indices calculated for application of L&G2015 to twenty-four study reaches across England

Figure 8-1 FIELD DATA RECORD SHEET adapted from L&G2015, for extracting information of fluvial features, attributes and land cover types through field measurement

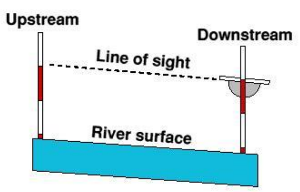
Location information

River Name: ……………………………………
Reach ID: ……………………………………
Region: ……………………………………
Start Grid Ref: ……………………………………
End Grid Ref: ……………………………………
Date: …………………..Time: ………..
Surveyor(s): ……………………………………

Local conditions

Weather conditions: ………………………………
……
………………………
Flow conditions: ………………………………
……
………………………

Field observations and measurements

Riverscape feature	Field data measurements			
	Count			
Tributaries	Count number of tributaries joining reach throughout reach length			
Palaeochannels	Measure length of palaeochannels and calculate as a % of channel length			
Wetlands	Estimate % area of wetlands present within floodplain			
Floodplain lakes	Count number of lakes within reach			
Floodplain physical habitat mosaic	Estimate number of separately coloured patches (Heterogeneity?) for both banks combined otherwise risk of double counting			
	River length (m)		Valley length (m)	
Sinuosity	Measure river length and valley length in the field			
	Elevation u/s		Elevation d/s	
Slope	Use dumpy level to measure slope			
	% length along left bank		% length along right bank	
Riparian / river bank woodland	Estimate length bordering channel (both banks) as a %		*Also, worth recording whether it is narrow, wide, continuous, and discontinuous – see paper on riparian benefits for rivers and optimum widths, lengths, composition! Density?	
Embankments	Estimate length			
	Embankment characteristic (circle appropriate)			
	Absent	Locally present	Discontinuous but extensive	Fully embanked on both sides

	% area left bank				% area right bank				
Floodplain forest	Estimate % area								
Woodland plantation	Estimate % area								
Agriculture	Estimate % area								
Urban areas	Estimate % area								
	Top			Middle			Bottom		
	River width (m)	Floodplain width left bank (m)	Floodplain width right bank (m)	River width (m)	Floodplain width left bank (m)	Floodplain width right bank (m)	River width (m)	Floodplain width left bank (m)	Floodplain width right bank (m)
River / river corridor ratio	Divide reach lengths into 3 and for top mid and bottom cross sections , measure channel width (Trupulse or tape measure), and delineate floodplain and measure floodplain width (Trupulse or tape measure), sum and then average for reach								
	Top (count)			Middle (count)			Bottom (count)		
Secondary channels or braiding	Divide reach lengths into 3 and for top mid and bottom cross sections, sum number of active thalwegs across corridor and average to gain a value for reach.								
Active channel complexity	Divide reach lengths into 3 and for top mid and bottom cross sections, record number of bars and backwaters, sum and then average for reach								
	Degree of naturalness (Circle appropriate)						Comments:		
Channel dynamism / 'naturalness'	Observe the 'naturalness of the reach by considering degree of human influence, presence of natural features vs man-made features Circle relevant category of naturalness plus comments								
	Man-made / artificial channel / impounded	Highly modified / regulated with weirs and bank protection		Channel appears natural but human modification of corridor	No human influence / wilderness channel				
Valley side connectivity	Determine extent of steep-sided slopes in proximity to channel (Visually / walking along river bank). Record as %								

Additional comments	

A.1 Appendix 3 Supplementary material for Chapter 5

A 3.1 Table 8-5 List of references which support linkages (positive and negative) between riverscape attributes and ecosystem services, showing individual confidence scores.

A 3.2 Excel spreadsheet containing the raw data, ecosystem service scores and river indices calculated for the application of the bespoke river ecosystem service assessment methodology to four study sites in England.

Table 8-5 List of references which support linkages (positive and negative) between riverscape attributes and ecosystem services, showing individual confidence scores.

Ecosystem service	Riverscape attributes and land cover type	Sub-category	Reference	Score	Positive / negative
Agricultural crops	Agriculture		Assessment, M.E., 2005. Millennium ecosystem assessment. Ecosystems and Human Well-Being: Biodiversity Synthesis, Published by World Resources Institute, Washington, DC.Vancouver	1	+
Agricultural crops	Agriculture		Power, A.G., 2010. Ecosystem services and agriculture: tradeoffs and synergies. Philosophical transactions of the royal society B: biological sciences, 365(1554), pp.2959-2971.	1	+
Agricultural crops	Agriculture		Robertson, G.P., Gross, K.L., Hamilton, S.K., Landis, D.A., Schmidt, T.M., Snapp, S.S. and Swinton, S.M., 2007. Farming for ecosystem services: An ecological approach to production agriculture. BioScience, 20, pp.1-12.	1	+
Agricultural crops	Agriculture		Scherr, S.J. and McNeely, J.A., 2008. Biodiversity conservation and agricultural sustainability: towards a new paradigm of 'ecoagriculture'landscapes. Philosophical Transactions of the Royal Society B: Biological Sciences, 363(1491), pp.477-494.	1	+
Agricultural crops	Agriculture		Swinton, S.M., Lupi, F., Robertson, G.P. and Hamilton, S.K., 2007. Ecosystem services and agriculture: cultivating agricultural ecosystems for diverse benefits.	1	+
Agricultural crops	Agriculture		Zhang, W., Ricketts, T.H., Kremen, C., Carney, K. and Swinton, S.M., 2007. Ecosystem services and dis-services to agriculture. Ecological economics, 64(2), pp.253-260.	1	+
Carbon sequestration and other GHGs	River floodplain area		D'elia, A.H., Liles, G.C., Viers, J.H. and Smart, D.R., 2017. Deep carbon storage potential of buried floodplain soils. Scientific reports, 7(1), p.8181.	1	+
Carbon sequestration and other GHGs	River floodplain area		Forshay, K.J. and Stanley, E.H., 2005. Rapid nitrate loss and denitrification in a temperate river floodplain. Biogeochemistry, 75(1), pp.43-64.	1	+
Carbon sequestration and other GHGs	River floodplain area		Richardson, W.B., Strauss, E.A., Bartsch, L.A., Monroe, E.M., Cavanaugh, J.C., Vingum, L. and Soballe, D.M., 2004. Denitrification in the Upper Mississippi River: rates, controls, and contribution to nitrate flux. Canadian Journal of Fisheries and Aquatic Sciences, 61(7), pp.1102-1112.	1	+
Carbon sequestration and other GHGs	River floodplain area		Roley, S. S., J. L. Tank, and M. A. Williams (2012), Hydrologic connectivity increases denitrification in the hyporheic zone and restored floodplains of an agricultural stream, J. Geophys. Res., 117, G00N04, doi:10.1029/2012JG001950.	1	+

Carbon sequestration and other GHGs	River floodplain area		Walling, D.E., Fang, D., Nicholas, A.P., Sweet, R.J., Rowan, J.S., Duck, R.W. and Werritty, A., 2006. River flood plains as carbon sinks. IAHS PUBLICATION, 306, p.460.	1	+
Carbon sequestration and other GHGs	Urban areas		Ward, H.C., Kotthaus, S., Grimmond, C.S.B., Bjorkegren, A., Wilkinson, M., Morrison, W.T.J., Evans, J.G., Morison, J.I.L. and Iamarino, M., 2015. Effects of urban density on carbon dioxide exchanges: Observations of dense urban, suburban and woodland areas of southern England. Environmental Pollution, 198, pp.186-200.	5	-
Carbon sequestration and other GHGs	Riparian buffer	Woodland	Rieger, I., Lang, F., Kowarik, I. and Cierjacks, A., 2014. The interplay of sedimentation and carbon accretion in riparian forests. Geomorphology, 214, pp.157-167.	2	+
Carbon sequestration and other GHGs	Riparian buffer	Woodland	Sutfin, N.A., Wohl, E.E. and Dwire, K.A., 2016. Banking carbon: a review of organic carbon storage and physical factors influencing retention in floodplains and riparian ecosystems. Earth Surface Processes and Landforms, 41(1), pp.38-60.	2	+
Carbon sequestration and other GHGs	Riparian buffer	Woodland	Gundersen, P., Laurén, A., Finér, L., Ring, E., Koivusalo, H., Sætersdal, M., Weslien, J.O., Sigurdsson, B.D., Högbom, L., Laine, J. and Hansen, K., 2010. Environmental services provided from riparian forests in the Nordic countries. Ambio, 39(8), pp.555-566.	2	+
Carbon sequestration and other GHGs	Riparian buffer	Woodland	Mackay, J.E., Cunningham, S.C. and Cavagnaro, T.R., 2016. Riparian reforestation: are there changes in soil carbon and soil microbial communities?. Science of the Total Environment, 566, pp.960-967.	1	+
Carbon sequestration and other GHGs	Riparian buffer		Maraseni, T.N. and Mitchell, C., 2016. An assessment of carbon sequestration potential of riparian zone of Condamine Catchment, Queensland, Australia. Land Use Policy, 54, pp.139-146.	1	+
Carbon sequestration and other GHGs	Riparian buffer	Woodland	Rheinhardt, R.D., Brinson, M.M., Meyer, G.F. and Miller, K.H., 2012. Carbon storage of headwater riparian zones in an agricultural landscape. Carbon balance and management, 7(1), p.4	1	+
Carbon sequestration and other GHGs	Floodplain forest		Cseh, V., Kiss, M. and Tanács, E., 2014. Carbon sequestration of floodplain forests: a case study from Hungary, Maros river valley. Tiscia, 40, pp.3-10.	1	+
Carbon sequestration and other GHGs	Floodplain forest		D'elia, A.H., Liles, G.C., Viers, J.H. and Smart, D.R., 2017. Deep carbon storage potential of buried floodplain soils. Scientific reports, 7(1), p.8181.	1	+
Carbon sequestration and other GHGs	Floodplain forest		Jindal, R., Swallow, B. and Kerr, J., 2008, May. Forestry-based carbon sequestration projects in Africa: Potential benefits and challenges. In Natural Resources Forum (Vol. 32, No. 2, pp. 116-130). Oxford, UK: Blackwell Publishing Ltd (peer-review)	2	+

