A new method for assessing river ecosystem services and its application to rivers in Scotland with and without nature conservation designations

Victoria Keele[1], Dave Gilvear[1], Andy Large[2], Angus Tree[3] & Philip Boon[4]

[1] School of Geography, Earth and Environmental Science, University of Plymouth, Plymouth, UK
[2] School of Geography, Politics and Sociology, Newcastle University, Newcastle upon Tyne, UK
[3] Scottish Natural Heritage, Inverness, UK
[4] Freshwater Biological Association, Ambleside, UK

Correspondence

Dave Gilvear, School of Geography, Earth and Environmental Science, University of Plymouth, Drake Circus, Plymouth, PL4 8AA, UK. Email: david.gilvear@plymouth.ac.uk

ABSTRACT

Based on a paired analysis, we describe a method for evaluating the potential of rivers with different physical characteristics to provide ecosystem services. Scores based on an extensive scientific literature review and expert opinion were applied to four sets of rivers in Scotland, with each pair comprising one river with a statutory nature conservation designation and one where such designations were largely absent. Data on physical habitat features and land cover were extracted manually from *Google Earth*™, based upon a previously published method expanded here to take account of cultural ecosystem services. Twenty physical habitat features and land-cover types and 13 ecosystem services (four provisioning, three regulating, and six cultural) were used in the analysis. Notable developments on the earlier approach included the full integration of cultural ecosystem services alongside provisioning, regulating and supporting services, introduction of confidence levels to river feature–ecosystem service linkages, and incorporation of valley floor surface area into one of the two scoring systems. Ecosystem scores for 500 m reaches along each river from source to mouth were calculated using Microsoft Excel, with results showing high reach-to-reach variability within individual rivers and significant differences between paired rivers. The four rivers with statutory nature conservation designations provided a greater range and typically higher ecosystem service scores than those with little or no designation, a result that has significant implications for river conservation and for framing catchment-level conservation policy.

Key words: ecosystem services, nature conservation, Special Areas of Conservation, *Google Earth*™

1. INTRODUCTION

It is widely accepted that understanding the range and level of ecosystem services provided by natural areas should form part of a strategic approach to environmental management (Daily, 1997; Millennium Ecosystem Assessment, 2005; Daily *et al.*, 2009). Yet there are persistent challenges in accurately quantifying the range and level of ecosystem service supply (De Groot, Alkemade, Braat, Hein, & Willemen, 2010; Carpenter *et al.*, 2009) of a given landscape type or specific process, in particular how to determine which landscape features or land-cover types best deliver specific ecosystem services and how to ensure the optimal number and level of those services remains a challenge. There is also a need to determine whether, and to what extent, 'near-natural' landscapes contribute more ecosystem services than highly modified or managed systems (Auerbach, Deisenroth, McShane, McClunet, & Poff, 2014), as this could provide further justification for their protection. For example, it has been suggested that landscapes with high biodiversity provide a greater number and abundance of ecosystem services (Balvanera *et al.*, 2006; Balvanera *et al.*, 2014;). This is significant, as studies (e.g. Costanza *et al.*, 1997) have suggested that, globally, the financial cost of ecosystem service loss caused by land-use change and attendant biodiversity loss is as high as $US 4.3–20.2 trillion per annum.

Many areas with near-natural landscapes and high biodiversity are afforded protection using nature conservation designations, but to date only limited research has been conducted to determine whether such protection at the landscape scale has the added benefit of offering long-term protection against the loss of ecosystem services (DeFries, Hansen, Turner, Reid, & Liu, 2007; Boulton, Ekebom, & Gislason, 2016; Hummel *et al.*, 2017). García-Márquez *et al.* (2017) demonstrated that only half of the areas in the Columbian Andes, where biodiversity and ecosystem service supply is high, lay within protected zones. Eastwood *et al.* (2016) conducted a paired approach at the landscape scale on protected and unprotected areas in Britain and concluded that protected areas provide higher levels of cultural and regulating ecosystem services. Similarly, Castro *et al.* (2015) found that protected areas in arid landscapes in Spain supplied marginally higher levels of regulating services.

Few studies have systematically quantified the ecosystem service potential of whole river ecosystems. A number have targeted only single services, such as nitrogen retention (Grizzetti, Bouraoui, & De Marsily, 2008; Lautenbach *et al.*, 2012; Natho, Venohr, Henle, & Schulz-Zunkel, 2013); water quality (Van Looy, Tormos, Souchon, & Gilvear, 2017); water provision (Notter, Hurni, Wiesmann, & Abbaspour, 2012) and flood regulation (Fu, Wang, Xu, & Yan, 2013; Thomas & Nisbet, 2007). There remains a paucity of tools to assess and quantify the ecosystem services generated by often complex river reaches and stream networks (Hanna, Tomscha, Ouellet Dallaire, & Bennett, 2017).

1.1 Cultural ecosystem services and rivers

Ecosystem services are often classified in four categories: 'regulating', 'provisioning', 'supporting', and 'cultural' (Millennium Ecosystem Assessment, 2005). Recently, a simpler three-fold classification of provisioning, regulating and cultural has become more accepted and this tripartite method is used in this study. The Economics of Ecosystems and Biodiversity project (TEEB, 2010), the UK National Ecosystem Assessment and the Common Classification of Ecosystem Services (CICES) all now consider supporting services to underpin the delivery of provisioning, regulating, and cultural services (Potschin & Haines-Young, 2011; Watson *et al.*, 2011). Typically, assessments of river ecosystem services carried out by environmental scientists and geomorphologists have tended to focus solely on provisioning and regulating services and avoid those aspects of natural–cultural heritage known collectively as 'cultural services'. A method for evaluating river ecosystem services derived by two of the workers on the present study (Large & Gilvear, 2015) is particularly relevant here, as it provides an expert-based, heuristic and scale-independent method for quantifying the ecosystem services related to the physical habitats found in a variety of river types worldwide. Assessments were conducted at the reach scale and amalgamated along the river length to determine where ecosystem service supply was significant and where it was not. The classification developed by Large and Gilvear (2015) was designed specifically to stimulate debate within the academic river science community, to promote heuristic development of ecosystem service assessment using feature identification, and to produce outputs that are easily accessible to and usable by river managers and practitioners. The authors acknowledged that their system would need to be adapted to make it more appropriate for use at national or regional levels, and to incorporate 'culture' more effectively, and so we do this here at the river corridor scale for several representative Scottish river systems.

For Scottish rivers, Eastwood *et al.* (2016) compared ecosystem services provided by the River Dee Special Area of Conservation (SAC) with those from the adjacent and unprotected River Don. Of the 24 services considered by Eastwood *et al.* (2016), seven were judged to be greater in the protected Dee compared with just two in the less-protected Don. However, Eastwood *et al.* (2016) did not break down their assessment into individual reaches, nor did they explicitly link the character of physical habitats to ecosystem service supply. As a result, information about where along the long profile ecosystem services were being generated and where they had been lost to environmental degradation was limited. Unlike Large and Gilvear (2015), the approach did not allow scenario generation for how habitat restoration could bring about improvements to ecosystem services. Quantification of spatial variability in a small number of ecosystem system services provided by riparian zones with differing habitat characteristics at the river network scale has been achieved (Van Looy *et al.*, 2017), but not specifically in relation to nature conservation designation.

This article presents a new method for assessing how the physical character and habitats of river *corridors* influences the provision of multiple ecosystem services. River corridors are defined as ecosystems where ecological processes are partly controlled by permanent or intermittent inundation (river channels) or occasional inundation by river water (floodplains and valley floors). The approach represents an advance as the detailed evaluation of cultural ecosystem services is carried out alongside those of provisioning and regulating. Using the river corridor as the unit of assessment, the approach allows assessments at the national level (here for Scotland) to be made. The study focused specifically on four sets of paired rivers in Scotland, with each pair comprising a river protected extensively by a statutory nature conservation designation and another river, geographically close, which was largely undesignated.

2. STUDY AREA AND RIVER SELECTION

Scotland provides an ideal location for research on river ecosystem services and the role played by nature conservation designations because of its wide range of river types that are protected by a variety of conservation designations. Scotland has a temperate–oceanic climate with an average annual rainfall of about 1500 mm that varies from more than 3000 mm in the mountainous areas of the west to less than 800 mm in the driest areas of the east. Scotland's rivers are characterized predominantly by gravel or boulders with cascade, step-pool, plane bed, pool-riffle, meandering, and wandering morphologies. Important habitats include exposed gravel bars, riffles, ancient floodplain forest, floodplain wetlands, and backwaters.

Scottish Natural Heritage (SNH) is the principal public body responsible for advising the Scottish Government on all matters related to the natural heritage. SNH's remit is to promote, care for, and improve the natural heritage; help people to enjoy nature responsibly; provide greater understanding and awareness of nature; and promote the sustainable use of Scotland's natural heritage (www.nature.scot). SNH is also the government agency responsible for the administration of conservation designations; in Scotland these designations are at the international, national, and local levels. Sites with international designations include two Biogenetic Reserves, three Geoparks, 51 Ramsar sites, 241 SACs, 153 Special Protection Areas, one World Heritage Site, and two Biosphere Reserves. National designations include 40 National Scenic Areas, two National Parks, 43 National Nature Reserves, and 1,423 Sites of Special Scientific Interest. Of all the designations, it is the SACs designated under the European Union Habitats Directive (Council of the European Communities, 1992) that afford the most robust protection to Scotland's rivers. Across Europe, SACs are designated to protect specific habitats and species listed in the annexes of the Habitats Directive. Twenty of Scotland's rivers are designated SACs, with the most common primary reasons for designation being the presence of freshwater pearl mussel (*Margaritifera margaritifera*: 12 rivers) and Atlantic salmon (*Salmo salar*: 10 rivers). Across all the 20 SACs there are a total of 31 primary reasons for designation.

Four rivers designated as SACs were chosen for this study: the Thurso, Dee, Almond (a tributary of the River Tay SAC), and the Teith (Figure 1). These rivers encompass a range of geomorphological river types and biogeographical settings. The headwaters of all four drain sparsely populated moorland catchments; further downstream villages and towns appear, and agriculture becomes more prominent on floodplains. The four rivers were paired with similar sized ones in close proximity but for the most part without nature conservation protection. The broad characteristics of the rivers selected, together with the reasons for designation, are shown in Table 1.

The ecosystem services provided by Scottish rivers have not been extensively explored at the national level although their importance to Scotland's economy through the provision of water for domestic, agricultural and industrial use, hydropower generation, and tourism is widely acknowledged. Rivers and streams contribute a significant proportion (38%) of domestic water supply in Scotland, and at present hydropower accounts for around 10% of Scotland's total electricity production (Sample, Baber, & Badger, 2016). Scottish rivers have particularly high recreational and touristic value. For example, Butler, Radford, Riddington, and Laughton (2009) estimated rod fishing on the River Spey in 2003 to be worth around £59 million. In another study, Riddington, Radford, and Higgins (2004) estimated that in 2003 sailing, rafting and canoeing in the Spey catchment generated around £1.7 million per annum. A Scottish household survey in 2004 found that approximately 6% of outdoor visits were to rivers, while 41% of visits were to local parks or open spaces where rivers may be important features of the landscape.

3. PROCEDURE FOR ASSESSING RIVER ECOSYSTEM SERVICES

The method for ecosystem service assessment developed here is an advance on the scoring system of Large and Gilvear (2015) and follows the broad approach to ecosystem service assessment introduced by Burkhard, Kroll, Müller, and Windhorst (2009). *Google Earth*™ imagery was assessed visually and/or measured using *Google Earth*™ tools to characterize the nature and extent of physical habitat and land cover of river reaches. Key theoretical and conceptual improvements include the removal of biodiversity as an ecosystem service. 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. The approach developed in this study assigns confidence levels to the linkages between ecosystem services based on extensive literature review; notably, there is a more complete incorporation of cultural services. The method comprises three basic steps that were used to design the assessment process: 1) the identification of the relevant 'riverscape' (*sensu stricto* Thorp, Thoms, & Delong, 2006) features and land-cover types that determine the type and level of ecosystem service; 2) the creation of a system for extracting the river landscape features from the remotely sensed data at the river reach scale; and 3) the establishment of a protocol for assigning features to individual river ecosystem services through a robust method for scoring and producing ecosystem service metrics.