Carbon sequestration and other GHGs	Floodplain forest	Lal, R., 2005. Forest soils and carbon sequestration. Forest ecology and management, 220(1-3), pp.242-258.	1	+
Carbon sequestration and other GHGs	Agriculture	Lanigan, G., Donnellan, T., Hanrahan, K., Carsten, P., Shalloo, L., Krol, D., Forrestal, P.J., Farrelly, N., O'Brien, D., Ryan, M. and Murphy, P., 2018. An analysis of abatement potential of Greenhouse Gas emissions in Irish agriculture 2021-2030. Teagasc.	4	-
Carbon sequestration and other GHGs	Floodplain forest	Lanigan, G., Donnellan, T., Hanrahan, K., Carsten, P., Shalloo, L., Krol, D., Forrestal, P.J., Farrelly, N., O'Brien, D., Ryan, M. and Murphy, P., 2018. An analysis of abatement potential of Greenhouse Gas emissions in Irish agriculture 2021-2030. Teagasc.	1	+
Carbon sequestration and other GHGs	Wetlands	Craft, C., Vymazal, J. and Kröpfelová, L., 2018. Carbon sequestration and nutrient accumulation in floodplain and depressional wetlands. Ecological Engineering, 114, pp.137-145.	1	+
Carbon sequestration and other GHGs	Wetlands	Mitsch, W.J., Zhang, L., Waletzko, E. and Bernal, B., 2014. Validation of the ecosystem services of created wetlands: two decades of plant succession, nutrient retention, and carbon sequestration in experimental riverine marshes. Ecological engineering, 72, pp.11-24.	1	+
Carbon sequestration and other GHGs	Wetlands	Villa, J.A. and Bernal, B., 2018. Carbon sequestration in wetlands, from science to practice: An overview of the biogeochemical process, measurement methods, and policy framework. Ecological Engineering, 114, pp.115-128	1	+
Carbon sequestration and other GHGs	Agriculture	Lal, R., 2008. Soil carbon stocks under present and future climate with specific reference to European ecoregions. Nutrient Cycling in Agroecosystems, 81(2), pp.113-127.	5	-
Carbon sequestration and other GHGs	Agriculture	Freibauer, A., Rounsevell, M.D., Smith, P. and Verhagen, J., 2004. Carbon sequestration in the agricultural soils of Europe. Geoderma, 122(1), pp.1-23.	4	-

Carbon sequestration and other GHGs	Agriculture	Bell, S., Barriocanal, C., Terrer, C. and Rosell-Melé, A., 2020. Management opportunities for soil carbon sequestration following agricultural land abandonment. Environmental Science & Policy, 108, pp.104-111.	4	-
Carbon sequestration and other GHGs	Agriculture	Vleeshouwers, L.M. and Verhagen, A., 2002. Carbon emission and sequestration by agricultural land use: a model study for Europe. Global change biology, 8(6), pp.519-530.	5	-
Carbon sequestration and other GHGs	Urban areas	Shao, G., Qian, T., Liu, Y. and Martin, B., 2008. The role of urbanisation in increasing atmospheric CO2 concentrations: Think globally, act locally. The International Journal of Sustainable Development & World Ecology, 15(4), pp.302-308.	5	-
Carbon sequestration and other GHGs	Agriculture	Cui, S., Shi, Y., Malik, A., Lenzen, M., Gao, B. and Huang, W., 2016. A hybrid method for quantifying China's nitrogen footprint during urbanisation from 1990 to 2009. Environment international, 97, pp.137-145.	5	-
Carbon sequestration and other GHGs	Agriculture	Skiba, U., Jones, S.K., Dragosits, U., Drewer, J., Fowler, D., Rees, R.M., Pappa, V.A., Cardenas, L., Chadwick, D., Yamulki, S. and Manning, A.J., 2012. UK emissions of the greenhouse gas nitrous oxide. Philosophical Transactions of the Royal Society B: Biological Sciences, 367(1593), pp.1175-1185.	5	-
Carbon sequestration and other GHGs	Urban areas	Skiba, U., Jones, S.K., Dragosits, U., Drewer, J., Fowler, D., Rees, R.M., Pappa, V.A., Cardenas, L., Chadwick, D., Yamulki, S. and Manning, A.J., 2012. UK emissions of the greenhouse gas nitrous oxide. Philosophical Transactions of the Royal Society B: Biological Sciences, 367(1593), pp.1175-1185.	5	-
Carbon sequestration and other GHGs	Agriculture	Blandford, D. and K. Hassapoyannes (2018), "The role of agriculture in global GHG mitigation", OECD Food, Agriculture and Fisheries Papers, No. 112, OECD Publishing, Paris, https://doi.org/10.1787/da017ae2-en.	4	-
Carbon sequestration and other GHGs	Urban areas	Dhakal, S., 2010. GHG emissions from urbanization and opportunities for urban carbon mitigation. Current Opinion in Environmental Sustainability, 2(4), pp.277-283.	4	-
Carbon sequestration and other GHGs	Urban areas	Parshall L, Gurney K, Hammer SA, Mendoza D, Zhou Y, Geethakumar S: Modeling energy consumption and CO2 emissions at the urban scale: methodological challenges and insights from the United States. Energy Policy, doi:10.1016/j.enpol.2009.07.006.	5	-
Carbon sequestration and other GHGs	Upland semi-natural habitats	R Gregg, J. L. Elias, I Alonso, I.E. Crosher and P Muto and M.D. Morecroft (2021) Carbon storage and sequestration by habitat: a review of the evidence (second edition) Natural England Research Report NERR094. Natural England, York.	1	+

Carbon sequestration and other GHGs	Lowland wetlands	R Gregg, J. L. Elias, I Alonso, I.E. Crosher and P Muto and M.D. Morecroft (2021) Carbon storage and sequestration by habitat: a review of the evidence (second edition) Natural England Research Report NERR094. Natural England, York.	1	+
Carbon sequestration and other GHGs	Upland semi-natural habitats	Bonn, A., Rebane, M. and Reid, C., 2009. Ecosystem services: a new rationale for conservation of upland environments. In Drivers of environmental change in uplands (pp. 476-502). Routledge.	1	+
Carbon sequestration and other GHGs	Upland semi-natural habitats	Parish F, Sirin A, Charman D, Joosten H, Minaeva T, Silvius M (Eds, 2008) Assessment on peatlands, biodiversity and climate change. Global Environment Centre, Kuala Lumpur and Wetlands International Wageningen, 179 p.	1	+
Carbon sequestration and other GHGs	Upland semi-natural habitats	England's peatlands: Carbon storage and greenhouse gases. Natural England (2010).	1	+
Carbon sequestration and other GHGs	Upland semi-natural habitats	Clarke, S.J., Harlow, J., Scott, A. and Phillips, M., 2015. Valuing the ecosystem service changes from catchment restoration: A practical example from upland England. Ecosystem Services, 15, pp.93-102.	1	+
Erosion regulation	River floodplain area	Loos and Shader., 2016 Reconnecting Rivers to Floodplains: Returning natural functions to restore rivers and benefit communities. Technical Report	2	+
Erosion regulation	River floodplain area	Opperman, J. R. Luster, B. McKenney, M. Roberts, A. Wrona Meadows. 2010. Ecologically functional floodplains: Connectivity, flow regime, and scale. Journal of the American Water Resources Association 46(2):211-226.	2	+
Erosion regulation	River floodplain area	Thompson, C.J., Fryirs, K. and Croke, J., 2016. The disconnected sediment conveyor belt: patterns of longitudinal and lateral erosion and deposition during a catastrophic flood in the Lockyer Valley, South East Queensland, Australia. River Research and Applications, 32(4), pp.540-551	1	+
Erosion regulation	Woody material	Bennett, S.J., Wu, W., Alonso, C.V. and Wang, S.S., 2008. Modeling fluvial response to in-stream woody vegetation: implications for stream corridor restoration. Earth Surface Processes and Landforms, 33(6), pp.890-909.	1	+
Erosion regulation	Woody material	Brooks, A.P., Gehrke, P.C., Jansen, J.D. and Abbe, T.B., 2004. Experimental reintroduction of woody debris on the Williams River, NSW: geomorphic and ecological responses. River Research and Applications, 20(5), pp.513-536.	1	+
Erosion regulation	Woody material	Lester, R.E. and Wright, W., 2009. Reintroducing wood to streams in agricultural landscapes: changes in velocity profile, stage and erosion rates. River research and applications, 25(4), pp.376-392.	1	+

Erosion regulation	Woody material		Shields Jr, F.D., Morin, N. and Cooper, C.M., 2001, March. Design of large woody debris structures for channel rehabilitation. In Proc., Federal Interagency Sedimentation Conf., 1947 to 2001, Seventh Conf. Proc.(CD-Rom).	1	+
Erosion regulation	Woody material		Wenzel, R., Reinhardt-Imjela, C., Schulte, A. and Bölscher, J., 2014. The potential of in-channel large woody debris in transforming discharge hydrographs in headwater areas (Ore Mountains, Southeastern Germany). Ecological engineering, 71, pp.1-9.	1	+
Erosion regulation	Geomorphic complexity	Aquatic vegetation	Gurnell, A.M., O'hare, M.T., O'hare, J.M., Scarlett, P. and Liffen, T.M., 2013. The geomorphological context and impact of the linear emergent macrophyte, Sparganium erectum L.: a statistical analysis of observations from British rivers. Earth Surface Processes and Landforms, 38(15), pp.1869-1880.	6	
Erosion regulation	Geomorphic complexity	Aquatic vegetation	Gurnell, A.M., Bertoldi, W. and Corenblit, D., 2012. Changing river channels: The roles of hydrological processes, plants and pioneer fluvial landforms in humid temperate, mixed load, gravel bed rivers. Earth-Science Reviews, 111(1-2), pp.129-141.	2	
Erosion regulation	Geomorphic complexity	Aquatic vegetation	Schulz, M., Kozerski, H.P., Pluntke, T. and Rinke, K., 2003. The influence of macrophytes on sedimentation and nutrient retention in the lower River Spree (Germany). Water Research, 37(3), pp.569-578.	6	
Erosion regulation	Riparian buffer		Beeson, C.E. and Doyle, P.F., 1995. Comparison of bank erosion at vegetated and non-vegetated channel bends. JAWRA Journal of the American Water Resources Association, 31(6), pp.983-990.	1	+
Erosion regulation	Riparian buffer	Herbaceous	Eekhout, J.P.C., Fraaije, R.G.A. and Hoitink, A.J.F., 2014. Morphodynamic regime change in a reconstructed lowland stream. Earth Surface Dynamics, 2(1), p.279.	2	+
Erosion regulation	Riparian buffer	Woodland	Laubel, A., Kronvang, B., Hald, A.B. and Jensen, C., 2003. Hydromorphological and biological factors influencing sediment and phosphorus loss via bank erosion in small lowland rural streams in Denmark. Hydrological Processes, 17(17), pp.3443-3463.	1	+
Erosion regulation	Riparian buffer	Woodland	Micheli, E.R., Kirchner, J.W. and Larsen, E.W., 2004. Quantifying the effect of riparian forest versus agricultural vegetation on river meander migration rates, Central Sacramento River, California, USA. River Research and Applications, 20(5), pp.537-548.	1	+
Erosion regulation	Riparian buffer	Woodland	Wynn, T.M., Mostaghimi, S., Burger, J.A., Harpold, A.A., Henderson, M.B. and Henry, L.A., 2004. Variation in root density along stream banks. Journal of Environmental Quality, 33(6), pp.2030-2039.	1	+
Erosion regulation	Riparian buffer	Woodland	Zaimes, G.N., Schultz, R.C. & Isenhart, T.M., 2006. Riparian land uses and precipitation influences on stream bank erosion in central Iowa. Journal of the American Water Resources Association 42: 83-97.	1	+

Erosion regulation	Agriculture		Micheli, E.R., Kirchner, J.W. and Larsen, E.W., 2004. Quantifying the effect of riparian forest versus agricultural vegetation on river meander migration rates, Central Sacramento River, California, USA. River Research and Applications, 20(5), pp.537-548.	5	-
Erosion regulation	Riparian buffer	Herbaceous	Wynn, T.M., Mostaghimi, S., Burger, J.A., Harpold, A.A., Henderson, M.B. and Henry, L.A., 2004. Variation in root density along stream banks. Journal of Environmental Quality, 33(6), pp.2030-2039.	2	+
Erosion regulation	Agriculture		Wynn, T.M., Mostaghimi, S., Burger, J.A., Harpold, A.A., Henderson, M.B. and Henry, L.A., 2004. Variation in root density along stream banks. Journal of Environmental Quality, 33(6), pp.2030-2039.	5	-
Fisheries / biological quality	Embankments / channelisation		Brookes, A., Gregory, K.J. and Dawson, F.H., 1983. An assessment of river channelization in England and Wales. Science of the Total Environment, 27(2-3), pp.97-111.	5	-
Fisheries / biological quality	Embankments / channelisation		Besacier-Monbertrand, A.L., Paillex, A. and Castella, E., 2014. Short-term impacts of lateral hydrological connectivity restoration on aquatic macroinvertebrates. River research and applications, 30(5), pp.557-570.	4	-
Fisheries / biological quality	Embankments / channelisation		Jones, M.J. and Stuart, I.G., 2008. Regulated floodplains–a trap for unwary fish. Fisheries management and Ecology, 15(1), pp.71-79.	4	-
Fisheries / biological quality	Embankments / channelisation		Jurajda, P., 1995. Effect of channelization and regulation on fish recruitment in a flood plain river. Regulated Rivers: Research & Management, 10(2-4), pp.207-215.	5	-
Fisheries / biological quality	Embankments / channelisation		Stoffels, R.J., Clarke, K.R., Rehwinkel, R.A. and McCarthy, B.J., 2014. Response of a floodplain fish community to river-floodplain connectivity: natural versus managed reconnection. Canadian Journal of Fisheries and Aquatic Sciences, 71(2), pp.236-245.	4	-
Fisheries / biological quality	Embankments / channelisation		Brooker, M.P., 1985. The ecological effects of channelization. The Geographical Journal, 151(1), pp.63-69.	5	-
Fisheries / biological quality	Embankments / channelisation		Bolland, J.D., Nunn, A.D., Lucas, M.C. and Cowx, I.G., 2015. The habitat use of young-of-the-year fishes during and after floods of varying timing and magnitude in a constrained lowland river. Ecological Engineering, 75, pp.434-440.	5	-
Fisheries / biological quality	Floodplain forest		Arantes, C.C., Winemiller, K.O., Petrere, M., Castello, L., Freitas, C.E. and Hess, L.L., 2017. Relationships between forest cover and fish diversity in the Amazon River floodplain. Journal of Applied Ecology.	1	+

Fisheries / biological quality	Floodplain forest		Davies, P.E. and Nelson, M., 1994. Relationships between riparian buffer widths and the effects of logging on stream habitat, invertebrate community composition and fish abundance. Marine and Freshwater Research, 45(7), pp.1289-1305.	1	+
Fisheries / biological quality	Floodplain forest		Lorion, C.M. and Kennedy, B.P., 2009. Riparian forest buffers mitigate the effects of deforestation on fish assemblages in tropical headwater streams. Ecological Applications, 19(2), pp.468-479.	1	+
Fisheries / biological quality	Floodplain forest		Wang, L., Lyons, J., Kanehl, P. and Gatti, R., 1997. Influences of watershed land use on habitat quality and biotic integrity in Wisconsin streams. Fisheries, 22(6), pp.6-12.	1	+
Fisheries / biological quality	Floodplain forest		Wright, J.P. and Flecker, A.S., 2004. Deforesting the riverscape: the effects of wood on fish diversity in a Venezuelan piedmont stream. Biological Conservation, 120(3), pp.439-447.	1	+
Fisheries / biological quality	Floodplain lake		Lehtonen, H. 1999. Rehabilitation of lakes for fish and fisheries in Europe — a review. Boreal Env. Res. 4: 137–143. ISSN 1239-6095	2	+
Fisheries / biological quality	Geomorphic complexity	Backwaters	Bolland, J.D., Nunn, A.D., Lucas, M.C. and Cowx, I.G., 2015. The habitat use of young-of-the-year fishes during and after floods of varying timing and magnitude in a constrained lowland river. Ecological Engineering, 75, pp.434-440.	1	+
Fisheries / biological quality	Geomorphic complexity	Backwaters	Humphries, P., Cook, R.A., Richardson, A.M., Serafini, L.G., 2006. Creating a disturbance: manipulating slackwaters in a lowland river. River Res. Appl. 22, 525–542.	1	+
Fisheries / biological quality	Geomorphic complexity	General	Garcia, X.F., Schnauder, I. and Pusch, M.T., 2012. Complex hydromorphology of meanders can support benthic invertebrate diversity in rivers. Hydrobiologia, 685(1), pp.49-68.	2	+
Fisheries / biological quality	Geomorphic complexity	General	Pearsons, T.N., Li, H.W., Lamberti, G.A., 1992. Influence of habitat complexity on resistance to flooding and resilience of stream fish assemblages. Trans. Am. Fish. Soc. 121, 427–436.	1	+
Fisheries / biological quality	Geomorphic complexity	Riffles	Fjeldstad, H.P., Barlaup, B.T., Stickler, M., Gabrielsen, S.E. and Alfredsen, K., 2012. Removal of weirs and the influence on physical habitat for salmonids in a Norwegian river. River research and applications, 28(6), pp.753-763.	1	+
Fisheries / biological quality	Geomorphic complexity	Riffles	Pulg, U., K. Sternecker, L. Trepl & G. Unfer, 2013. Restoration of spawning habitats of brown trout (Salmo trutta) in a regulated chalk stream. River Research and Applications 29: 172–182.	1	+
Fisheries / biological quality	Geomorphic complexity	General	Schmutz, S., Jurajda, P., Kaufmann, S., Lorenz, A.W., Muhar, S., Paillex, A., Poppe, M. and Wolter, C., 2016. Response of fish assemblages to hydromorphological restoration in central and northern European rivers. Hydrobiologia, 769(1), pp.67-78.	1	+

Fisheries / biological quality	Geomorphic complexity	General	Roni, P., 2019. Does river restoration increase fish abundance and survival or concentrate fish? The effects of project scale, location, and fish life history. Fisheries, 44(1), pp.7-19.	2	+
Fisheries / biological quality	Geomorphic complexity	General	Smokorowski, K.E. and Pratt, T.C., 2007. Effect of a change in physical structure and cover on fish and fish habitat in freshwater ecosystems–a review and meta-analysis. Environmental Reviews, 15(NA), pp.15-41.	1	+
Fisheries / biological quality	Geomorphic complexity	Aquatic vegetation	Fleming, J.P., Madsen, J.D. and Dibble, E.D., 2011. Macrophyte re-establishment for fish habitat in Little Bear Creek Reservoir, Alabama, USA. Journal of Freshwater Ecology, 26(1), pp.105-114.	1	+
Fisheries / biological quality	Geomorphic complexity	Aquatic vegetation	Wang, J., Song, X., Zou, G. and Zhou, W., 2013. Effects of Aquatic Vegetation on Fish Assemblages in a Freshwater River of Taihu Lake Basin, East China.	1	+
Fisheries / biological quality	Geomorphic complexity	Aquatic vegetation	Williams, A.E., Hendry, K., Bradley, D.C., Waterfall, R. and Cragg-Hine, D., 2005. The importance of habitat heterogeneity to fish diversity and biomass. Journal of Fish Biology, 67, pp.261-278.	1	+
Fisheries / biological quality	Geomorphic complexity	General	Kail, J., Brabec, K., Poppe, M. and Januschke, K., 2015. The effect of river restoration on fish, macroinvertebrates and aquatic macrophytes: a meta-analysis. Ecological Indicators, 58, pp.311-321.	1	+
Fisheries / biological quality	Geomorphic complexity	General	Haase, P., Hering, D., Jähnig, S.C., Lorenz, A.W. and Sundermann, A., 2013. The impact of hydromorphological restoration on river ecological status: a comparison of fish, benthic invertebrates, and macrophytes. Hydrobiologia, 704(1), pp.475-488.	2	+
Fisheries / biological quality	Geomorphic complexity	General	Pretty, J.L., Harrison, S.S.C., Shepherd, D.J., Smith, C., Hildrew, A.G. and Hey, R.D., 2003. River rehabilitation and fish populations: assessing the benefit of instream structures. Journal of applied ecology, 40(2), pp.251-265.	3	/
Fisheries / biological quality	Geomorphic complexity	Bars , pools, riffles	Harrison, L. R., C. J. Legleiter, M. A. Wydzga, and T. Dunne (2011), Channel dynamics and habitat development in a meandering, gravel bed river, Water Resources. Res., 47, W04513, doi:10.1029/2009WR008926.	1	+
Fisheries / biological quality	Geomorphic complexity	Bars , pools, riffles	Freedman, J.A., Carline, R.F. and Stauffer Jr, J.R., 2013. Gravel dredging alters diversity and structure of riverine fish assemblages. Freshwater Biology, 58(2), pp.261-274.	1	+
Fisheries / biological quality	Geomorphic complexity	Bars (gravel)	Baras, E., Philippart, J.C. and Nindaba, J., 1996. Importance of gravel bars as spawning grounds and nurseries for European running water cyprinids. In Proceedings of the second IAHR Symposium on Habitats Hydraulics. Ecohydraulics 2000, Vol A (pp. 367-378). INRS-Eau.	1	+