3.1 Stage 1 - Linking river landscape features/attributes to ecosystem service supply

Thirteen ecosystem services were identified as pertinent to Scottish rivers from a list compiled in consultation with key personnel from Scottish environmental organizations. Four were provisioning services (water supply, hydroelectric power production, agriculture, timber production), three were regulating (natural flood regulation, climate regulation, water quality), and initially seven were cultural services (aesthetic value, social relations, inspiration, education/knowledge, cultural heritage, spirituality/religion, recreation) (Table 3). The selection method was similar to that of Nordlund, Koch, Barbier, and Creed (2016) who used an open-floor discussion with experts to fill the matrix; the experts were encouraged to add, remove, or change services to determine a final list. Twenty features and land-cover types were identified as representative of the river corridor landscapes of Scotland, relevant to the provision of ecosystem services, and identifiable or measurable with *Google Earth*™. The final selection of features and land-cover types was based on attempts to reduce the effort of data capture and to avoid duplication whereby more than one feature was accounting for a single riverscape function. Any such duplication would potentially produce a bias towards ecosystem services supported by those features and land-cover types. Table 2 shows the theoretical linkages between features and land cover, and provisioning and regulating ecosystem services for all 20 features considered here. In total there were 55 linkages, both positive and negative. An extensive literature search of more than 180 articles (31% water quality; 30% climate regulation; 15% water supply; 15% natural flood regulation; 3% Timber production; 3% agriculture; 3% hydropower production) was used to establish the linkages, and assign a level of confidence in the relationship for provisioning and regulating services. Jacobs, Burkhard, Van Daele, Staes, and Schneiders (2015) suggested that matrices that do not present measures of uncertainty are of limited use. The level of confidence in each linkage was described as 'high', 'medium', or 'low', with scores assigned based on expert judgement, although a number of published empirical studies were used as a guide. A confidence score of 1, 2, or 3 was assigned if 1–2, 3–4, or >5 papers were identified, respectively. No score meant that evidence of a linkage was not apparent from the literature. The strength and relevance of empirical research was also considered and thus some confidence scores differ from this guide. Any uncertainties are likely to be the result of limited data on the subject (Balvanera *et al.*, 2014) or because of an incomplete theoretical understanding of the link between ecosystem attributes and ecosystem service supply (Benayas, Newton, Diaz, & Bullock, 2009; Bastian, 2013; Ricketts *et al.*, 2016).

Linkages of cultural services to the presence or absence of features and to land cover were established separately to the other services. The definition of cultural services was based on the answers given by respondents to a photo preference questionnaire survey in which the responses on seven cultural services were based on photographs of rivers containing each feature or land-cover type. Sixty-two respondents completed the questionnaire, also providing ancillary information on age, gender and profession. Using *Survey Monkey* software, respondents were asked whether they would visit the river type for the range of cultural services using a 5-point classification of 'never', 'rarely', 'sometimes', 'frequently', or 'very frequently'. Only those services with a mean score equating to 'sometimes'/'frequently' were included in the matrix. Respondents were also asked to say whether or not they believed that there is a link between the features and land-cover types, and to explain their motivation for appreciating the cultural aspects of certain habitats and features. Riverscape features/attributes, weirs, channelization, morphology and width were not included thereby permitting a short, easily understood survey. Results are shown in Tables 3 and 4. Based on this information a mean 'expert score' (See Section 3.3) was then attributed to each cultural ecosystem service for each relevant riverscape feature and land-cover type. Spirituality/religion was removed from the matrix following the outcome of a cultural ecosystem service survey. This allowed scores for cultural services, comparable with those for provisioning and regulating services, to be incorporated within the *Google Earth*™ based approach to mapping river ecosystem services (Large & Gilvear, 2015). Unlike the scores for provisioning and regulating services, those for cultural services were not assigned confidence scores. This was due to the scores being derived in a different way from provisioning and regulating..

3.2. *Stage 2 - Extraction of river landscape features from remotely sensed data*

Data on riverscape features and land cover were extracted using the method of Large and Gilvear (2015). This involves using colour, texture, and shapes in *Google Earth*™ imagery, and is easy to use by individuals with basic experience of rivers and basic skills in interpreting aerial imagery. Table 5 lists the features used, the evidence as observed in *Google Earth*™, and the protocols for measurement. Channel morphology was classified according to a Scottish Environment Protection Agency (SEPA) typology (cascade, step-pool, plane bed, pool-riffle, meandering, and wandering/braided being the main types) based on the study of Montgomery and Buffington (1997). Large and Gilvear (2015) identified the scale of data extraction as an important issue and proposed variable reach scales according to river size. The method used here for rivers in Scotland was applied at a consistent scale of 500 m reaches; this corresponds to standard methods used by other UK classifications including the River Habitat Survey (Raven, Holmes, Dawson, & Everard, 1998) and Urban River Survey (Shuker, Gurnell, & Raco, 2012). Large and Gilvear (2015) highlighted issues in identifying river corridor width in low-lying landscapes of the UK where there are few apparent breaks of slope and in upland valleys where field patterns can obscure where the edges of the valley floor meet valley sides. River corridor width in the present study was therefore set by the boundaries of 1 in 100-year indicative flood maps. These are available for the whole of Scotland, modelled by the UK Centre for Ecology and Hydrology (CEH: Figure 2).

3.3 *Scoring system for assigning river landscape features/attributes to individual river ecosystem services*

An integer-based scoring system for the reach, using a class interval of 10 and ranging from 0-100%, was adopted for classification. A score of 0-10 meant 'virtually absent' and 91-100 implied 'near maximum' potential contribution (either positive or negative (see Table 2) for an individual provisioning or regulating ecosystem service (Table 2; Table 6). If assessing all seven provisioning and regulating services, the maximum non area-weighted reach score was 700. Reach scores for cultural services were assigned in the same way but with a maximum score of 600 per reach as six cultural services were identified. Area-weighted scores were derived by multiplying the area of valley floor of each 500 m reach in hectares by the reach score. Each reach was also given a confidence score. Reach confidence scores are the sum of the matrix confidence scores given for all feature–service relationships identified within the reach. A rule-based approach that focused on the measured features was used to assign scores for provisioning and regulating services. Scoring cultural services was based on the data of the photographic preference questionnaire survey and the values are shown in Table 4. As the intention is to make this method equally accessible to river experts and non-experts alike, equal weighting was applied across all ecosystem services. How services are valued is a societal decision.

3.4 *River indices*

All calculations were done using universally available Excel software. Excel spreadsheets have been used in other research that produced ecosystem service capacity scores (Bowd, Quinn, Kotze, Hay, & Mander, 2012; Large & Gilvear, 2015; Nordlund *et al.*, 2016), and to estimate the contribution of habitats to ecosystem service supply (Christie & Rayment, 2012). A matrix was constructed listing the 20 river features and their reach scores (determined from the *Google Earth*™ imagery using the scoring system outlined in Table 5). Some river corridor features may exert a greater influence on ecosystem service capacity than others; this was considered by applying weightings based on expert judgement. Each feature score was multiplied by its corresponding weighting and then all weighted feature scores summed to provide ecosystem service capacity scores. Weightings may be altered in applying the matrix to rivers in other biogeographical environments. The formulae written also accounted for negative relationships, as understanding adverse impacts alongside positive ones is critical to managing landscapes for ecosystem services (Rodríguez *et al.*, 2006; Seppelt, Dormann, Eppink, Lautenbach, & Schmidt, 2011; Potschin & Haines-Young, 2011). For example, hydropower, although providing a utilitarian service, can impair several other services such as fish production, water quality and habitat provision (Ziv, Baran, Nam, Rodríguez-Iturbe, & Levin, 2012). Negative scores could therefore be attributed to an individual ecosystem service if a given land-cover type or riverscape feature had more adverse outcomes than positive ones. Values of accumulated ecosystem services for the reach from other land cover or features would then be reduced by the negative score but not below a value of zero, as zero was the minimum score permissible for an individual reach (as we argue that a negative ecosystem service is conceptually not feasible). Using the summing feature in Excel, a range of indices was determined from the matrix. The following seven scores were derived for the reach scale: 'number of features/ land cover'; 'number of benefitting ecosystem services'; 'individual ecosystem service reach'; 'provisioning service'; 'regulating service'; 'cultural ecosystem service'; and 'total reach ecosystem services'. These were summed and average river scores calculated per 500 m reach. The higher the score the greater the quality and/or abundance of the ecosystem services and environmental quality of the river landscape providing that service. Raw scores were also multiplied by the area of each reach (measured using the 'Polygon Tool' in *Google Earth*™) to give a better indication of the spatial abundance of the ecosystem service provided.

3.5 *Statistical analysis*

To determine the effect of statutory protected areas on ecosystem service supply, the differences between the pairs of rivers were assessed using a Mann–Whitney U test for all ecosystem services and total ecosystem service scores, both unweighted and area weighted. For each pair of rivers, 34 tests were undertaken for each of the 20 ecosystem service scores listed in Table 2.

4. RESULTS

4.1 *Reach score variability and river long profile patterns from source to mouth*

Individual ecosystem scores were created for each 500m reach along the eight rivers surveyed. These scores were amalgamated to provide reach-level scores for provisioning, regulating and cultural categories of services. The individual ecosystem scores were summed to give a total ecosystem service score for each reach. The maximum and minimum reach scores for each river are presented in Table 7. Unweighted total ecosystem scores ranged from 0 to 870. Weighted scores were significantly influenced by the area of active valley floor, with valley floor areas varying between 0.7 and 111.5 ha per 500 m reach, resulting in weighted scores from 0 to 32,753.5 for individual reaches. This clearly demonstrates the value of floodplain connectivity with the main channel in raising ecosystem service provision. The pattern of weighted scores shown along the rivers broadly mimics the pattern of reach scale variability in valley floor area, but with notable positive and negative residuals (Figure 3). The river long-profile plots in Figure 3 show the contribution of individual ecosystem services to the total score for each reach along the river. Plots demonstrate high reach-to-reach variability but with a general pattern of higher ecosystem service scores in mid-reaches, with a greater dominance of agriculture further downstream. For example, the total area-weighted ecosystem service score for the River Forth (Figure 3H) is >10,000 9 km from the source, but <2000 just 2 km further downstream. Despite the high heterogeneity, regional patterns emerge. On the River Forth, higher values are apparent between 9-30 river kilometres downstream with lower values observed upstream and downstream of this extended reach. Downstream of 30 river kilometres from the source, agriculture dominates provisioning and regulating ecosystem services. Examination of cultural services provided on the Forth shows the same pattern with ecosystem services again peaking between 9-30 km from the source, with values further downstream on average only one-fifth of those upstream (Figure 3H). It is beyond the scope of this paper to examine and explain long-profile patterns in relation to the wider geography of the eight individual catchments, but this information would undoubtedly have value for catchment management strategies.

4.2 *Differences between rivers with varying levels of nature conservation designations*

Of the 68 tests undertaken on the area-weighted scores, the differences for 46 reaches were statistically significant, and of the 68 tests performed on the non-weighted scores the differences for 43 are statistically significant (Table 8; Table 9). There are statistical differences in the range and type of service provided, with regulating services being prominent. All four lesser-protected rivers show greater agricultural intensity, and this affects total ecosystem service scores for these river systems. Although the 'undesignated' rivers were not chosen to be different from their designated counterparts, three of the four protected rivers (the Dee, Teith, and Almond) as opposed to one non-protected river (the Forss) have significantly higher total regulating scores. It should be noted that although the Forss has no river-focused nature conservation designations, it flows through remote areas of Scotland and significant proportions of the wider catchment can be classed as near-natural, e.g. Broubster Leans SAC, a transition mire and quaking bog. For natural flood mitigation and water quality regulation, the protected rivers Dee, Teith and Almond, and the unprotected River Forss have significantly greater potential. The Dee and Almond scores indicated greater potential for climate change mitigation.

In comparison with provisioning and regulating services, the pattern for cultural services is less obvious. One protected river (the Thurso) and one unprotected river (the Don) were calculated to have higher total cultural service scores than the others. Two unprotected rivers (the Don and Earn) and one protected river (the Teith) have greater potential for aesthetic value and recreation. The potential for education was significantly greater for two protected rivers (the Dee and Thurso) and two unprotected rivers (the Forth and Earn) but with little difference seen between them. Scores for social relations services are significantly higher for only two of the protected rivers (the Dee and Almond).

4.2 *Paired river systems*

When examining paired river systems, the protected Dee and the unprotected Don contrast the most, with statistically significant differences in 13 of the 17 ecosystem service metrics. In nine of the 13, it is the protected River Dee that provides greater ecosystem service potential. Of the four instances when the Don provides greater potential, three result from cultural service scores being elevated by site-specific factors. Both the River Teith and River Forth pairing, and the River Almond and River Earn pairing, had statistically significant differences in 11 of the 17 metrics. However, between separate paired rivers, the relationships are quite different. The paired rivers Teith and Forth are like the paired Dee and Don with the protected River Teith having greater potential for nine metrics and the unprotected Forth supplying greater potential for only two metrics: agriculture and education provision. The paired rivers Almond and Earn were harder to separate, with the protected River Almond significantly greater for six metrics and the less protected Earn for five. Of the six scenarios where the River Almond has greater potential, four were metrics relating to regulating services. In contrast, of the five scenarios where the River Earn had greater ecosystem service potential, three were related to cultural service provision. The paired rivers Thurso and Forss were the most similar, with differences in only eight of the 17 metrics. Two of the three occurrences where protected area potential was calculated as greater resulted from elevated scores for cultural services.