Fisheries / biological quality	Geomorphic complexity	Aquatic vegetation	Smith, C.D., Quist, M.C. and Hardy, R.S., 2016. Fish assemblage structure and habitat associations in a large western river system. River Research and Applications, 32(4), pp.622-638.	1	+
Fisheries / biological quality	Geomorphic complexity	Aquatic vegetation	Harrison, S.S., 2000. The importance of aquatic margins to invertebrates in English chalk streams. Archiv für Hydrobiologie, pp.213-240.	1	+
Fisheries / biological quality	Geomorphic complexity	Aquatic vegetation	Velle, G., Skoglund, H. and Barlaup, B.T., 2021. Effects of nuisance submerged vegetation on the fauna in Norwegian rivers. Hydrobiologia, pp.1-18.	1	+
Fisheries / biological quality	Geomorphic complexity	Aquatic vegetation	Beland, K.F., Trial, J.G. and Kocik, J.F., 2004. Use of riffle and run habitats with aquatic vegetation by juvenile Atlantic salmon. North American Journal of Fisheries Management, 24(2), pp.525-533.	1	+
Fisheries / biological quality	Geomorphic complexity	Backwaters	Grift, R., Buijse, A.D., Van Densen, W.L.T. and Klein Breteler, J.G.P., 2001. Restoration of the river-floodplain interaction: benefits for the fish community in the River Rhine. Large Rivers, pp.173-185.	1	+
Fisheries / biological quality	Geomorphic complexity	Backwaters	Grift, R.E., Buijse, A.D., Van Densen, W.L.T., Machiels, M.A.M., Kranenbarg, J., Klein Breteler, J.G.P. and Backx, J.J.G.M., 2003. Suitable habitats for 0-group fish in rehabilitated floodplains along the lower River Rhine. River Research and Applications, 19(4), pp.353-374.	1	+
Fisheries / biological quality	Geomorphic complexity	Backwaters	Schmutz, S., Jurajda, P., Kaufmann, S., Lorenz, A.W., Muhar, S., Paillex, A., Poppe, M. and Wolter, C., 2016. Response of fish assemblages to hydromorphological restoration in central and northern European rivers. Hydrobiologia, 769(1), pp.67-78.	2	+
Fisheries / biological quality	Geomorphic complexity	Backwaters	Lusk, S., Halačka, K. and Lusková, V., 2003. Rehabilitating the floodplain of the lower River Dyje for fish. River Research and Applications, 19(3), pp.281-288.	1	+
Fisheries / biological quality	Geomorphic complexity	Backwaters	Rosenfeld, J. S., E. Raeburn, P. C. Carrier, and R. Johnson. 2008. Effects of side-channel structure on productivity of floodplain habitats for juvenile Coho Salmon. North American Journal of Fisheries Management 28:1108–1119.	1	+
Fisheries / biological quality	Geomorphic complexity	Backwaters	Simons, J.H., Bakker, C., Schropp, M.H., Jans, L.H., Kok, F.R. and Grift, R.E., 2001. Man-made secondary channels along the River Rhine (The Netherlands); results of post-project monitoring. River Research and Applications, 17(4-5), pp.473-491.	1	+
Fisheries / biological quality	Geomorphic complexity	Backwaters	Watkins, C.J., Stevens, B.S., Quist, M.C., Shepard, B.B. and Ireland, S.C., 2015. Patterns of Fish Assemblage Structure and Habitat Use among Main-and Side-Channel Environments in the Lower Kootenai River, Idaho. Transactions of the American Fisheries Society, 144(6), pp.1340-1355.	1	+

Fisheries / biological quality	Geomorphic complexity	Woody material	Humphries, P., Cook, R.A., Richardson, A.M., Serafini, L.G., 2006. Creating a disturbance: manipulating slackwaters in a lowland river. River Res. Appl. 22, 525–542.	1	+
Fisheries / biological quality	Geomorphic complexity	Pools / slackwaters	Garcia, X.F., Schnauder, I. and Pusch, M.T., 2012. Complex hydromorphology of meanders can support benthic invertebrate diversity in rivers. Hydrobiologia, 685(1), pp.49-68.	1	+
Fisheries / biological quality	Geomorphic complexity	Boulders	Branco, P., Boavida, I., Santos, J.M., Pinheiro, A. and Ferreira, M.T., 2013. Boulders as building blocks: improving habitat and river connectivity for stream fish. Ecohydrology, 6(4), pp.627-634.	1	+
Fisheries / biological quality	Geomorphic complexity	Boulders	Cowx, I.G. and Gerdeaux, D., 2004. The effects of fisheries management practises on freshwater ecosystems. Fisheries Management and Ecology, 11(3-4), pp.145-151	1	+
Fisheries / biological quality	Geomorphic complexity	Boulders	de Jong, M.V.Z. and Cowx, I.G., 2016. Long-term response of salmonid populations to habitat restoration in a boreal forest stream. Ecological Engineering, 91, pp.148-157.	1	+
Fisheries / biological quality	Geomorphic complexity	Boulders	Vlach, P., Dusek, J., Svátora, M. and Moravec, P., 2005. Fish assemblage structure, habitat and microhabitat preference of five fish species in a small stream. Folia Zoologica, 54(4), p.421.	1	+
Fisheries / biological quality	Geomorphic complexity	Boulders	Lepori, F., Palm, D., Brännäs, E. and Malmqvist, B., 2005. Does restoration of structural heterogeneity in streams enhance fish and macroinvertebrate diversity?. Ecological Applications, 15(6), pp.2060-2071.	3	/
Fisheries / biological quality	Geomorphic complexity	Pools / slackwaters	Summers, D.W., Giles, N. and Stubbing, D.N., 2008. Rehabilitation of brown trout, Salmo trutta, habitat damaged by riparian grazing in an English chalkstream. Fisheries Management and Ecology, 15(3), pp.231-240.	2	+
Fisheries / biological quality	Geomorphic complexity	Woody material	Hafs, A.W., Harrison, L.R., Utz, R.M. and Dunne, T., 2014. Quantifying the role of woody debris in providing bioenergetically favourable habitat for juvenile salmon. Ecological modelling, 285, pp.30-38.	1	+
Fisheries / biological quality	Geomorphic complexity	Woody material	Howson, T.J., Robson, B.J. and Mitchell, B.D., 2010. Patch-specific spawning is linked to restoration of a sediment-disturbed lowland river, south-eastern Australia. Ecological Engineering, 36(7), pp.920-929.	2	+
Fisheries / biological quality	Geomorphic complexity	Woody material	Nagayama, S. and Nakamura, F., 2010. Fish habitat rehabilitation using wood in the world. Landscape and Ecological Engineering, 6(2), pp.289-305.	2	+
Fisheries / biological quality	Geomorphic complexity	Woody material	Opperman, J., 2006. Maintaining wood in streams: A vital action for fish conservation. UCANR Publications.	2	+

Fisheries / biological quality	Geomorphic complexity	Woody material	Roni, P., Beechie, T., Pess, G. and Hanson, K., 2014. Wood placement in river restoration: fact, fiction, and future direction. Canadian Journal of Fisheries and Aquatic Sciences, 72(3), pp.466-478.	1	+
Fisheries / biological quality	Geomorphic complexity	Woody material	Wright, J.P. and Flecker, A.S., 2004. Deforesting the riverscape: the effects of wood on fish diversity in a Venezuelan piedmont stream. Biological Conservation, 120(3), pp.439-447.	1	+
Fisheries / biological quality	Geomorphic complexity	Woody material	Grabowski, R.C., Gurnell, A.M., Burgess-Gamble, L., England, J., Holland, D., Klaar, M.J., Morrissey, I., Uttley, C. and Wharton, G., 2019. The current state of the use of large wood in river restoration and management. Water and Environment Journal, 33(3), pp.366-377.	1	+
Fisheries / biological quality	Riparian buffer	Woodland	Baxter, C.V., Fausch, K.D. and Carl Saunders, W., 2005. Tangled webs: reciprocal flows of invertebrate prey link streams and riparian zones. Freshwater biology, 50(2), pp.201-220	1	+
Fisheries / biological quality	Riparian buffer	Woodland	Bolland, J.D., 2008. Factors affecting the dispersal of coarse fish (Doctoral dissertation, University of Hull).	1	+
Fisheries / biological quality	Riparian buffer	Woodland	Broadmeadow, S.B., Jones, J.G., Langford, T.E.L., Shaw, P.J. and Nisbet, T.R. (2010). The influence of riparian shade on lowland stream water temperatures in southern England and their viability for brown trout. River Research and Applications DOI: 10.1002/rra.1354. Lenane, R, 2012. Keeping rivers cool: getting ready for climate change by creating riparian shade. Environ-ment Agency, Bristol.	1	+
Fisheries / biological quality	Riparian buffer	Woodland	Dugdale, S.J., Malcolm, I.A., Kantola, K. and Hannah, D.M., 2018. Stream temperature under contrasting riparian forest cover: Understanding thermal dynamics and heat exchange processes. Science of the Total Environment, 610, pp.1375-1389.	1	+
Fisheries / biological quality	Riparian buffer	Woodland	Garner, G., Malcolm, I.A., Sadler, J.P. and Hannah, D.M., 2014. What causes cooling water temperature gradients in a forested stream reach?. Hydrology and Earth System Sciences, 18(12), pp.5361-5376.	1	+
Fisheries / biological quality	Riparian buffer	Herbaceous	Grift, R.E., Buijse, A.D., Van Densen, W.L.T., Machiels, M.A.M., Kranenbarg, J., Klein Breteler, J.G.P. and Backx, J.J.G.M., 2003. Suitable habitats for 0-group fish in rehabilitated floodplains along the lower River Rhine. River Research and Applications, 19(4), pp.353-374.	1	+
Fisheries / biological quality	Riparian buffer	Woodland	Nakano, S. and Murakami, M., 2001. Reciprocal subsidies: dynamic interdependence between terrestrial and aquatic food webs. Proceedings of the National Academy of Sciences, 98(1), pp.166-170.	1	+