Examining the area-weighted ecosystem services reveals some statistically significant differences between all four protected versus unprotected/less protected Scottish rivers for total ecosystem service scores. For three pairs (Dee and Don, Teith and Forth, and Thurso and Forss) the protected river had the higher score, whereas for one pair (Almond and Earn) it was the unprotected River Earn (Table 8). Total regulating service scores were also statistically different for three of the four paired systems. Regulating service potential was greater for the protected Dee and Teith and the unprotected Earn. Water quality regulation was the only regulating service found to be different for all four pairs of rivers. The potential for water quality regulation was higher in three protected rivers (Dee, Teith, and Almond) and one unprotected (Forss Water). Natural flood mitigation scores displayed the same differences as the total regulating score, and with a ratio of 2:1 there was an indication that protected rivers have greater potential for natural flood mitigation. The potential for climate change regulation was also significantly greater for two protected rivers (Dee and Almond) compared with their unprotected counterparts but was not identified as greater in any of the unprotected rivers. Total cultural service scores were also significantly different for three of the four pairs; however, the three pairs were different from those identified from the other total scores, with the protected rivers Teith and Thurso and the unprotected Earn having the higher scores. For aesthetic value and recreation, the protected rivers Teith and Thurso and unprotected Don and Earn had greater potential, while for education/knowledge value it was the protected Dee and Thurso and the unprotected Forth and Earn. The potential for social relations is only different for two pairs; in both cases it was the protected river that had the greater potential (Dee and Almond). Both unprotected and protected rivers can have amenity land present, but those rivers in catchments with larger human populations would be expected to have a greater extent of this land-use category.

5. DISCUSSION

5.1 A*ppraisal of utility of the approach*

This study represents a significant improvement on the Large and Gilvear (2015) approach to river ecosystem service assessment as cultural ecosystem services were incorporated more methodically and in greater detail. The approach to assessing river ecosystem services was based on Large and Gilvear (2015), linking individual features and land cover to an inherent set of attributes and environmental processes that cascade one or multiple ecosystem services. The information for undertaking the assessments is widely accessible from *Google Earth™* and from a UK-wide database showing the extent of 1:100-year fluvial flooding. Here, for the first time we incorporate cultural ecosystem services using the same scoring system as for provisioning and regulating services. The last two of these are scored based on quantification of riverscape features and land cover using *Google Earth*™, whereas links between riverscape features and land cover and cultural services was established differently - by photo preference questionnaire survey.

The method does not require specialist skills, and the data needed can be easily extracted from the available imagery and from hydrological databases. The straightforward scoring system provides easy uptake and so could help to resolve the problem identified by Langhans, Lienert, Schuwirth, & Reichert (2013) of how to carry out comparable river assessments across national and international boundaries. The approach described here incorporates the area of the valley floor or floodplain within the assessment procedure. It also allows individual reaches to be assessed and quantification of the spatial pattern of service provision, whether for an individual ecosystem service (IESS) value or across the full spectrum of ecosystem services (TESS value). Identifying 'hotspots' and areas devoid of ecosystem services within river networks or across catchments is also potentially of value to catchment managers, as areas or reaches with lower levels of ecosystem service supply can be examined to determine whether this is a product of inherent river system variability, a result of degree of legislative protection, or an indicator of environmental degradation.

5.2 *Challenges and opportunities*

The method described here provides a basis for river management that not only addresses the protection of habitats and species but also ecosystem services. It will need to be refined to suit the geographical region in which it is used, and the method will evolve as the nature of the linkages between river landscape features and land-cover types, and ecosystem services becomes more firmly established. Several assumptions, albeit based on the expert knowledge of river scientists, are made about links between river landscape features and provisioning and regulating ecosystem services, both in the method developed by Large and Gilvear (2015) and the approach described here for paired Scottish catchments. These assumptions are reflected in the uncertainty scores given to individual linkages, but even where these assumptions are scientifically valid, they still might not be universally applicable. As such, a critical assessment of how scores are assigned and the rules for scoring will always be required. In particular, the scoring system for cultural services may not be overly robust, owing to size and representativeness of any questionnaire survey carried out. Nonetheless, the approach does illustrate how reliable scores can be obtained for assessing cultural ecosystem services as well as for the others. As such, the incorporation of cultural ecosystem services using a photo preference questionnaire survey is seen as a significant advance, but a challenge with cultural ecosystem service scores remains in the variety of ways in which they are categorized. For example, water-based recreation can be treated as one category or sub-divided into several, such as kayaking, rafting, rowing, swimming, windsurfing and snorkelling.

All the rivers in this study were examined from source to mouth with the justification for focusing only on the main channel and not the tributaries being that SAC designations are often used specifically for the river main stem. Accounting for the provision of ecosystem services in lower-order watercourses is still needed to gain an understanding of ecosystem service provision in river networks. Using *Google Earth™* also presented problems. For example, defining the limits of river corridor width required an alternative approach using flood inundation. Kail, Jahnig, & Hering (2009) have used a similar flood inundation modelling approach in defining river corridors for two German streams.

5.3 *Protected areas and ecosystem service supply*

One of the aims of this article was to determine whether rivers protected for nature conservation have the added benefit of offering long-term protection against the loss of ecosystem services (DeFries *et al.*, 2007; Boulton *et al.*, 2016; Harrison et al., 2016; Hummel *et al.*, 2017). Previous studies suggest that protected areas may support high levels of ecosystem services, even if only marginally (Castro *et al.*, 2015). Studies have also shown that high levels of ecosystem services are also supplied elsewhere in the catchment landscape (García Márquez *et al.*, 2017). This study lends support to the idea that river landscapes protected for nature conservation may support higher levels of ecosystem services across provisioning, regulating and cultural categories; however, more river network-focused studies need to be undertaken in a range of differing environments to confirm this. The results presented here also illustrate the high level of spatial heterogeneity in ecosystem service supply along the length of a river. This heterogeneity can be from reach to neighbouring reach, as well as within and outside of statutory protected areas.

6. CONCLUSIONS

Based on four paired Scottish rivers, we show that rivers protected for their nature conservation value will often provide a greater range and level of ecosystem services than their unprotected counterparts. Although this is unsurprising, as ecosystem structure, ecological functioning, and environmental processes will typically be less modified by human activities in protected systems, the method described here offers a practical approach for mapping main-stem ecosystem service provision. The method presented here has a range of applications, from assessing the value of rivers protected by nature conservation designations, to assessing where river restoration may be beneficial. Large and Gilvear (2015) demonstrated through scenario-testing how restoration at the reach scale can be evaluated in terms of enhancing ecosystem services towards maximum-attainable values. Although not a feature of the study described here, the scenario-testing potential is similarly available for the method incorporating cultural ecosystem services. Given the time-consuming nature of the manual approach referred to above, further development is needed on automating the measurement of river landscape features. Accurate automated image classification is not yet fully feasible, however, owing to radiometric distortion. With current rates of evolution of 'virtual globe' technology it is anticipated that the next significant advance will be the development of global imaging platforms making high resolution multi- or hyperspectral data more freely available.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, [Gilvear DJ], upon reasonable request.

ACKNOWLEDGEMENTS

This work was funded by Scottish Natural Heritage via their PhD studentship bursary scheme. Figure 3 includes images from *Google Earth*™, and from the following suppliers: Infoterra Ltd & Bluesky, Getmapping plc (see Figure captions for precise attributions). In using these images, we have conformed to guidelines available from https://www.google.com/permissions/geoguidelines/attr-guide.html (accessed 31 January 2019) including image attributions in the Figure caption that conform to 'the text of your attribution must say the name "Google" and the relevant data provider(s), such as "Map data: Google, DigitalGlobe".

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Table 1

The eight rivers used in the study, shown in protected (P) and unprotected (U) pairs, with information on their catchment areas, mean flow, and the species present that justified the designation of each river

River	**U/P**	**Catchment area (km^2)**	**Mean annual flow ($m^3 s^{-1}$)**	**Species justifying designation**	
				Common name	Scientific name
Thurso	P	413	9.1	Atlantic salmon	*Salmo salar*
Forss	U	130	Not known	---	---
Dee	P	2080	24.6	Freshwater pearl mussel Otter Atlantic salmon	*Margaritifera margaritifera* *Lutra lutra* *Salmo salar*
Don	U	1280	21.2	---	---
Teith	P	518	24.6	Sea lamprey Brook lamprey River lamprey	*Petromyzon marinus* *Lampetra planeri* *Lampetra fluviatilis*
Forth	U	1036	24.7		
Almond	P	360	6.2	Sea lamprey Brook lamprey River lamprey Atlantic salmon Otter	*Petromyzon marinus* *Lampetra planeri* *Lampetra fluviatilis* *Salmo salar* *Lutra lutra*
Earn	U	590	22.8	---	---

Table 2

A matrix linking the seven provisioning and regulating ecosystem services to riverscape features and land cover

	Provisioning				Regulating		
	Water supply	Agriculture	Timber production	HEP production	Natural flood mitigation	Climate regulation	Water quality
River width	3						
Morphology					-		
Weirs	3						-
Channelization (including embankments)					2		1
Land cover type							
Woodland							
Broadleaf/Mixed	2		3		3	3	3
Conifer	3		3		3	3	2
Young woodland	3		3		-	1	1
Felled	2				3	3	3
Floodplain forest	-				3	-	2
Riparian buffer							
Woodland buffer					2	-	3
Herbaceous buffer					1	1	3
Lakes and wetlands							
Floodplain lake	-				-	-	-
Natural lake	3				1	3	-
Upland wetland	3				3	-	3
Lowland wetland	-				3	-	3
'Altered' land							
Agricultural land		3				3	3
Amenity land					-	-	-
Dam and reservoir unit	3			3		2	3
Urban areas	3				3		3

	River corridor feature **positively contributes** to ecosystem service capacity
	River corridor feature **negatively contributes** to ecosystem service capacity
1	**Very little** relevant scientific literature supporting linkage
2	**Moderate** relevant scientific literature supporting linkage
3	**Abundant strong** relevant scientific literature supporting linkage
	More research required: Insufficient evidence currently available but a linkage is possible
	Conflicting evidence: Evidence is available but contradicting and/or a range of other variables must be known to more accurately determine linkage

Table 3

The percentage of respondents to the photo-preference questionnaire survey on cultural ecosystem services who considered there to be a link between the riverscape feature/land cover and the cultural service

Riverscape feature/land cover	Aesthetic value	Social relations	Inspiration	Education/ Knowledge	Cultural heritage	Spirituality/religion	Recreation	Number of comments
Cultural heritage feature	13.3	4.4	4.4	8.8	60	0	8.8	45
Waterfalls	35.5	2.2	8.8	0	4.4	4.4	15.5	45
Land cover types								
Agricultural land	18.8	5.8	1.5	5.8	4.3	1.5	33.3	69
Amenity land	12.7	14.5	0	3.6	1.8	0	25.5	55
Felled woodland	0	1.8	0	5.5	3.6	0	0	55
Lowland wetlands/ floodplain lakes	40	4.4	2.2	4.4	2.2	0	22	45
Reservoirs and lakes	18.3	2	0	4.1	8.2	0	28.6	49
Upland wetlands	25	2.3	2.3	0	4.5	0	22.7	44
Urban areas	4.4	0	0	0	4.4	0	28.9	45
Woodlands	20	7.1	0	2.4	0	2.4	28.6	42

Table 4

Mean perception survey participant score for the linkage between riverscape feature and land cover, and cultural ecosystem service. Shaded boxes indicate a significant link. A score of zero denotes 'never' and a score of 4 'very frequently' (Spirituality/religion was removed from the matrix and analysis on the basis of these data).