Fisheries / biological quality	Riparian buffer	Woodland	Vieira, T.B. and Tejerina-Garro, F.L., 2020. Relationships between environmental conditions and fish assemblages in tropical savanna headwater streams. Scientific reports, 10(1), pp.1-12.	1	+
Fisheries / biological quality	Riparian buffer	Woodland	Roth, T.R., Westhoff, M.C., Huwald, H., Huff, J.A., Rubin, J.F., Barrenetxea, G., Vetterli, M., Parriaux, A., Selker, J.S. and Parlange, M.B., 2010. Stream temperature response to three riparian vegetation scenarios by use of a distributed temperature validated model. Environmental science & technology, 44(6), pp.2072-2078.	1	+
Fisheries / biological quality	River floodplain area		Amoros, C. and Bornette, G., 2002. Connectivity and biocomplexity in waterbodies of riverine floodplains. Freshwater biology, 47(4), pp.761-776.	1	+
Fisheries / biological quality	River floodplain area		Bolland, J.D., Nunn, A.D., Lucas, M.C. and Cowx, I.G., 2015. The habitat use of young-of-the-year fishes during and after floods of varying timing and magnitude in a constrained lowland river. Ecological Engineering, 75, pp.434-440.	1	+
Fisheries / biological quality	River floodplain area		Grift, R., Buijse, A.D., Van Densen, W.L.T. and Klein Breteler, J.G.P., 2001. Restoration of the river-floodplain interaction: benefits for the fish community in the River Rhine. Large Rivers, pp.173-185.	1	+
Fisheries / biological quality	River floodplain area		Obolewski, K., Glińska-Lewczuk, K., Burandt, P., Kobus, S., Strzelczak, A. and Timofte, C., 2016. RESPONSE OF THE FISH COMMUNITY TO OXBOW LAKE RESTORATION IN A LOW-GRADIENT RIVER FLOODPLAIN. Environmental Engineering & Management Journal (EEMJ), 15(6).	1	+
Fisheries / biological quality	River floodplain area		Pander, J., Mueller, M. and Geist, J., 2015. Succession of fish diversity after reconnecting a large floodplain to the upper Danube River. Ecological Engineering, 75, pp.41-50.	1	+
Fisheries / biological quality	River floodplain area		Schmutz, S., Jurajda, P., Kaufmann, S., Lorenz, A.W., Muhar, S., Paillex, A., Poppe, M. and Wolter, C., 2016. Response of fish assemblages to hydromorphological restoration in central and northern European rivers. Hydrobiologia, 769(1), pp.67-78.	1	+
Fisheries / biological quality	River floodplain area		Lusk, S., Halačka, K. and Lusková, V., 2003. Rehabilitating the floodplain of the lower River Dyje for fish. River Research and Applications, 19(3), pp.281-288.	2	+
Fisheries / biological quality	Reservoir and dam unit		Turgeon, K., Turpin, C. and Gregory-Eaves, I., 2019. Dams have varying impacts on fish communities across latitudes: A quantitative synthesis. Ecology letters, 22(9), pp.1501-1516.	5	-
Fisheries / biological quality	Reservoir and dam unit				

Fisheries / biological quality	Weirs	Fish passage	Pini Prato, E., Comoglio, C. and Calles, O., 2011. A simple management tool for planning the restoration of river longitudinal connectivity at watershed level: priority indices for fish passes. Journal of Applied Ichthyology, 27, pp.73-79.	5	-
Fisheries / biological quality	Weirs	HEP	Calles, O.; Greenberg, L., 2009: Connectivity is a two-way street-the need for a holistic approach to fish passage problems in regulated rivers. River Res. Appl. 25, 1268–1286. doi: 10.1002/rra.1228.	4	-
Fisheries / biological quality	Weirs	Fish passage	Calles, O.; Greenberg, L., 2005: Evaluation of nature-like fishways for re-establishing connectivity in fragmented salmonid populations in the River Ema˚n. River Res. Appl. 21, 951–960. doi: 10.1002/ rra.865.	2	+
Fisheries / biological quality	Weirs	HEP	Calles, O.; Olsson, I. C.; Comoglio, C.; Kemp, P.; Blunden, L.; Schmitz, M.; Greenberg, L. A., 2010: Size-dependent mortality of migratory silver eels at a hydropower plant, and implications for escapement to the sea. Freshw. Biol. 55, 2167–2180. doi: 10.1111/ j.1365-2427.2010.02459.x	5	-
Fisheries / biological quality	Weirs	HEP	Habit, E., Belk, M. and Parra, O. (2007) Response of the Riverine Fish Community to the Construction and Operation of a Diversion Hydropower Plant in Central Chile. Aquat. Conserv., 17 (1), 37–49.	4	-
Fisheries / biological quality	Weirs	HEP	Anderson, E., Freeman, M. and Pringle, C. (2006) Ecological Consequences of Hydropower Development in Central America: Impacts of Small Dams and Water Diversion on Neotropical Stream Fish Assemblages. River Res. Appl., 22 (4), 397–411	5	-
Fisheries / biological quality	Weirs	HEP	Ovidio, M., Capra, H. and Philippart, J.C., 2008. Regulated discharge produces substantial demographic changes on four typical fish species of a small salmonid stream. Hydrobiologia, 609(1), pp.59-70.	5	-
Fisheries / biological quality	Weirs	Original	Mueller, M., Pander, J. and Geist, J., 2011. The effects of weirs on structural stream habitat and biological communities. Journal of Applied Ecology, 48(6), pp.1450-1461.	5	-
Fisheries / biological quality	Weirs	HEP	Anderson, D., Moggridge, H., Warren, P. and Shucksmith, J., 2015. The impacts of 'run-of-river'hydropower on the physical and ecological condition of rivers. Water and Environment Journal, 29(2), pp.268-276.	5	-
Fisheries / biological quality	Weirs	Fish passage	Cooke, S.J. and Hinch, S.G., 2013. Improving the reliability of fishway attraction and passage efficiency estimates to inform fishway engineering, science, and practice. Ecological Engineering, 58, pp.123-132.	4	-
Fisheries / biological quality	Weirs	Original	Gauld, N.R., Campbell, R.N.B. and Lucas, M.C., 2013. Reduced flow impacts salmonid smolt emigration in a river with low-head weirs. Science of the total environment, 458, pp.435-443.	5	-

Fisheries / biological quality	Weirs	Original	Lucas, M.C., Bubb, D.H., JANG, M.H., Ha, K. and Masters, J.E., 2009. Availability of and access to critical habitats in regulated rivers: Effects of low-head barriers on threatened lampreys. Freshwater Biology, 54(3), pp.621-634.	5	-
Fisheries / biological quality	Weirs	Original	O'Connor, J.P., O'Mahony, D.J., O'Mahony, J.M. and Glenane, T.J., 2006. Some impacts of low and medium head weirs on downstream fish movement in the Murray–Darling Basin in southeastern Australia. Ecology of Freshwater Fish, 15(4), pp.419-427.	4	-
Fisheries / biological quality	Weirs	Original	Ovidio, M. and Philippart, J.C., 2002. The impact of small physical obstacles on upstream movements of six species of fish. In Aquatic Telemetry (pp. 55-69). Springer, Dordrecht.	4	-
Fisheries / biological quality	Weirs	Original	Atkinson, S., Bruen, M., O'Sullivan, J.J., Turner, J.N., Ball, B., Carlsson, J., Bullock, C., Casserly, C.M. and Kelly-Quinn, M., 2020. An inspection-based assessment of obstacles to salmon, trout, eel and lamprey migration and river channel connectivity in Ireland. Science of The Total Environment, 719, p.137215.	5	-
Fisheries / biological quality	Weirs	Fish passage	Noonan, M.J., Grant, J.W. and Jackson, C.D., 2012. A quantitative assessment of fish passage efficiency. Fish and Fisheries, 13(4), pp.450-464.	5	-
Fisheries / biological quality	Weirs	Fish passage	Silva, A.T., Lucas, M.C., Castro-Santos, T., Katopodis, C., Baumgartner, L.J., Thiem, J.D., Aarestrup, K., Pompeu, P.S., O'Brien, G.C., Braun, D.C. and Burnett, N.J., 2018. The future of fish passage science, engineering, and practice. Fish and Fisheries, 19(2), pp.340-362.	3	
Fisheries / biological quality	Washlands		Morris, J., Bailey, A.P., Lawson, C.S., Leeds-Harrison, P.B., Alsop, D. and Vivash, R., 2008. The economic dimensions of integrating flood management and agri-environment through washland creation: a case from Somerset, England. Journal of Environmental Management, 88(2), pp.372-381.	3	
Fisheries / biological quality	Washlands		Siwek, A., 2007. The ecological value of floodplains: Implication for washland creation on rural floodplains along the River Trent.	2	+
Fisheries / biological quality	Mid-channel islands		Gilvear, D. and Willby, N., 2006. Channel dynamics and geomorphic variability as controls on gravel bar vegetation; River Tummel, Scotland. River Research and Applications, 22(4), pp.457-474.	2	+
Fisheries / biological quality	Mid-channel islands		Gurnell, A.M. and Petts, G.E., 2002. Island-dominated landscapes of large floodplain rivers, a European perspective. Freshwater Biology, 47(4), pp.581-600.	2	

Fisheries / biological quality	Mid-channel islands		Gurnell, A.M., Petts, G.E., Hannah, D.M., Smith, B.P., Edwards, P.J., Kollmann, J., Ward, J.V. and Tockner, K., 2001. Riparian vegetation and island formation along the gravel-bed Fiume Tagliamento, Italy. Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group, 26(1), pp.31-62.	2	
Fisheries / biological quality	Mid-channel islands		Ward, J.V., Tockner, K., Edwards, P.J., Kollmann, J., Gurnell, A.M., Petts, G.E., Bretschko, G. and Rossaro, B., 2000. Potential role of island dynamics in river ecosystems. Internationale Vereinigung für theoretische und angewandte Limnologie: Verhandlungen, 27(5), pp.2582-2585.	2	
HEP	Weirs	HEP	Punys, P., Kvaraciejus, A., Dumbrauskas, A., Šilinis, L. and Popa, B., 2019. An assessment of micro-hydropower potential at historic watermill, weir, and non-powered dam sites in selected EU countries. Renewable Energy, 133, pp.1108-1123.	1	+
HEP	Weirs	HEP	Bracken, L.J., Bulkeley, H.A. and Maynard, C.M., 2014. Micro-hydro power in the UK: The role of communities in an emerging energy resource. Energy Policy, 68, pp.92-101.	2	+
HEP	Weirs	HEP	Aggidis, G.A., Luchinskaya, E., Rothschild, R. and Howard, D.C., 2010. The costs of small-scale hydro power production: Impact on the development of existing potential. Renewable Energy, 35(12), pp.2632-2638.	2	+
Microclimate regulation	Wetlands		Kelvin, J., Acreman, M.C., Harding, R.J. and Hess, T.M., 2017. Micro-climate influence on reference evapotranspiration estimates in wetlands. Hydrological sciences journal, 62(3), pp.378-388.	1	+
Microclimate regulation	Wetlands		McLaughlin, D.L. and Cohen, M.J., 2013. Realizing ecosystem services: wetland hydrologic function along a gradient of ecosystem condition. Ecological Applications, 23(7), pp.1619-1631.	2	+
Microclimate regulation	Wetlands		Şimşek, Ç.K. and Ödül, H., 2018. Investigation of the effects of wetlands on micro-climate. Applied Geography, 97, pp.48-60.	1	+
Microclimate regulation	Wetlands		Sun, R., Chen, A., Chen, L. and Lü, Y., 2012. Cooling effects of wetlands in an urban region: the case of Beijing. Ecological Indicators, 20, pp.57-64.	2	+
Microclimate regulation	Wetlands		Zhang, W., Zhu, Y. and Jiang, J., 2016. Effect of the urbanization of wetlands on microclimate: a case study of Xixi Wetland, Hangzhou, China. Sustainability, 8(9), p.885.	2	+
Microclimate regulation	Riparian buffer	Woodland	Broadmeadow, S.B., Jones, J.G., Langford, T.E.L., Shaw, P.J. and Nisbet, T.R. (2010). The influence of riparian shade on lowland stream water temperatures in southern England and their viability for brown trout. River Research and Applications DOI: 10.1002/rra.1354. Lenane, R, 2012. Keeping rivers cool: getting ready for climate change by creating riparian shade. Environ-ment Agency, Bristol.	1	+