Riverscape feature/land cover	**Aesthetic value**	**Social relations**	**Inspiration**	**Education/ Knowledge**	**Cultural heritage**	**Spirituality/religion**	**Recreation**
Cultural heritage feature	2.5	2.1	1.5	1.7	2.5	0.6	2.3
Waterfalls	3.2	2.3	2.2	2.2	1.7	1.4	3.0
Land cover type							
Woodland	3	2.3	1.9	2.1	1.6	1.1	2.9
Felled woodland	1.6	1.0	0.9	1.7	1.2	0.5	1.8
Upland wetlands	3.0	2.0	1.8	2.0	1.7	1.2	2.9
Lowland wetlands/ Floodplain lake	2.2	1.7	1.3	1.8	1.5	0.8	2.4
Agricultural land	3	1.8	1.6	2.1	1.8	1.0	3.1
Amenity land	2.6	2.2	1.3	1.7	1.7	0.8	2.6
Natural lake/ Reservoir	2.4	1.8	1.4	1.8	1.7	0.8	2.5
Urban areas	1.3	1.6	0.8	1.2	1.4	0.4	1.6

Table 5

Observable evidence of the riverscape features and land cover on *Google Earth*™ and the measurement protocol for extracting the information necessary for populating the Excel-based ecosystem service assessment spreadsheet

Riverscape feature/land cover	Observable evidence In *Google Earth™*	Measurement protocol
River width	Wetted width and unvegetated exposed sediment	Average of three measurements. Measure top, middle and bottom.
River morphology	Morphological features identifiable include large exposed boulders, pools, riffles, bars and meanders	Classify using SEPA reach typology
Weirs	Structure that spans the width or partial width of the channel with water pooling behind it	Note number and if they span the full channel width
Channelization (including embankments)	Including straightened reaches and reaches with reinforced beds and banks, also look for raised parallel features of earth or constructed materials.	Estimate the percentage of the channel that appears to be channelized or embanked
Forest		
Broadleaf/Mixed	Mixed colour woodland with green-brown species present, trees have wide canopies and/or a combination of mixed colour woodland with green-brown species present and dark green trees with narrower canopies	Estimate the percentage cover within the defined river corridor
Conifer	Dark green forest, trees have narrow canopies and often appear in linear patterns, shadows often pointed	Estimate the percentage cover within the defined river corridor
Young woodland	Evidence of tree planting – tree widths seem smaller, trees may be planted in a linear fashion, likely to be gaps between all trees.	Estimate the percentage cover within the defined river corridor
Felled ground/ prepared for planting	Ground which appears bare or with stumps present, may be surrounded by mature trees	Estimate the percentage cover within the defined river corridor
Floodplain forest	A patch of broadleaf forest near to the river channel that looks as if it might flood frequently. Does not extend beyond corridor.	Estimate the percentage cover within the defined river corridor
Riparian buffer strips		
Woodland buffer	A linear strip of trees located parallel to the channel, not extensive in width	Estimate percentage of river bank with buffer adjacent
Herbaceous buffer	A linear strip of light green or mottled green located parallel to the channel, not extensive in width	Estimate percentage of river bank with buffer adjacent
Lakes and wetlands		
Floodplain lake	A body of water located on the floodplain	Estimate percentage cover within the defined river corridor
Natural lake	A large body of water located along the river course that is not held behind a dam	Estimate percentage of river corridor area that contains the lake

Upland wetlands	Located in upland areas, dark or rough looking patches of vegetation away from the channel (upland over ca 250m - http://jncc.defra.gov.uk/page-1436)	Estimate the percentage cover within the defined river corridor
Lowland wetlands	Located in lowland areas, dark or rough-looking patches of vegetation located proximal to the channel	Estimate the percentage cover within the defined river corridor
Agricultural land	**Arable**: Fields with boundaries containing evidence of crops including plough lines and linear lines of vegetation separated by tractor wheel tracks **Livestock**: In the uplands may be rough grassland with evidence of livestock whereas in the lowlands likely to be grass fields also with evidence of livestock.	Estimate the percentage cover within the defined river corridor
Amenity land	Grassland adjacent to the channel that looks managed, may contain evidence of mowing lines or recreational features such as sports pitch markings/posts or picnic benches	Estimate the percentage cover within the defined river corridor
Dam-Reservoir unit	A large concrete structure holding back water with a lower elevation below the structure	Estimate the percentage of river corridor area that contains the dam feature
Urban areas	Areas of dense settlement	Estimate the percentage cover within the defined river corridor

Table 6

The rules for assigning scores to the Excel-based ecosystem service assessment spreadsheet based upon values extracted from *Google Earth™* using protocols outlined in Table 5

	Score										
Feature/ attribute	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
River width	>5m	5-15m	15-25m	25-35m	35-45m	45-55m	55-65m	65-75m	75-85m	85-95m	>95m
Weirs							partial		Full weir		1+
Channeli-zation	>5%	5-10%	10-20%	20-30%	30-40%	40-50%	50-60%	60-70%	70-80%	80-90%	>90%
Forest											
-Broadleaf/ Mixed	>5%	5-10%	10-20%	20-30%	30-40%	40-50%	50-60%	60-70%	70-80%	80-90%	>90%
-Conifer	>5%	5-10%	10-20%	20-30%	30-40%	40-50%	50-60%	60-70%	70-80%	80-90%	>90%
-Young	>5%	5-10%	10-20%	20-30%	30-40%	40-50%	50-60%	60-70%	70-80%	80-90%	>90%
-Felled	>5%	5-10%	10-20%	20-30%	30-40%	40-50%	50-60%	60-70%	70-80%	80-90%	>90%
-Floodplain	>5%	5-10%	10-20%	20-30%	30-40%	40-50%	50-60%	60-70%	70-80%	80-90%	>90%
Riparian buffer strips											
Woodland buffer	>5%	5-10%	10-20%	20-30%	30-40%	40-50%	50-60%	60-70%	70-80%	80-90%	>90%
Herbaceous buffer	>5%	5-10%	10-20%	20-30%	30-40%	40-50%	50-60%	60-70%	70-80%	80-90%	>90%
Lakes and wetlands											
Floodplain lake	>5%	1-5%	5-10%	10-15%	15-20%	20-25%	25-30%	30-35%	35-40%	40-45%	>45%
Natural lake	>5%	5-10%	10-20%	20-30%	30-40%	40-50%	50-60%	60-70%	70-80%	80-90%	No river, just lake
-Upland wetlands	>5%	5-10%	10-20%	20-30%	30-40%	40-50%	50-60%	60-70%	70-80%	80-90%	>90%
-Lowland wetland	>5%	5-10%	10-20%	20-30%	30-40%	40-50%	50-60%	60-70%	70-80%	80-90%	>90%
Agricultural land	>5%	5-10%	10-20%	20-30%	30-40%	40-50%	50-60%	60-70%	70-80%	80-90%	>90%
Amenity land	>5%	5-10%	10-20%	20-30%	30-40%	40-50%	50-60%	60-70%	70-80%	80-90%	>90%
Dam-reservoir	>5%	5-10%	10-20%	20-30%	30-40%	40-50%	50-60%	60-70%	70-80%	80-90%	No river, just reservoir
Urban area	>5%	5-10%	10-20%	20-30%	30-40%	40-50%	50-60%	60-70%	70-80%	80-90%	>90%
Heritage feature (number)	0	1	2	3	4	5	6	7	8	9	10
Waterfall (number)	0	1	2	3	4	5	6	7	8	9	10

Table 7

Reach average, minimum and maximum scores for each river to which the assessment was applied separated into (A) total ecosystem service scores, (B) provisioning ecosystem service scores, (C) regulating ecosystem service scores and (D) cultural ecosystem service scores. Non-area weighted maximum theoretical possible score is 400 for provisioning, 300 for regulating and 600 for cultural ecosystem services

(A)

Total Ecosystem Service Scores						
	Non-Area weighted score		Area-weighted score		Area (ha)	
River	Minimum	Maximum	Minimum	Maximum	Smallest	Largest
Protected Dee	0	860	0	13718	2.3	42.2
Unprotected Don	0	849	0	14386.4	1.9	37.9
Protected Teith	225	618	767.9	32753.5	2.2	76.88
Unprotected Forth	59	870	1334.4	22114.4	4	111.5
Protected Almond	67.5	698	0	14772.6	0.7	47.1
Unprotected Earn	77	648	898.4	31575.9	2.2	56.9
Protected Thurso	111	493	921.7	22872.2	1.9	64
Unprotected Forss	77	479	253.5	31775.8	0.7	94.4

(B)

Provisioning Ecosystem Service Scores						
	Non-Area-weighted score		Area-weighted score		Area (ha)	
River	Minimum	Maximum	Minimum	Maximum	Smallest	Largest
Protected Dee	0	200	0	5655.1	2.3	42.2
Unprotected Don	0	184	0	4135.9	1.9	37.9
Protected Teith	4	180	8.7	9035.4	2.2	76.88
Unprotected Forth	4	124	90.4	5377.7	4	111.5
Protected Almond	0	166	0	5077	0.71	47.1
Unprotected Earn	30	168	250.5	6762.4	2.2	56.9
Protected Thurso	4	210	0	12791.3	1.9	64
Unprotected Forss	0	200	0	7156.8	0.7	94.4

(C)

Regulating Ecosystem Service Scores						
	Non-Area-weighted Score		Area-weighted score		Area (ha)	
River	Minimum	Maximum	Minimum	Maximum	Smallest	Largest
Protected Dee	0	300	0	5527.7	2.3	42.2
Unprotected Don	0	300	0	3115.9	1.9	37.9
Protected Teith	0	300	0	10687.2	2.2	76.88
Unprotected Forth	0	280	90.5	5377.7	4	111.5
Protected Almond	0	300	0	1674.7	0.71	47.1
Unprotected Earn	0	300	0	10907.1	2.2	56.9
Protected Thurso	0	200	0	7030.2	1.9	64
Unprotected Forss	0	200	0	14164.6	0.7	94.4

(D)

Cultural Ecosystem Service Scores						
	Non-Area-weighted score		Area-weighted score		Area (ha)	
River	**Minimum**	**Maximum**	**Minimum**	**Maximum**	**Smallest**	**Largest**
Protected Dee	0	432.5	0	10391.5	2.3	42.2
Unprotected Don	0	442.5	0	9095.2	1.9	37.9
Protected Teith	150	420	325.4	17873.6	2.2	76.88
Unprotected Forth	0	290	0	13767.7	4	111.5
Protected Almond	47.5	365	0	8020.9	0.71	47.1
Unprotected Earn	45	317.5	502.1	13906.5	2.2	56.9
Protected Thurso	60	305	529.2	10959.6	1.9	64
Unprotected Forss	45	282.5	107.4	16289.2	0.7	94.4

Table 8

Comparison of area-weighted and non-weighted average reach scores for the pairs of protected and largely unprotected rivers by nature conservation designations with Mann–Whitney statistically significant differences highlighted. A) Rivers Thurso and Forss, B) Rivers Dee and Don, C) Rivers Almond and Earn, D) Rivers Teith and Forth. 'Area weighted' are the scores multiplied by reach area in hectares. Non-weighted scores can range from 0-700 (figures in brackets: % of maximum potential reach value) for provisioning and regulating services, and 600 for cultural services

(A)

		River Thurso Protected	River Forss Unprotected	Statistically Different?
Total average ecosystem service scores per reach				
Area-weighted	Mean	5433.5	3716.8	
	Median	4063.1	2372.4	Protected Greater
Non-weighted	Mean	346.5 (49)	351.3 (50)	
	Median	350.3 (50)	354 (51)	No
Total average provisioning service scores per reach				
Area-weighted	Mean	1174.3	483.8	
	Median	611.6	62.4	Protected Greater
Non-weighted	Mean	57.9 (8)	32 (5)	
	Median	43 (6)	4 (<1)	Protected Greater
Total average regulating service scores per reach				
Area-weighted	Mean	1404.3	1450.7	
	Median	1005.6	1093.4	No
Non-weighted	Mean	104.5 (16)	152.5 (22)	
	Median	100.5 (15)	187 (29)	Unprotected Greater
Total average cultural service scores per reach				
Area-weighted	Mean	2855	1782	
	Median	2104.8	1068.9	Protected Greater
Non-weighted	Mean	184.1 (23)	166.7 (20)	
	Median	180 (22)	150 (18)	Protected Greater

(B)

		Dee Protected	Don Unprotected	Statistically Different?
Total average ecosystem service scores per reach				
Area-weighted	Mean	5089.9	4517.5	
	Median	4712.5	3715	Protected Greater
Non-weighted	Mean	381 (54)	385.3 (55)	
	Median	352.5 (50)	368 (53)	No
Total average provisioning service scores per reach				
Area-weighted	Mean	1390.1	1164.6	
	Median	1255.5	982	Protected Greater
Non-weighted	Mean	94.6 (13)	92.5 (13)	
	Median	108 (16)	102 (15)	Protected Greater
Total average regulating service scores per reach				
Area-weighted	Mean	1066.2	534.2	
	Median	920.9	430.3	Protected Greater
Non-weighted	Mean	87.3	54.9	
	Median	72.5	42.5	Protected Greater
Total average cultural service scores per reach				
Area-weighted	Mean	2633.6	2818.7	
	Median	2250.5	2324.7	No
Non-weighted	Mean	199 (24)	237.8 (29)	
	Median	187.5 (23)	232.5 (28)	Unprotected Greater

(C)

		River Almond Protected	River Earn Unprotected	Statistically Different?
Total average ecosystem service scores per reach				
Area-weighted	Mean	2569.5	6992	
	Median	2256.7	5916.1	Unprotected Greater
Non-weighted	Mean	441.4 (63)	401.9 (57)	
	Median	419 (60)	397.8 (56)	No
Total average provisioning service scores per reach				
Area-weighted	Mean	567.7	1903.9	
	Median	481	1600.9	Unprotected Greater
Non-weighted	Mean	89.7 (12)	108 (15)	
	Median	94 (13)	112 (16)	Unprotected Greater
Total average regulating service scores per reach				
Area-weighted	Mean	625	1903	
	Median	597.2	815.3	Unprotected Greater
Non-weighted	Mean	122.2 (17)	63 (9)	
	Median	100 (14)	57.5 7)	Protected Greater
Total average cultural service scores per reach				
Area-weighted	Mean	1376.9	4085.1	
	Median	1089.4	3336.1	Unprotected Greater
Non-weighted	Mean	229.5 (27)	230.9 (27)	
	Median	240 (29)	225 (26)	No

(D)

		River Teith Protected	River Forth Unprotected	Statistically Different?
Total average ecosystem service scores per reach				
Area-weighted	Mean	7374.4	5494.4	
	Median	6073.1	3681.6	Protected Greater
Non-weighted	Mean	439 (63)	350.6 (50)	
	Median	403.8 (58)	360 (52)	Protected Greater
Total average provisioning service scores per reach				
Area-weighted	Mean	1609.8	1317.8	
	Median	1182.4	848	No
Non-weighted	Mean	88 (12)	83.8 (11)	
	Median	100 (14)	98 (14)	Protected Greater
Total average regulating service scores per reach				
Area-weighted	Mean	1973.3	1004.8	
	Median	1751.9	389	Protected Greater
Non-weighted	Mean	129.2 (18)	64.1 (9)	
	Median	112 (16)	40 (6)	Protected Greater
Total average cultural service scores per reach				
Area-weighted	Mean	3724.5	3172	
	Median	3057.3	2164.8	Protected Greater
Non-weighted	Mean	221.5 (36)	202.8 (34)	
	Median	210 (35)	225 (37)	No

Table 9

Non-weighted (A) and weighted (B) statistical outcomes showing differences between the paired rivers in relation to ecosystem service classes. Rivers indicated in bold are those with unprotected status but higher ecosystem service supply in that category

(A)

Ecosystem service class	**Rivers**	**Number of protected rivers with statistically higher ecosystem service supply**	**Number of unprotected rivers with statistically higher ecosystem service supply**
Total Ecosystem Service Score	Teith,	1	
Total Provisioning Scores	Dee, Teith, **Earn, Forss**	2	2
Water supply	Dee, Teith, Thurso	3	
Agriculture	**Don, Forth, Earn, Forss**		4
Timber	Dee, Teith, Almond	3	
HEP			
Total Regulating Scores	Dee, Teith, Almond, **Forss**	3	1
Natural flood mitigation	Dee, Teith, Almond, **Forss**	3	1
Climate regulation	Dee, Almond	2	
Water quality regulation	Dee, Teith, Almond, **Forss**	3	1
Total Cultural Service Scores	**Don,** Thurso	1	1
Aesthetic value	**Don**, Teith, **Earn**	1	2
Social relations	Dee, Almond	2	
Inspiration			
Education/knowledge	Dee, **Forth, Earn**, Thurso	2	2
Heritage			
Recreation	**Don,** Teith, **Earn**	1	2

B)

Ecosystem Service Class	**Rivers**	**Number of protected rivers with statistically higher ecosystem service supply**	**Number of unprotected rivers with statistically higher ecosystem service supply**
Total Ecosystem Service Score	Dee, Teith**, Earn**, Thurso	3	1
Total Provisioning Scores	Dee, **Earn**, Thurso	2	1
Water supply	Dee, Teith, **Earn**, Thurso	3	1
Agriculture	**Don, Forth, Earn, Forss**		4
Timber	Dee, Teith	2	
HEP			
Total Regulating Scores	Dee, Teith, **Earn**	2	1
Natural flood mitigation	Dee, Teith, **Earn**	2	1
Climate regulation	Dee, Almond	2	
Water quality regulation	Dee, Teith, Almond, **Forss**	3	1
Total Cultural Service Scores	Teith, **Earn**, Thurso	2	1
Aesthetic value	**Don**, Teith, **Earn**, Thurso	2	2
Social relations	Dee, Almond	2	
Inspiration			
Education/knowledge	Dee, **Forth, Earn**, Thurso	2	2
Heritage			
Recreation	**Don**, Teith, **Earn**, Thurso	2	2

FIGURES

Figure 1

A map of Scotland showing the location of the eight individual rivers studied and their pairing according to levels of nature protection by statutory designations.

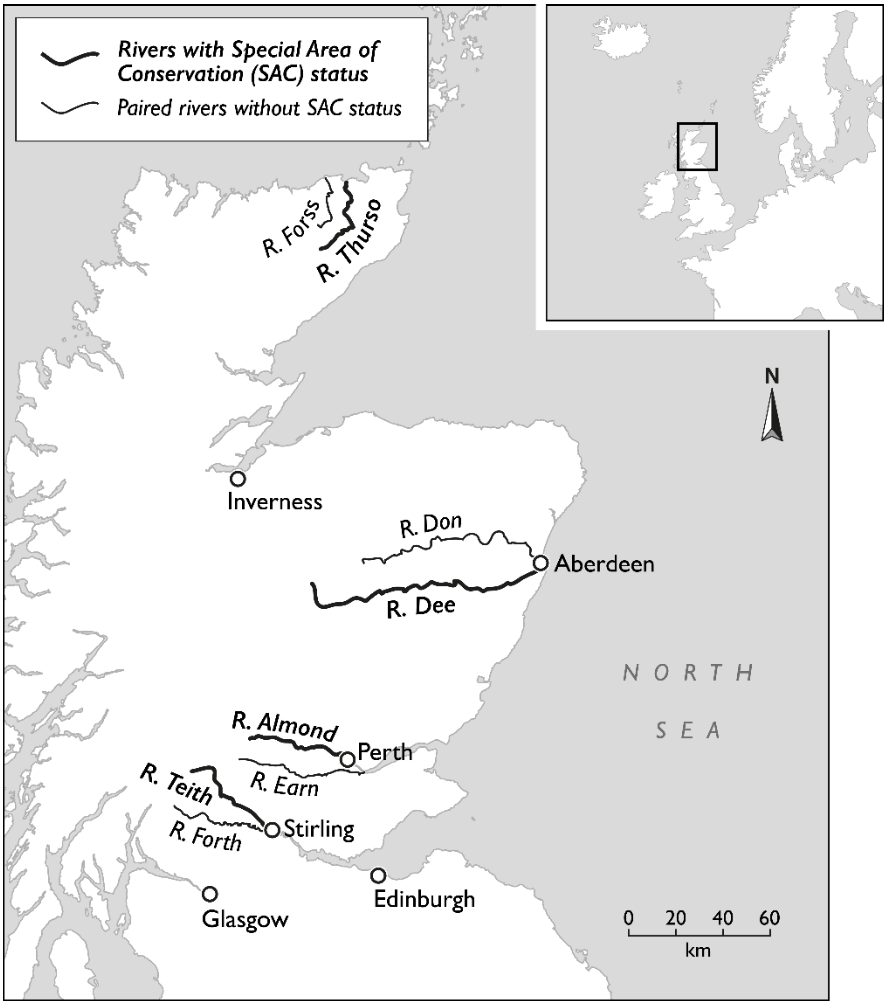
Figure 2

A *Google Earth*™ image showing the delineation of the floodplain and demarcation of 500 m reach lengths and river sinuosity. The aerial image was downloaded from *Google Earth*™ on 29 January 2019 with the following copyright: Image ©2018 Getmapping plc

Figure 3

Downstream changes in area-weighted ecosystem service scores for the eight rivers together with the area of floodplain/valley floor for each 500 m reach. Long profiles for provisioning and regulating and cultural services are separated only for clarity. (A) River Thurso, (B) River Forss, (C) River Dee (D), River Don, (E) Almond, (F) Earn, (G) Teith, (H), Forth. The dotted lines represent the valley floor area in hectares for each 500 m reach. A and B, C and D, E and F, and G and H are the nature conservation protected and unprotected paired rivers.

Figure 1

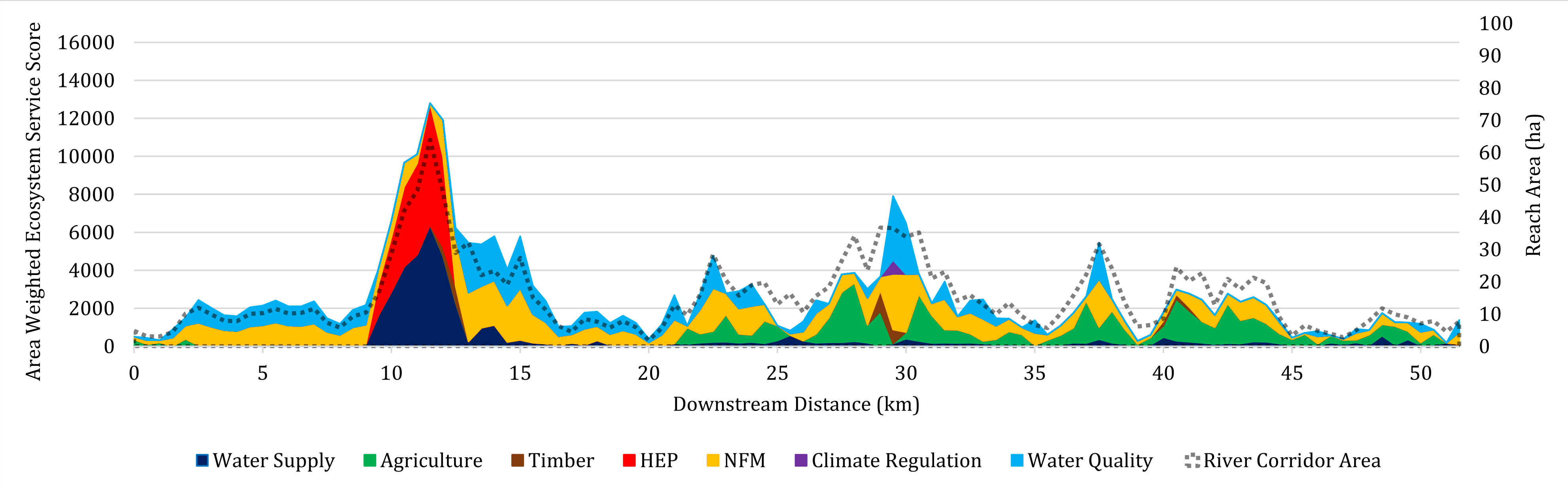


Rivers with Special Area of Conservation (SAC) status
Paired rivers without SAC status
R. Forss
R. Thurso
N
Inverness
R. Don
Aberdeen
R. Dee
NORTH
SEA
R. Almond
Perth
R. Earn
R. Teith
Stirling
R. Forth
Edinburgh
Glasgow
0 20 40 60
km

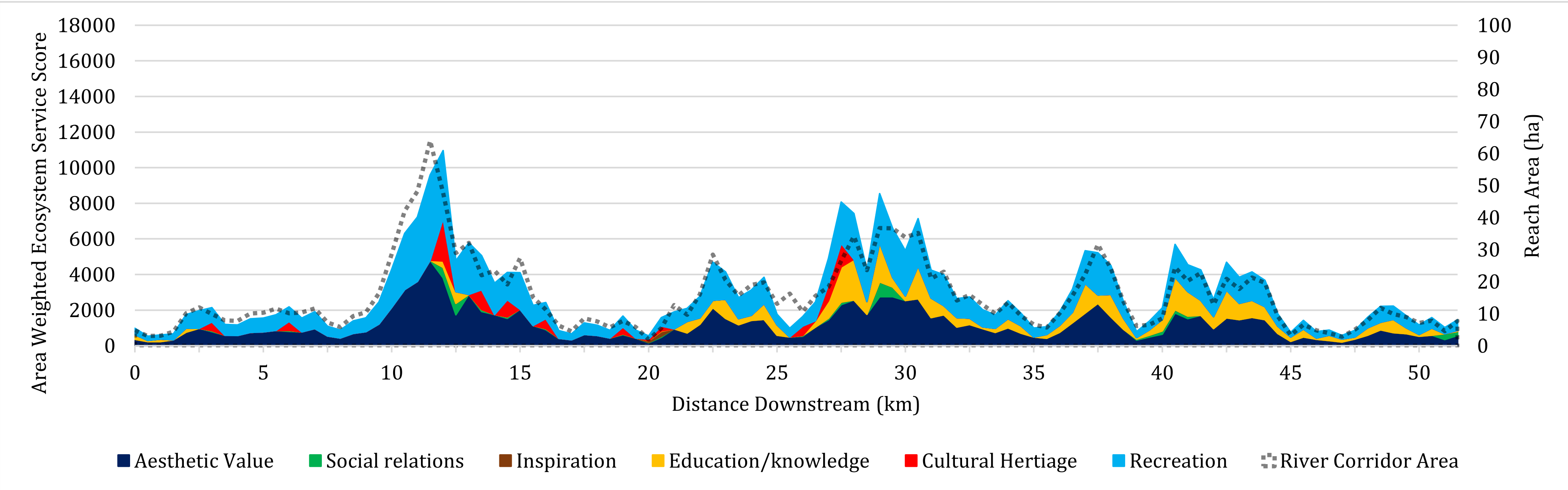
Figure 2

Figure 3

A)