Microclimate regulation	Riparian buffer	Woodland	Dugdale, S.J., Malcolm, I.A., Kantola, K. and Hannah, D.M., 2018. Stream temperature under contrasting riparian forest cover: Understanding thermal dynamics and heat exchange processes. Science of the Total Environment, 610, pp.1375-1389.	1	+
Microclimate regulation	Riparian buffer	Woodland	Garner, G., Malcolm, I.A., Sadler, J.P. and Hannah, D.M., 2014. What causes cooling water temperature gradients in a forested stream reach?. Hydrology and Earth System Sciences, 18(12), pp.5361-5376.	1	+
Microclimate regulation	Riparian buffer	Woodland	Roth, T.R., Westhoff, M.C., Huwald, H., Huff, J.A., Rubin, J.F., Barrenetxea, G., Vetterli, M., Parriaux, A., Selker, J.S. and Parlange, M.B., 2010. Stream temperature response to three riparian vegetation scenarios by use of a distributed temperature validated model. Environmental science & technology, 44(6), pp.2072-2078.	1	+
Microclimate regulation	Riparian buffer	Woodland	Sugimoto, S., Nakamura, F. and Ito, A., 1997. Heat budget and statistical analysis of the relationship between stream temperature and riparian forest in the Toikanbetsu River basin, northern Japan. Journal of forest research, 2(2), pp.103-107.	1	+
Microclimate regulation	Riparian buffer	Woodland	Kaushal, S.S., Likens, G.E., Jaworski, N.A., Pace, M.L., Sides, A.M., Seekell, D., Belt, K.T., Secor, D.H. and Wingate, R.L., 2010. Rising stream and river temperatures in the United States. Frontiers in Ecology and the Environment, 8(9), pp.461-466.	1	+
Timber	Woodland plantation		Assessment, M.E., 2005. Millennium ecosystem assessment. Ecosystems and Human Well-Being: Biodiversity Synthesis, Published by World Resources Institute, Washington, DC.	1	+
Timber	Woodland plantation		Fares, S., 2015. Five steps for managing Europe's forests. Nature, 519(7544), p.407.	2	+
Timber	Woodland plantation		Hicks, C., Woroniecki, S., Fancourt, M., Bieri, M., Garcia Robles, H., Trumper, K. and Mant, R., 2014. The relationship between biodiversity, carbon storage and the provision of other ecosystem services: Critical Review for the Forestry Component of the International Climate Fund. UNEPWCMC, Cambridge, UK.	2	+
Timber	Woodland plantation		Khan, J., Greene, P. and Hoo, K.W., 2013. Measuring UK woodland ecosystem assets and ecosystem services.	2	+
Timber	Woodland plantation		Sing, L., Ray, D. and Watts, K., 2015. Ecosystem services and forest management. Research Note-Forestry Commission, (020).	2	+
Water quality	Floodplain forest		Sweeney, B.W. and Newbold, J.D., 2014. Streamside forest buffer width needed to protect stream water quality, habitat, and organisms: a literature review. JAWRA Journal of the American Water Resources Association, 50(3), pp.560-584.	1	+

Water quality	Floodplain forest		Gundersen, P., Laurén, A., Finér, L., Ring, E., Koivusalo, H., Sætersdal, M., Weslien, J.O., Sigurdsson, B.D., Högbom, L., Laine, J. and Hansen, K., 2010. Environmental services provided from riparian forests in the Nordic countries. Ambio, 39(8), pp.555-566.	1	+
Water quality	River floodplain area		Ahilan, S., Guan, M., Sleigh, A., Wright, N. and Chang, H., 2018. The influence of floodplain restoration on flow and sediment dynamics in an urban river. Journal of Flood Risk Management, 11, pp.S986-S1001.	1	+
Water quality	River floodplain area		Hein, T., Baart, I., Bondar-Kunze, E., Preiner, S., Weigelhofer, G., Schoenbrunner, I.M., Tritthart, M., Pinay, G. and Welti, N., How restoration measures can affect biogeochemical cycles in protected floodplain areas along the Danube River.	1	+
Water quality	River floodplain area		McMillan, S.K. and Noe, G.B., 2017. Increasing floodplain connectivity through urban stream restoration increases nutrient and sediment retention. Ecological engineering, 108, pp.284-295.	1	+
Water quality	River floodplain area		Richardson, W.B., Strauss, E.A., Bartsch, L.A., Monroe, E.M., Cavanaugh, J.C., Vingum, L. and Soballe, D.M., 2004. Denitrification in the Upper Mississippi River: rates, controls, and contribution to nitrate flux. Canadian Journal of Fisheries and Aquatic Sciences, 61(7), pp.1102-1112.	1	+
Water quality	River floodplain area		Song, S., Schmalz, B. and Fohrer, N., 2015. Simulation, quantification and comparison of in-channel and floodplain sediment processes in a lowland area–A case study of the Upper Stör catchment in northern Germany. Ecological indicators, 57, pp.118-127.	1	+
Water quality	River floodplain area		Surridge, B.W., Heathwaite, A.L. and Baird, A.J., 2012. Phosphorus mobilisation and transport within a long-restored floodplain wetland. Ecological engineering, 44, pp.348-359.	3	/
Water quality	River floodplain area		Thompson, C.J., Fryirs, K. and Croke, J., 2016. The disconnected sediment conveyor belt: patterns of longitudinal and lateral erosion and deposition during a catastrophic flood in the Lockyer Valley, South East Queensland, Australia. River Research and Applications, 32(4), pp.540-551.	1	+
Water quality	Geomorphic complexity	Aquatic vegetation	Dhote, S. and Dixit, S., 2007. Role of macrophytes in improving water quality of an aquatic ecosystem. Journal of Applied Sciences and Environmental Management, 11(4), pp.131-135.	1	+
Water quality	Geomorphic complexity	Aquatic vegetation	Schulz, M., Kozerski, H.P., Pluntke, T. and Rinke, K., 2003. The influence of macrophytes on sedimentation and nutrient retention in the lower River Spree (Germany). Water Research, 37(3), pp.569-578.	1	+

Water quality	Riparian buffer	Woodland	Anbumozhi, V., Radhakrishnan, J. and Yamaji, E., 2005. Impact of riparian buffer zones on water quality and associated management considerations. Ecological Engineering, 24(5), pp.517-523.	1	+
Water quality	Riparian buffer	Woodland	Balestrini, R., Arese, C., Delconte, C.A., Lotti, A., Salerno, F., 2011. Nitrogen removal in subsurface water by narrow buffer strips in the intensive farming landscape of the Po River watershed, Italy, Ecological Engineer-ing 37, 148-157. doi: 10.1016/j.ecoleng.2010.08.003.	1	+
Water quality	Riparian buffer	Woodland	Broadmeadow, S. and Nisbet, T.R., 2004. The effects of riparian forest management on the freshwater environment: a literature review of best management practice. Hydrology and Earth System Sciences Discussions, 8(3), pp.286-305	2	+
Water quality	Riparian buffer	Woodland	Connolly, N.M., Pearson, R.G., Loong, D., Maughan, M. and Brodie, J., 2015. Water quality variation along streams with similar agricultural development but contrasting riparian vegetation. Agriculture, ecosystems & environment, 213, pp.11-20.	1	+
Water quality	Riparian buffer		Dosskey, M.G., Vidon, P., Gurwick, N.P., Allan, C.J., Duval, T.P. and Lowrance, R., 2010. The role of riparian vegetation in protecting and improving chemical water quality in streams. JAWRA Journal of the American Water Resources Association, 46(2), pp.261-277.	1	+
Water quality	Riparian buffer	Herbaceous	Mayer, P.M., Reynolds, S.K., McCutchen, M.D. and Canfield, T.J., 2007. Meta-analysis of nitrogen removal in riparian buffers. Journal of environmental quality, 36(4), pp.1172-1180.	1	+
Water quality	Riparian buffer	Woodland	Miller, R.B., Fox, G.A., Penn, C.J., Wilson, S., Parnell, A., Purvis, R.A. and Criswell, K., 2014. Estimating sediment and phosphorus loads from streambanks with and without riparian protection. Agriculture, ecosystems & environment, 189, pp.70-81.	1	+
Water quality	Riparian buffer	Woodland	Sweeney, B.W. and Newbold, J.D., 2014. Streamside forest buffer width needed to protect stream water quality, habitat, and organisms: a literature review. JAWRA Journal of the American Water Resources Association, 50(3), pp.560-584.	1	+
Water quality	Wetlands		Ghermandi, A., Van Den Bergh, J.C., Brander, L.M., de Groot, H.L. and Nunes, P.A., 2010. Values of natural and human-made wetlands: A meta-analysis. Water Resources Research, 46(12)	2	+
Water quality	Wetlands		HANSSON, L.A., Brönmark, C., Anders Nilsson, P. and Åbjörnsson, K., 2005. Conflicting demands on wetland ecosystem services: nutrient retention, biodiversity or both?. Freshwater Biology, 50(4), pp.705-714.	2	+
Water quality	Wetlands		Laterra, P., Booman, G.C., Picone, L., Videla, C. and Orúe, M.E., 2018. Indicators of nutrient removal efficiency for riverine wetlands in agricultural landscapes of Argentine Pampas. Journal of environmental management, 222, pp.148-154.	1	+