Area Weighted Ecosystem Service Score
16000
14000
12000
10000
8000
6000
4000
2000
0
100
90
80
70
60
50
40
30
20
10
0
Reach Area (ha)
0
5
10
15
20
25
30
35
40
45
50
Downstream Distance (km)
Water Supply
Agriculture
Timber
HEP
NFM
Climate Regulation
Water Quality
River Corridor Area



Area Weighted Ecosystem Service Score
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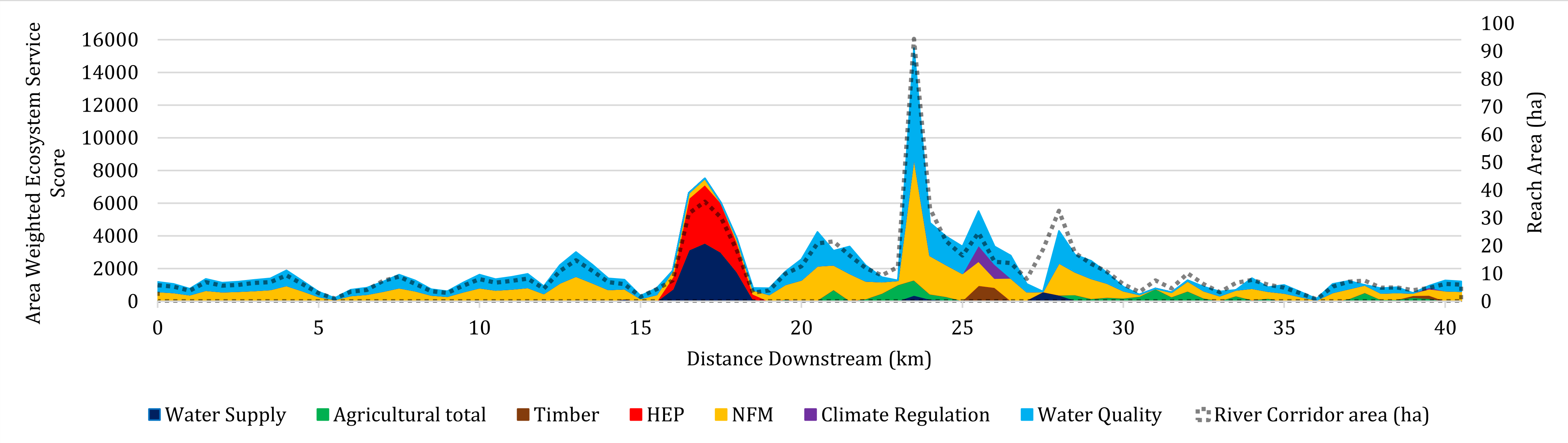
16000
14000
12000
10000
8000
6000
4000
2000
0
100
90
80
70
60
50
40
30
20
10
0
Reach Area (ha)
0
5
10
15
20
25
30
35
40
45
50
Distance Downstream (km)
Aesthetic Value
Social relations
Inspiration
Education/knowledge
Cultural Hertiage
Recreation
River Corridor Area

B)



Area Weighted Ecosystem Service Score
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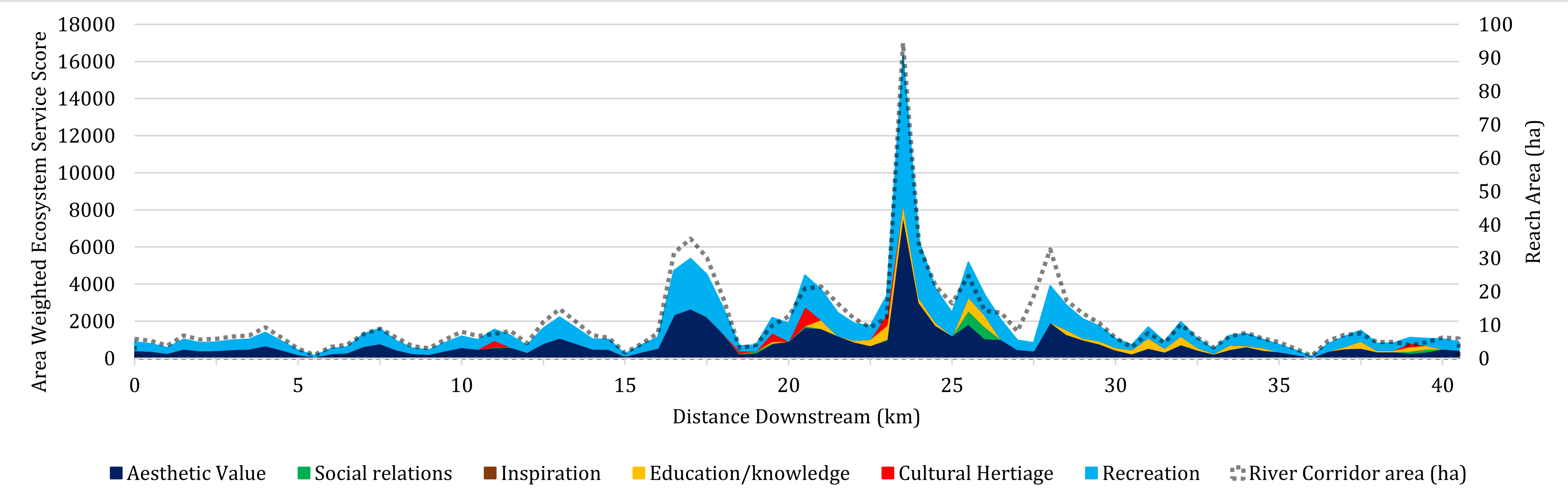
14000
12000
10000
8000
6000
4000
2000
0
100
90
80
70
60
50
40
30
20
10
0
Reach Area (ha)
0
5
10
15
20
25
30
35
40
Distance Downstream (km)
Water Supply
Agricultural total
Timber
HEP
NFM
Climate Regulation
Water Quality
River Corridor area (ha)



Area Weighted Ecosystem Service Score
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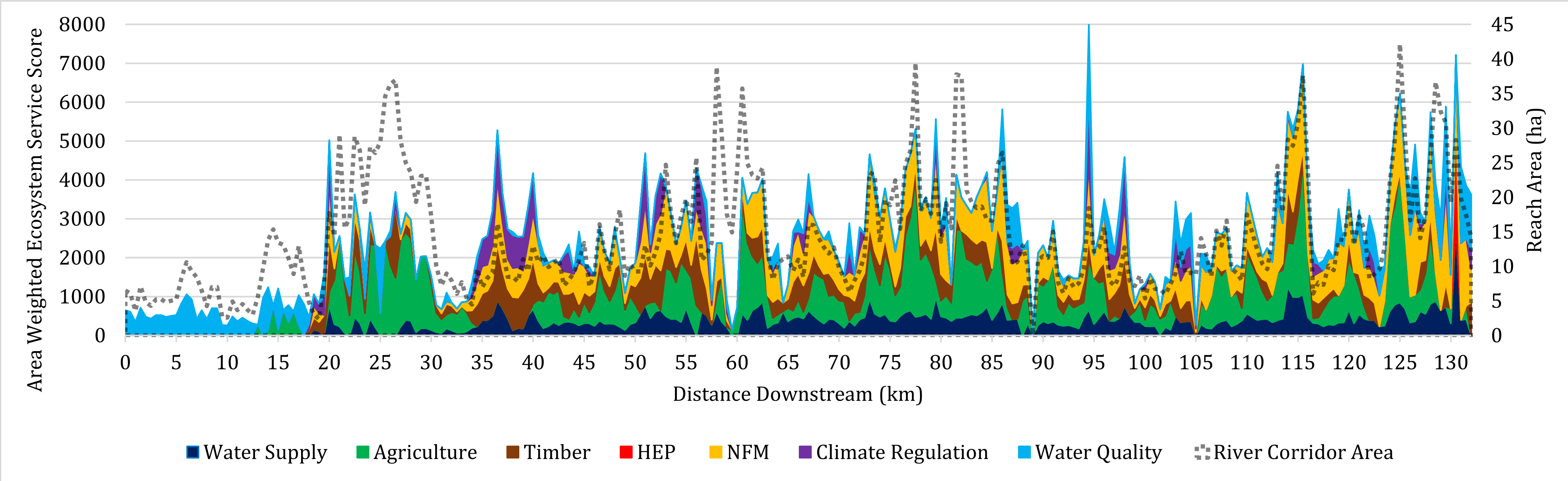
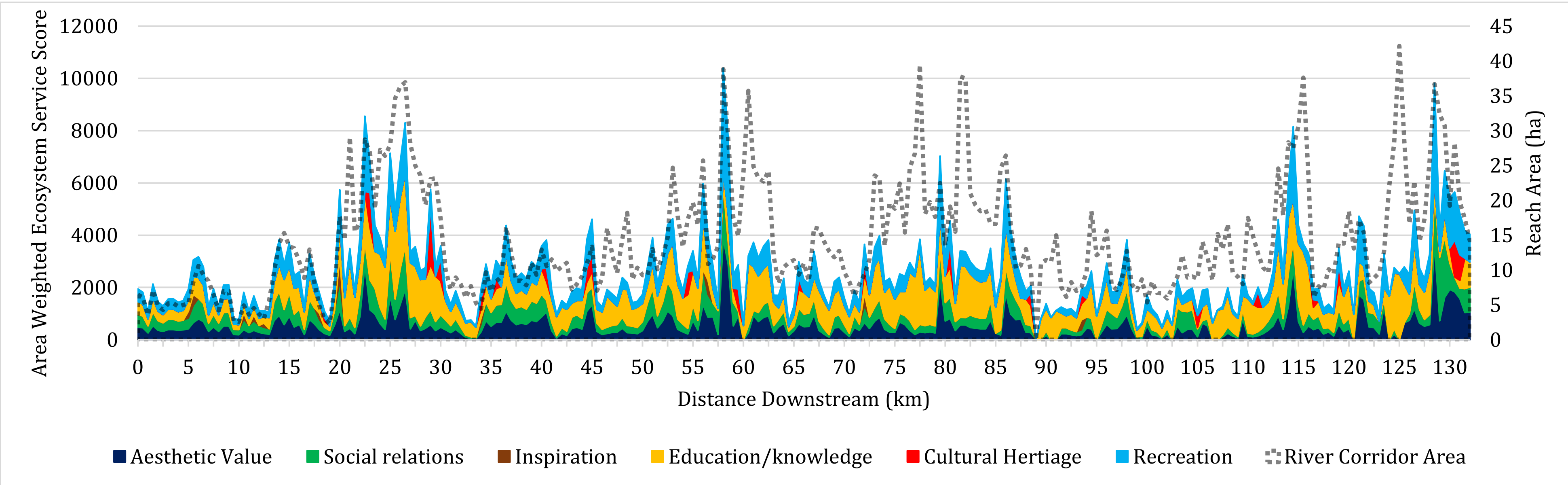
16000
14000
12000
10000
8000
6000
4000
2000
0
100
90
80
70
60
50
40
30
20
10
0
Reach Area (ha)
0
5
10
15
20
25
30
35
40
Distance Downstream (km)
Aesthetic Value
Social relations
Inspiration
Education/knowledge
Cultural Hertiage
Recreation
River Corridor area (ha)

c)

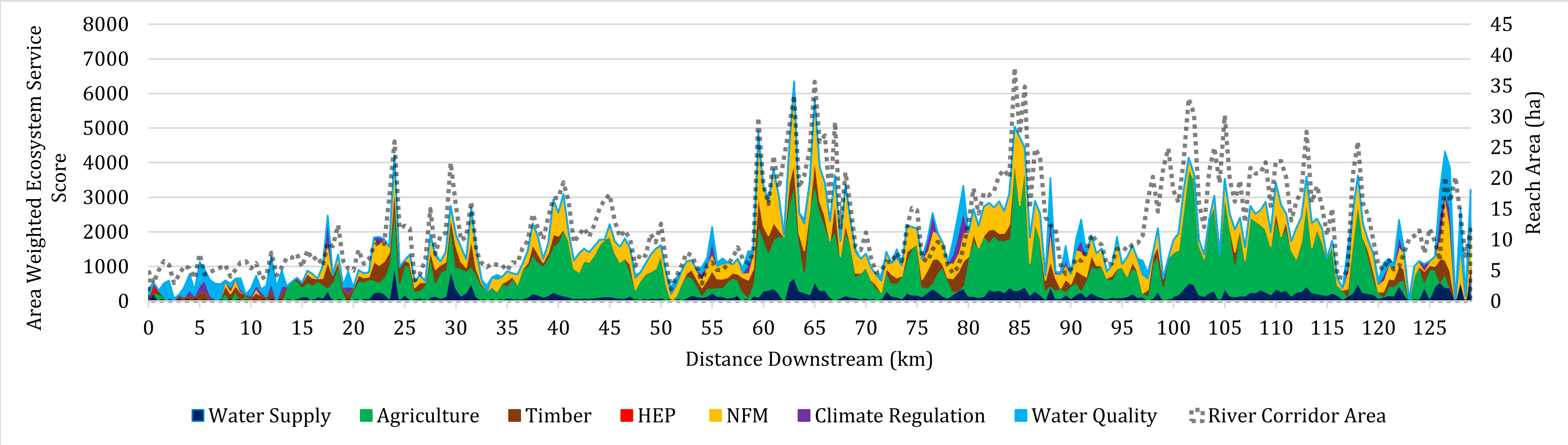


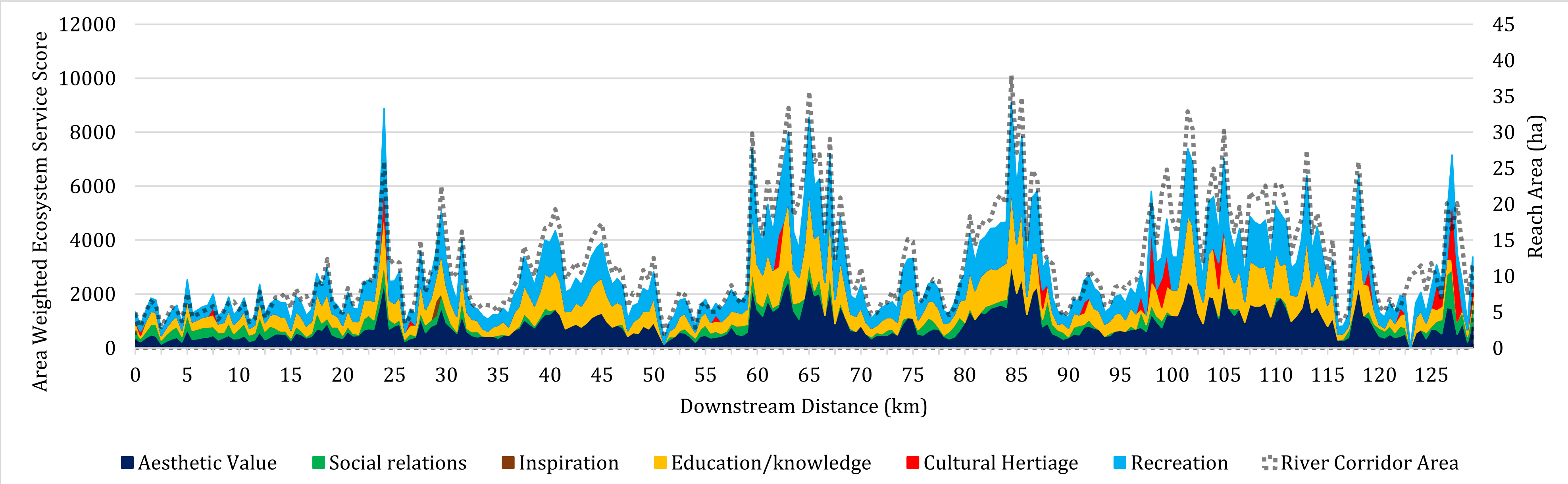
Area Weighted Ecosystem Service Score
8000
7000
6000
5000
4000
3000
2000
1000
0
Reach Area (ha)
45
40
35
30
25
20
15
10
5
0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 105 110 115 120 125 130
Distance Downstream (km)
Water Supply
Agriculture
Timber
HEP
NFM
Climate Regulation
Water Quality
River Corridor Area



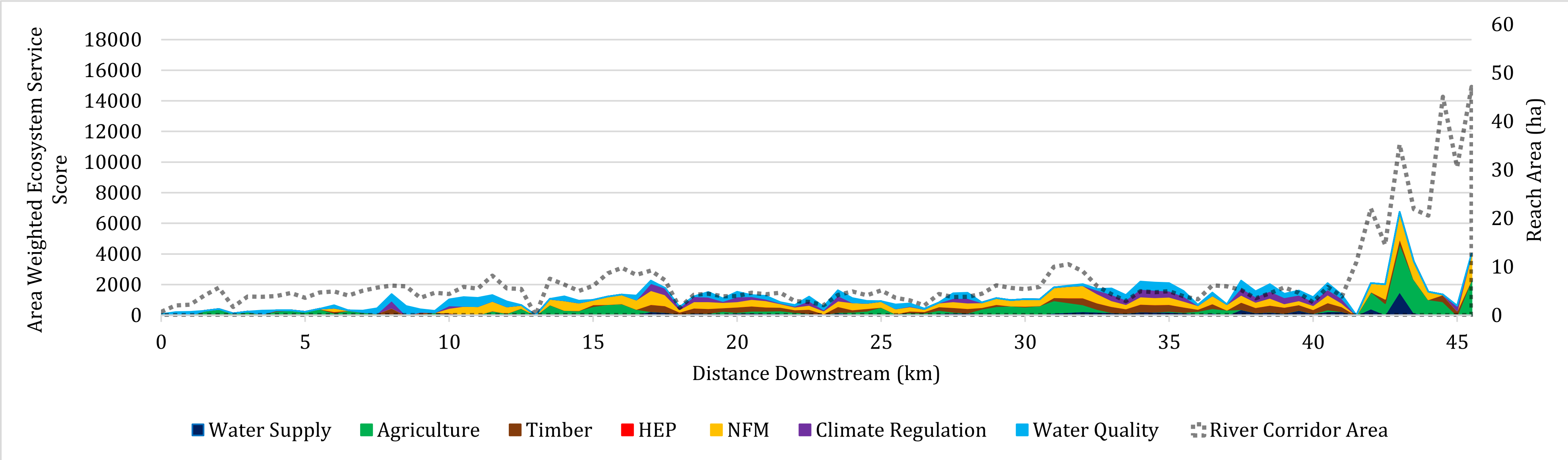
Area Weighted Ecosystem Service Score
12000
10000
8000
6000
4000
2000
0
Reach Area (ha)
45
40
35
30
25
20
15
10
5
0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 105 110 115 120 125 130
Distance Downstream (km)
Aesthetic Value
Social relations
Inspiration
Education/knowledge
Cultural Hertiage
Recreation
River Corridor Area

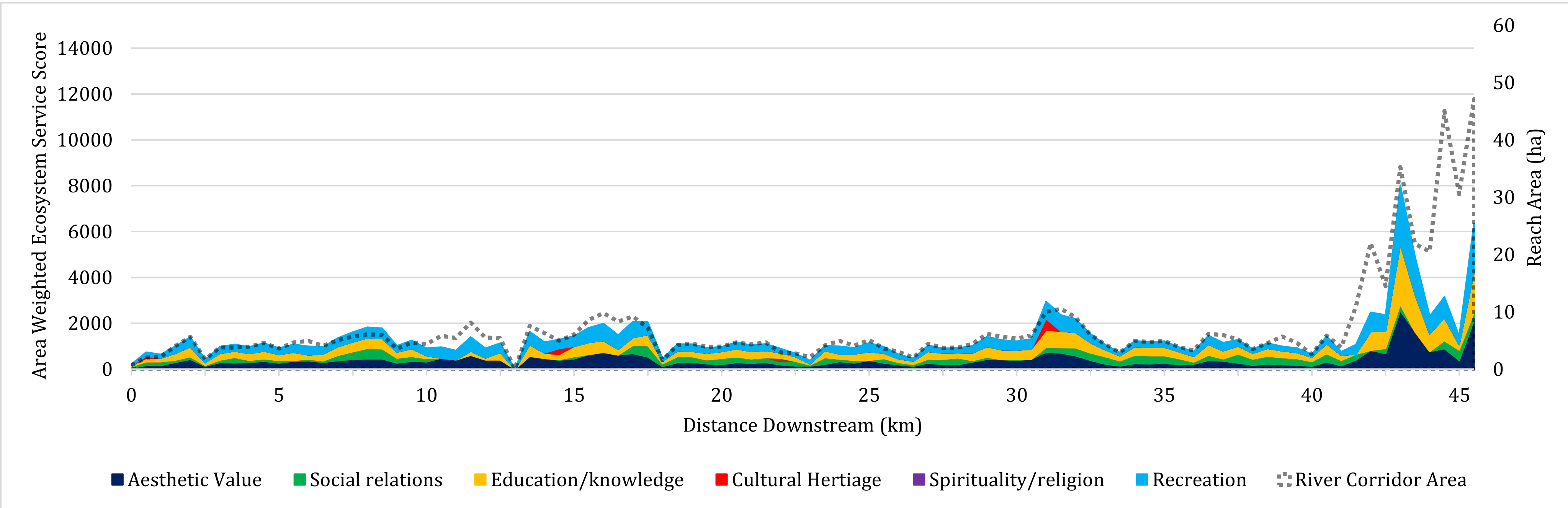
D)


Area Weighted Ecosystem Service Score
Reach Area (ha)
Distance Downstream (km)
Water Supply
Agriculture
Timber
HEP
NFM
Climate Regulation
Water Quality
River Corridor Area

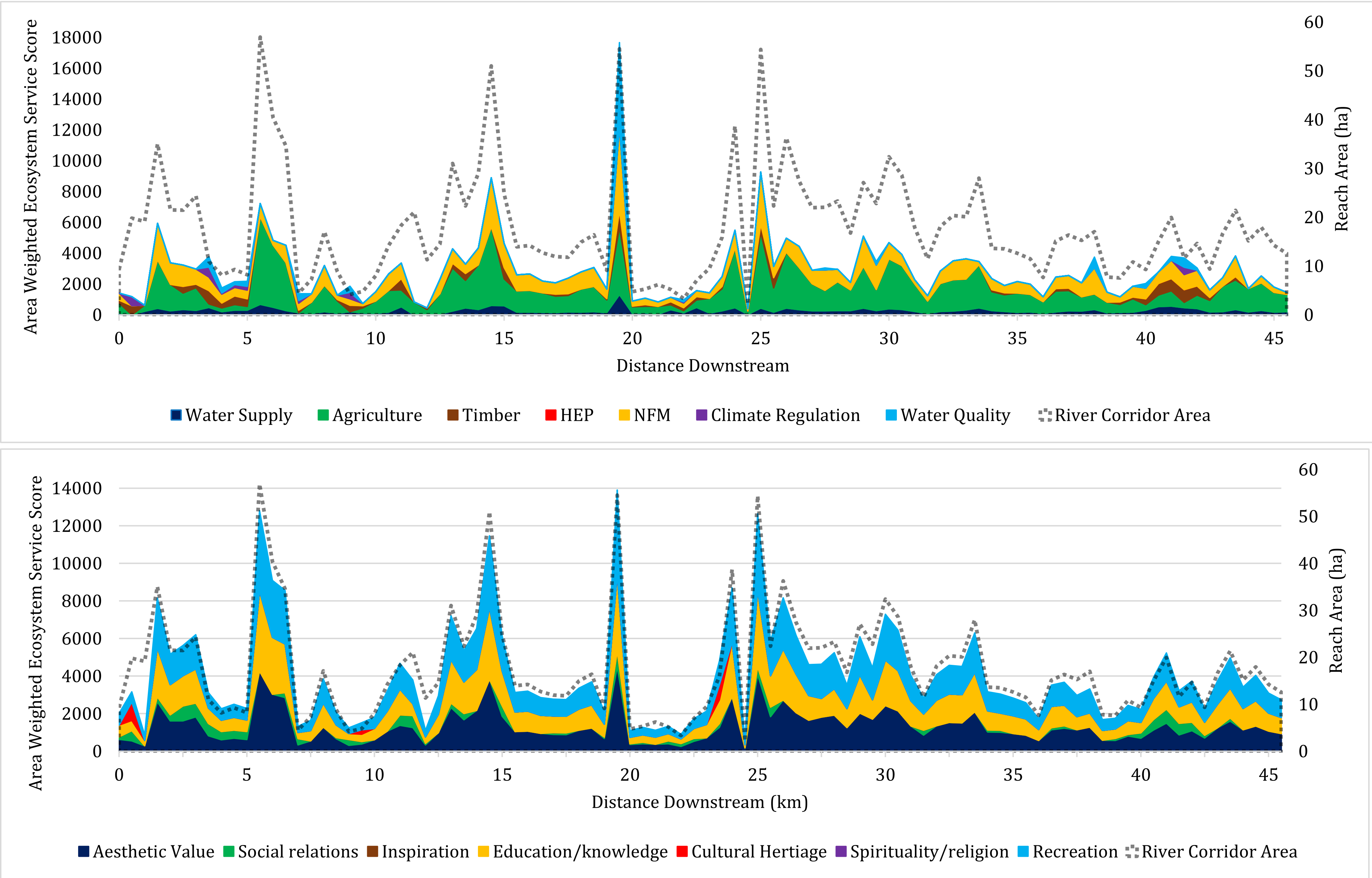

Area Weighted Ecosystem Service Score
Reach Area (ha)
Downstream Distance (km)
Aesthetic Value
Social relations
Inspiration
Education/knowledge
Cultural Hertiage
Recreation
River Corridor Area