Water quality	Wetlands	Mitsch, W.J., Zhang, L., Waletzko, E. and Bernal, B., 2014. Validation of the ecosystem services of created wetlands: two decades of plant succession, nutrient retention, and carbon sequestration in experimental riverine marshes. Ecological engineering, 72, pp.11-24.	2	+
Water quality	Wetlands	Verhoeven, J.T., Arheimer, B., Yin, C. and Hefting, M.M., 2006. Regional and global concerns over wetlands and water quality. Trends in ecology & evolution, 21(2), pp.96-103.	1	+
Water quality	Aquatic vegetation	Cotton, J.A., Wharton, G., Bass, J.A.B., Heppell, C.M. and Wotton, R.S., 2006. The effects of seasonal changes to in-stream vegetation cover on patterns of flow and accumulation of sediment. Geomorphology, 77(3-4), pp.320-334.	2	
Water quality	Urban areas	McGrane, S.J., 2016. Impacts of urbanisation on hydrological and water quality dynamics, and urban water management: a review. Hydrological Sciences Journal, 61(13), pp.2295-2311.	5	-
Water quality	Urban areas	Permatasari, P.A., Setiawan, Y., Khairiah, R.N. and Effendi, H., 2017. The effect of land use change on water quality: A case study in Ciliwung Watershed. In IOP Conference Series: Earth and Environmental Science (Vol. 54, No. 1, p. 012026). IOP Publishing.	5	-
Water quality	Urban areas	Ding, J., Jiang, Y., Fu, L., Liu, Q., Peng, Q. and Kang, M., 2015. Impacts of land use on surface water quality in a subtropical River Basin: a case study of the Dongjiang River Basin, Southeastern China. Water, 7(8), pp.4427-4445.	5	-
Water quality	Urban areas	Miller, J.D. and Hutchins, M., 2017. The impacts of urbanisation and climate change on urban flooding and urban water quality: A review of the evidence concerning the United Kingdom. Journal of Hydrology: Regional Studies, 12, pp.345-362.	5	-
Water quality	Urban areas	Goonetilleke, A. and Thomas, E.C., 2004. Water quality impacts of urbanisation: Relating water quality to urban form.	4	-
Water quality	Urban areas	Duh, J.D., Shandas, V., Chang, H. and George, L.A., 2008. Rates of urbanisation and the resiliency of air and water quality. Science of the total environment, 400(1-3), pp.238-256.	4	-
Water quality	Felled plantation	Laudon, H., Kuglerová, L., Sponseller, R.A., Futter, M., Nordin, A., Bishop, K., Lundmark, T., Egnell, G. and Ågren, A.M., 2016. The role of biogeochemical hotspots, landscape heterogeneity, and hydrological connectivity for minimizing forestry effects on water quality. Ambio, 45(2), pp.152-162.	5	-
Water quality	Felled plantation	Koralay, N. and Ömer, K.A.R.A., 2018. Forestry activities and surface water quality in a rainfall watershed. European Journal of Forest Engineering, 4(2), pp.70-82.	5	-

Water quality	Geomorphic complexity	Aquatic vegetation	Gurnell, A.M., Bertoldi, W. and Corenblit, D., 2012. Changing river channels: The roles of hydrological processes, plants and pioneer fluvial landforms in humid temperate, mixed load, gravel bed rivers. Earth-Science Reviews, 111(1-2), pp.129-141.	2	
Water quality	Agriculture		Holden, J., Haygarth, P.M., Dunn, N., Harris, J., Harris, R.C., Humble, A., Jenkins, A., MacDonald, J., McGonigle, D.F., Meacham, T. and Orr, H.G., 2017. Water quality and UK agriculture: challenges and opportunities. Wiley Interdisciplinary Reviews: Water, 4(2), p.e1201.	4	-
Water quality	Agriculture		Jarvie, H.P., Withers, P.J.A., Bowes, M.J., Palmer-Felgate, E.J., Harper, D.M., Wasiak, K., Wasiak, P., Hodgkinson, R.A., Bates, A., Stoate, C. and Neal, M., 2010. Streamwater phosphorus and nitrogen across a gradient in rural–agricultural land use intensity. Agriculture, ecosystems & environment, 135(4), pp.238-252.	5	-
Water quality	Agriculture		Connolly, N.M., Pearson, R.G., Loong, D., Maughan, M. and Brodie, J., 2015. Water quality variation along streams with similar agricultural development but contrasting riparian vegetation. Agriculture, ecosystems & environment, 213, pp.11-20.	5	-
Water quality	Agriculture		Sharpley, A., 2016. Managing agricultural phosphorus to minimize water quality impacts. Scientia Agricola, 73(1), pp.1-8.	5	-
Water quality	Agriculture		Sharpley, A.N., Bergström, L., Aronsson, H., Bechmann, M., Bolster, C.H., Börling, K., Djodjic, F., Jarvie, H.P., Schoumans, O.F., Stamm, C. and Tonderski, K.S., 2015. Future agriculture with minimized phosphorus losses to waters: Research needs and direction. Ambio, 44(2), pp.163-179.	5	-
Water quality	Agriculture		Birgand, F., Skaggs, R.W., Chescheir, G.M. and Gilliam, J.W., 2007. Nitrogen removal in streams of agricultural catchments—a literature review. Critical Reviews in Environmental Science and Technology, 37(5), pp.381-487.	5	-
Water regulation / Natural flood management	River floodplain area		Acreman, M.C., Riddington, R. and Booker, D.J., 2003. Hydrological impacts of floodplain restoration: a case study of the River Cherwell, UK. Hydrology and Earth System Sciences Discussions, 7(1), pp.75-85.	1	+
Water regulation / Natural flood management	River floodplain area		Ahilan, S., Guan, M., Sleigh, A., Wright, N. and Chang, H., 2016. The influence of floodplain restoration on flow and sediment dynamics in an urban river. Journal of Flood Risk Management.	1	+
Water regulation /	River floodplain area		CLILVERD, H.M., THOMPSON, J.R., HEPPELL, C.M., SAYER, C.D. and AXMACHER, J.C., 2016. Coupled hydrological/hydraulic modelling of river restoration impacts and floodplain hydrodynamics. River Research and Applications, 32 (9), 1927-1948.	1	+

Natural flood management				
Water regulation / Natural flood management	River floodplain area	EA Technical Report 2017. Working with Natural Processes evidence directory - Appendix 2. Literature Review:	2	+
Water regulation / Natural flood management	River floodplain area	Opperman, J.J., Galloway, G.E., Fargione, J., Mount, J.F., Richter, B.D. and Secchi, S., 2009. Sustainable floodplains through large-scale reconnection to rivers. Science, 326(5959), pp.1487-1488.	1	+
Water regulation / Natural flood management	River floodplain area	Addy, S. and Wilkinson, M.E., 2021. Embankment lowering and natural self-recovery improves river-floodplain hydro-geomorphic connectivity of a gravel bed river. Science of The Total Environment, 770, p.144626.	1	+
Water regulation / Natural flood management	River floodplain area	Opperman, Jeffrey J., Ryan Luster, Bruce A. McKenney, Michael Roberts, and Amanda Wrona Meadows, 2010. Ecologically Functional Floodplains: Connectivity, Flow Regime, and Scale. Journal of the American Water Resources Association (JAWRA) 46(2):211-226.	2	+
Water regulation / Natural flood management	Reservoir and dam unit	Patterson, C., Rosenberg, T. and Warren, A., 2016. Design, operation and adaptation of reservoirs for flood storage. Environment Agency, Deanery Road, Bristol, United Kingdom.	1	+
Water regulation / Natural flood management	Woody material	Kitts, D.R., 2010. The hydraulic and hydrological performance of large wood accumulations in a low-order forest stream. PhD thesis, University of Southampton	2	+
Water regulation / Natural flood management	Woody material	ODONI, N.A. AND LANE, S.N. 2010. Assessment of the impact of upstream land management measures on flood flows in Pickering using OVERFLOW. Contract report to Forest Research for the Slowing the Flow at Pickering project. Durham: Durham University.	2	+
Water regulation / Natural flood management	Woody material	Spray, C., Baillie, A., Chalmers, H., Comins, L., Black, A., Dewell, E., Ncube, S., Perez, K., Ball, T., Archer, N. and MacDonald, A., 2017, January. Eddleston Water Project report 2016. Tweed Forum.	2	+

Water regulation / Natural flood management	Woody material	THOMAS, H. AND NISBET, T., 2012. Modelling the hydraulic impact of reintroducing large woody debris into watercourses. Journal of Flood Risk Management, 5 (2), 164-174.	2	+
Water regulation / Natural flood management	Woody material	Wenzel, R., Reinhardt-Imjela, C., Schulte, A. and Bölscher, J., 2014. The potential of in-channel large woody debris in transforming discharge hydrographs in headwater areas (Ore Mountains, Southeastern Germany). Ecological engineering, 71, pp.1-9.	1	+
Water regulation / Natural flood management	Floodplain forest	Dixon, S.J., Sear, D.A., Odoni, N.A., Sykes, T. and Lane, S.N., 2016. The effects of river restoration on catchment scale flood risk and flood hydrology. Earth Surface Processes and Landforms, 41(7), pp.997-1008.	1	+
Water regulation / Natural flood management	Floodplain forest	Nisbet, T.R. and Thomas, H., 2006. The role of woodland in flood control: a landscape perspective.	2	+
Water regulation / Natural flood management	Floodplain forest	Nisbet, T.R. and Thomas, H., 2008. Restoring floodplain woodland for flood alleviation. Final report for the Department for Environment, Food and Rural Affairs. Project SLD2316, DEFRA, London.	1	+
Water regulation / Natural flood management	Floodplain forest	O'CONNELL, J., 2008. Modelling the effects of floodplain woodland in flood mitigation. A short-term case study. Irish Forestry, 65 (1-2), 17-36.	1	+
Water regulation / Natural flood management	Floodplain forest	Thomas, H. and Nisbet, T.R., 2007. An assessment of the impact of floodplain woodland on flood flows. Water and Environment Journal, 21(2), pp.114-126.	1	+
Water regulation / Natural flood management	Felled plantation	Robinson M, Cognard-Plancq AL, Cosandey C, David J, Durand P, Fuhrer H-W, Hall R, Hendriques MO, Marc V, McCarthy R, McDonnell M, Martin C, Nisbet T, O'Dea P, Rodgers M, Zollner A. 2003. Studies of the impact of forests on peak flows and baseflows: a European perspective. Forest Ecology and Management 186: 85–97.	5	-
Water regulation / Natural flood management	Felled plantation	Robinson, M. and Dupeyrat, A., 2005. Effects of commercial timber harvesting on streamflow regimes in the Plynlimon catchments, mid-Wales. Hydrological Processes, 19(6), pp.1213-1226.	5	-