E)


Area Weighted Ecosystem Service Score
Reach Area (ha)
Distance Downstream (km)
Water Supply
Agriculture
Timber
HEP
NFM
Climate Regulation
Water Quality
River Corridor Area


Area Weighted Ecosystem Service Score
Reach Area (ha)
Distance Downstream (km)
Aesthetic Value
Social relations
Education/knowledge
Cultural Hertiage
Spirituality/religion
Recreation
River Corridor Area

F)


Area Weighted Ecosystem Service Score
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
Reach Area (ha)
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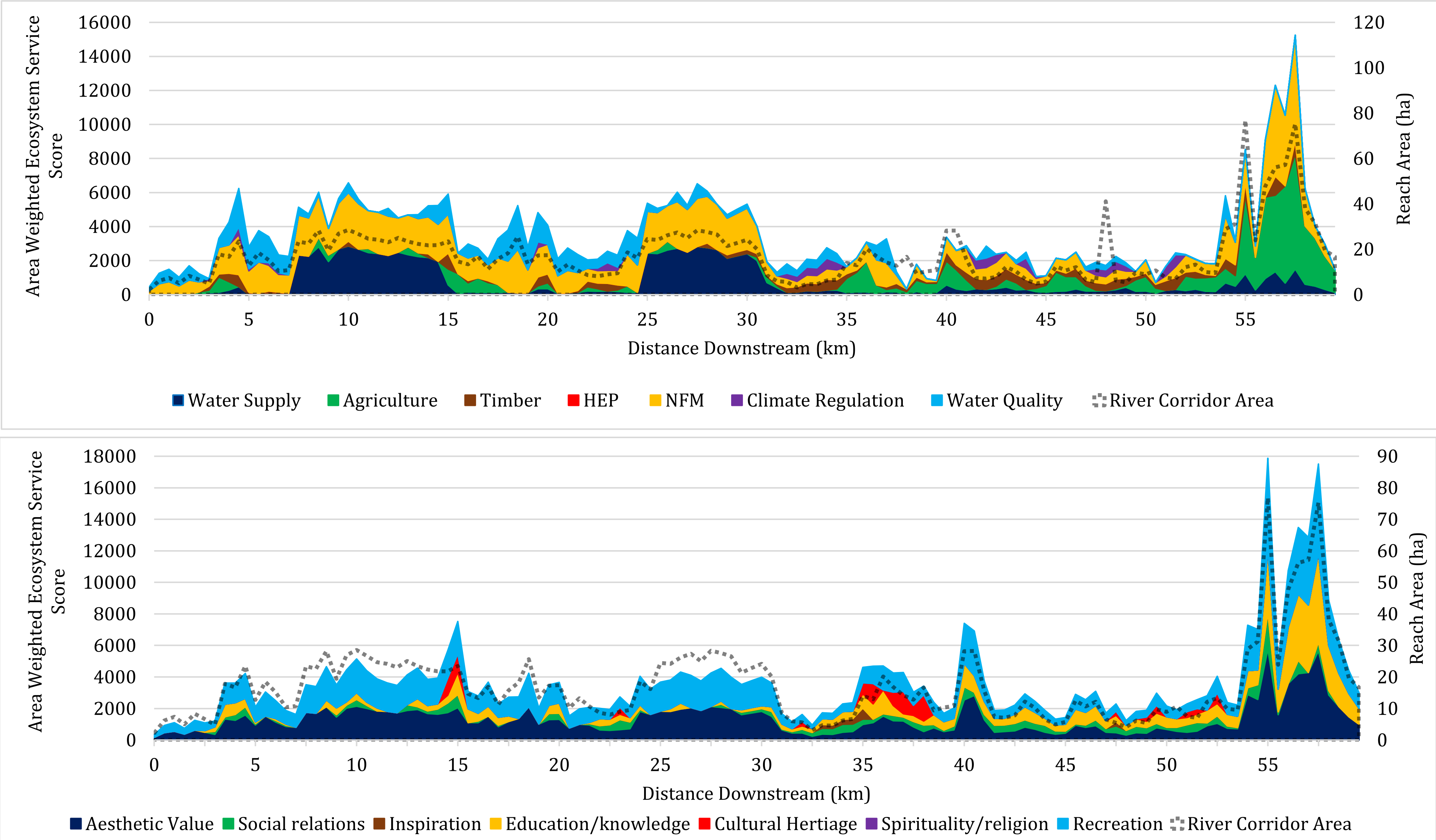
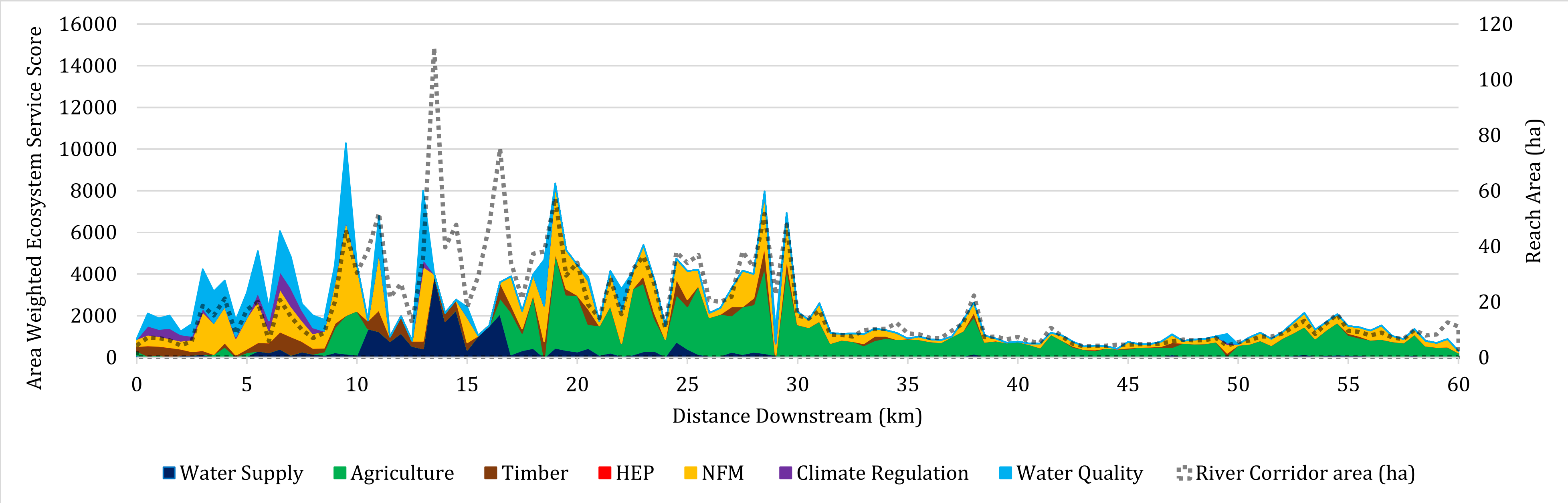
50
40
30
20
10
0
0
5
10
15
20
25
30
35
40
45
Distance Downstream
Water Supply
Agriculture
Timber
HEP
NFM
Climate Regulation
Water Quality
River Corridor Area
Area Weighted Ecosystem Service Score
14000
12000
10000
8000
6000
4000
2000
0
Reach Area (ha)
Distance Downstream (km)
Aesthetic Value
Social relations
Inspiration
Education/knowledge
Cultural Hertiage
Spirituality/religion
Recreation
River Corridor Area

G)

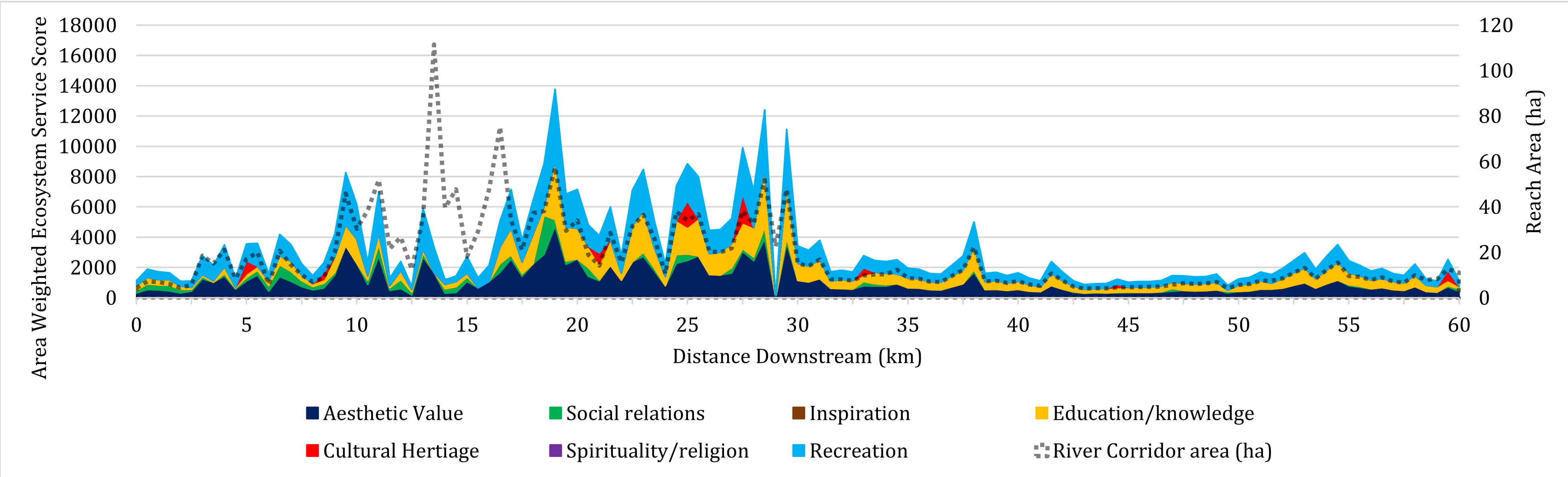


Area Weighted Ecosystem Service Score
Reach Area (ha)
Distance Downstream (km)
Water Supply
Agriculture
Timber
HEP
NFM
Climate Regulation
Water Quality
River Corridor Area
Area Weighted Ecosystem Service Score
Reach Area (ha)
Distance Downstream (km)
Aesthetic Value
Social relations
Inspiration
Education/knowledge
Cultural Hertiage
Spirituality/religion
Recreation
River Corridor Area

H)



Area Weighted Ecosystem Service Score
16000
14000
12000
10000
8000
6000
4000
2000
0
120
100
80
60
40
20
0
Reach Area (ha)
0
5
10
15
20
25
30
35
40
45
50
55
60
Distance Downstream (km)
Water Supply
Agriculture
Timber
HEP
NFM
Climate Regulation
Water Quality
River Corridor area (ha)



Area Weighted Ecosystem Service Score
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
120
100
80
60
40
20
0
Reach Area (ha)
0
5
10
15
20
25
30
35
40
45
50
55
60
Distance Downstream (km)
Aesthetic Value
Social relations
Inspiration
Education/knowledge
Cultural Hertiage
Spirituality/religion
Recreation
River Corridor area (ha)