Water regulation / Natural flood management	Riparian buffer	Woodland	Anderson, B.G., Rutherfurd, I.D. and Western, A.W., 2006. An analysis of the influence of riparian vegetation on the propagation of flood waves. Environmental Modelling & Software, 21(9), pp.1290-1296.	2	+
Water regulation / Natural flood management	Riparian buffer	Woodland	Dixon, S.J., Sear, D.A., Odoni, N.A., Sykes, T. and Lane, S.N., 2016. The effects of river restoration on catchment scale flood risk and flood hydrology. Earth Surface Processes and Landforms, 41(7), pp.997-1008.	1	+
Water regulation / Natural flood management	Riparian buffer	Woodland	GHAVASIEH, A.R., POULARD, C., ND PASQUIER, A., 2006. Effect of roughened strips on flood propagation: assessment on representative virtual cases and validation. Journal of Hydrology, 318 (1), 121-137.	2	+
Water regulation / Natural flood management	Riparian buffer	Woodland	Liu, Y.B., Gebremeskel, S., Smedt, F.D., Hoffmann, L. and Pfister, L., 2004. Simulation of flood reduction by natural river rehabilitation using a distributed hydrological model. Hydrology and Earth System Sciences, 8(6), pp.1129-1140.	1	+
Water regulation / Natural flood management	Riparian buffer	Woodland	ODONI, N.A. AND LANE, S.N. 2010. Assessment of the impact of upstream land management measures on flood flows in Pickering using OVERFLOW. Contract report to Forest Research for the Slowing the Flow at Pickering project. Durham: Durham University.	1	+
Water regulation / Natural flood management	Wetlands		Bullock, A. and Acreman, M., 2003. The role of wetlands in the hydrological cycle. Hydrology and Earth System Sciences Discussions, 7(3), pp.358-389.	3	+
Water regulation / Natural flood management	Wetlands		Kadykalo, A.N. and Findlay, C.S., 2016. THE FLOW REGULATION SERVICES OF WETLANDS DATABASE META-DATA Ecosystem Services, 20, 91-103. doi: https://doi.org/10.1016/j.ecoser.2016.06.005	2	+
Water regulation / Natural flood management	Wetlands		Fossey, M. and Rousseau, A.N., 2016. Can isolated and riparian wetlands mitigate the impact of climate change on watershed hydrology? A case study approach. Journal of environmental management, 184, pp.327-339.	2	+
Water regulation / Natural flood management	Washlands		Morris, J.H.T.M., Hess, T.M., Gowing, D.J.G., Leeds-Harrison, P.B., Bannister, N., Vivash, R.M.N. and Wade, M., 2005. A framework for integrating flood defence and biodiversity in washlands in England. International Journal of River Basin Management, 3(2), pp.105-115.	2	+

Water regulation / Natural flood management	Washlands	Morris, J., Bailey, A.P., Lawson, C.S., Leeds-Harrison, P.B., Alsop, D. and Vivash, R., 2008. The economic dimensions of integrating flood management and agri-environment through washland creation: a case from Somerset, England. Journal of Environmental Management, 88(2), pp.372-381.	1	+
Water regulation / Natural flood management	Washlands	Morris, J., Hess, T.M., Gowing, D.J., Leeds-Harrison, P.B., Bannister, N., Wade, M. and Vivash, R.M. (2004). Integrated Washland Management for Flood Defence and Biodiversity. Report to Department for Environment, Food and Rural Affairs & English Nature. Cranfield University at Silsoe, Bedfordshire, UK. March 2004	1	+
Water regulation / Natural flood management	Washlands	https://environmentagency.blog.gov.uk/2020/03/10/the-history-and-importance-of-the-river-aire-washlands/	1	
Water regulation / Natural flood management	Washlands	Carter, J A. Design and development of the flood storage and amenity reservoirs of the Rother Valley Country Park. United Kingdom: N. p., 1984. Web.	1	+
Water regulation / Natural flood management	Agriculture	Rouquette, J.R., Posthumus, H., Morris, J., Hess, T.M., Dawson, Q.L. and Gowing, D.J.G., 2011. Synergies and trade-offs in the management of lowland rural floodplains: an ecosystem services approach. Hydrological sciences journal, 56(8), pp.1566-1581.	2	+
Water regulation / Natural flood management	Agriculture	Mobilising flood risk management services from rural land: principles and practice	2	+
Water regulation / Natural flood management	Agriculture	O'Connell, P.E., Ewen, J., O'Donnell, G. and Quinn, P., 2007. Is there a link between agricultural land-use management and flooding?. Hydrology and Earth System Sciences, 11(1), pp.96-107.	4	-
Water regulation / Natural flood management	Urban areas	McGrane, S.J., 2016. Impacts of urbanisation on hydrological and water quality dynamics, and urban water management: a review. Hydrological Sciences Journal, 61(13), pp.2295-2311.	5	-
Water regulation / Natural flood management	Urban areas	Dams, J., Dujardin, J., Reggers, R., Bashir, I., Canters, F. and Batelaan, O., 2013. Mapping impervious surface change from remote sensing for hydrological modeling. Journal of Hydrology, 485, pp.84-95.	5	-

Water regulation / Natural flood management	Urban areas	Jongman, B., 2018. Effective adaptation to rising flood risk. Nature communications, 9(1), pp.1-3.	4	-
Water regulation / Natural flood management	Urban areas	Skougaard Kaspersen, P., Høegh Ravn, N., Arnbjerg-Nielsen, K., Madsen, H., and Drews, M.: Comparison of the impacts of urban development and climate change on exposing European cities to pluvial flooding, Hydrol. Earth Syst. Sci., 21, 4131–4147, https://doi.org/10.5194/hess-21-4131-2017, 2017.	5	-
Water regulation / Natural flood management	Urban areas	Sofia, G., Roder, G., Dalla Fontana, G. and Tarolli, P., 2017. Flood dynamics in urbanised landscapes: 100 years of climate and humans' interaction. Scientific reports, 7(1), pp.1-12.	4	-
Water regulation / Natural flood management	Urban areas	Miller, J.D. and Hutchins, M., 2017. The impacts of urbanisation and climate change on urban flooding and urban water quality: A review of the evidence concerning the United Kingdom. Journal of Hydrology: Regional Studies, 12, pp.345-362.	5	-
Water regulation / Natural flood management	Urban areas	Poelmans, L., Rompaey, A.V., Ntegeka, V. and Willems, P., 2011. The relative impact of climate change and urban expansion on peak flows: a case study in central Belgium. Hydrological Processes, 25(18), pp.2846-2858.	5	-
Water regulation / Natural flood management	Urban areas	O'Shea, T.E. and Lewin, J., 2020. Urban flooding in Britain: an approach to comparing ancient and contemporary flood exposure. Natural Hazards, 104(1), pp.581-591.	5	-
Water regulation / Natural flood management	Embankments / channelisation	Di Baldassarre, G., Castellarin, A. and Brath, A., 2009. Analysis of the effects of levee heightening on flood propagation: example of the River Po, Italy. Hydrological sciences journal, 54(6), pp.1007-1017.	4	-
Water regulation / Natural flood management	Embankments / channelisation	Heritage, G. and Entwistle, N.S., 2020. Quantifying the impact of channelisation on channel behaviour and coarse sediment budgets over a decadal scale: Implications for managing downstream flood risk. Water.	4	-
Water regulation / Natural flood management	Upland semi-natural habitats	Shuttleworth, E.L., Evans, M.G., Pilkington, M., Spencer, T., Walker, J., Milledge, D. and Allott, T.E., 2019. Restoration of blanket peat moorland delays stormflow from hillslopes and reduces peak discharge. Journal of Hydrology X, 2, p.100006.	1	+

Water regulation / Natural flood management	Upland semi-natural habitats		Holden, J., Kirkby, M.J., Lane, S.N., Milledge, D.G., Brookes, C.J., Holden, V. and McDonald, A.T., 2008. Overland flow velocity and roughness properties in peatlands. Water Resources Research, 44(6).	2	+
Water regulation / Natural flood management	Upland semi-natural habitats		Goudarzi, S., Milledge, D.G., Holden, J., Evans, M.G., Allott, T.E., Shuttleworth, E.L., Pilkington, M. and Walker, J., 2021. Blanket Peat Restoration: Numerical Study of the Underlying Processes Delivering Natural Flood Management Benefits. Water Resources Research, 57(4), p.e2020WR029209.	1	+
Water regulation / Natural flood management	Upland semi-natural habitats		GAO, J., HOLDEN, J. AND KIRKBY, M., 2016. The impact of land-cover change on flood peaks in peatland basins. Water Resources Research, 52 (5), 3477-3492.	1	+
Water regulation / Natural flood management	Upland semi-natural habitats		PILKINGTON, M., WALKER, J., MASKILL, R., ALLOTT, T. AND EVANS, M., 2015. Restoration of blanket bogs; flood risk reduction and other ecosystem benefits. Final report of the Making Space for Water project. Edale, Derbyshire: Moors for the Future Partnership. Available from: http://www.moorsforthefuture.org.uk/sites/default/files/Summary.a.pdf [Accessed 13/07/21]	1	+
Water supply	Floodplain lakes		Reynaud, A. and Lanzanova, D., 2017. A global meta-analysis of the value of ecosystem services provided by lakes. Ecological Economics, 137, pp.184-194 (global meta-analysis)	2	+
Water supply	Wetlands		Bullock, A. and Acreman, M., 2003. The role of wetlands in the hydrological cycle. Hydrology and Earth System Sciences Discussions, 7(3), pp.358-389	2	+
Water supply	Wetlands		Wong, C.P., Jiang, B., Bohn, T.J., Lee, K.N., Lettenmaier, D.P., Ma, D. and Ouyang, Z., 2017. Lake and wetland ecosystem services measuring water storage and local climate regulation. Water Resources Research, 53(4), pp.3197-3223.	2	+
Water supply	Floodplain lakes		Wong, C.P., Jiang, B., Bohn, T.J., Lee, K.N., Lettenmaier, D.P., Ma, D. and Ouyang, Z., 2017. Lake and wetland ecosystem services measuring water storage and local climate regulation. Water Resources Research, 53(4), pp.3197-3223.	2	+
Water supply	Reservoir and dam unit		Rood, S. B., S.M. Samuelson, J.H. Braatne, C.R. Gourley, F.M.R. Hughes, J.M. Mahoney. 2005. Managing river flows to restore floodplain forests. Frontiers in Ecology and the Environment 3(4): 193-201	2	+
Water supply	Weirs	HEP	Woods, G., Tickle, A., Chandler, P., Beardmore, J. and Pymm, R., 2010. Peak power: Developing micro hydro power in the peak district, friends of the peak district, UK.	1	+

Water supply	Upland semi-natural habitats		Bonn, A., Rebane, M. and Reid, C., 2009. Ecosystem services: a new rationale for conservation of upland environments. In Drivers of environmental change in uplands (pp. 476-502). Routledge.	2	+
Fisheries / biological quality	Geomorphic complexity	Woody material	Roni, P., Beechie, T., Pess, G. and Hanson, K., 2015. Wood placement in river restoration: fact, fiction, and future direction. Canadian Journal of Fisheries and Aquatic Sciences, 72(3), pp.466-478.	1	+
Water quality	Riparian buffer	Woodland	Mayer, P.M., Reynolds, S.K., McCutchen, M.D. and Canfield, T.J., 2007. Meta-analysis of nitrogen removal in riparian buffers. Journal of environmental quality, 36(4), pp.1172-1180.	1	+