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USING GOOGLE EARTH, A VIRTUAL-GLOBE IMAGING PLATFORM, FOR ECOSYSTEM SERVICES-BASED RIVER ASSESSMENT

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ABSTRACT

A methodology for reach-based river ecosystem service assessment of eight ecosystem functions using remote sensing via *Google Earth* is presented. The number of publications addressing *Google Earth* and ecosystem services has grown significantly since 2005, yet this powerful remote sensing platform remains under-used in river science. Theoretical linkages between eighteen riverscape fluvial features, attributes and land cover types, observable and measurable on Google Earth, and resultant river ecosystem service delivery are central to the methodology. Using this framework, we build on earlier ecosystem service conceptual models to develop a rules-based scoring approach and apply it to three rivers of differing size and character from source to mouth. The aim was to devise a robust ecosystem services assessment tool applicable to any ecoregion and to rivers of any size, degree of human modification and character. Reach or sector scales are river length dependent. The minimum reach scale recommended is 500 metres and a 10 km sector length was used on the longest of our three rivers. Two key metrics, the individual ecosystem service score and the total ecosystems service score, are derived at the river reach scale from source to mouth. Scoring is on a 0-3 scale with zero representing an absent or virtually no ecosystem service value and 3 an optimal or maximum value. Output is best expressed in score per kilometre of river length. The exercise showed the tool to be applicable across two ecoregions and to rivers of varying size, level of human modification and character. While requiring further refinement, the approach shows that ecosystem service assessments based on virtual-globes can be universally applied providing valuable information on riverscape ecosystem service delivery.

Keywords

Google Earth; remote sensing; ecosystem services; virtual globe; rivers; river assessment.

INTRODUCTION

Over the past decade, river science has evolved as a discipline in terms of recognising the need for multidisciplinary approaches to understanding river systems in a way that better meets the needs of society. Yet as Thorp *et al.* (2006) highlight, relatively natural or pristine segments of small to large rivers are increasingly rare throughout much of the world, making it a ‘formidable task’ to study and manage such systems. The lack of baselines as to river ecosystem function also hinders understanding of what ecosystem services are still delivered under anthropogenically-altered conditions. While we know that rivers play a central role in underpinning society’s activities and health, it is clear that, in the Anthropocene (Crutzen and Stoermer, 2000), the majority of rivers in more populated catchments no longer behave according to their Holocene ‘norms’. Appreciation of the ecosystem services provided by intact and semi-natural aquatic and terrestrial ecosystems (e.g. Postel and Carpenter, 1997; Strange *et al.*, 1999; Nelson *et al.* 2009) has grown over the last two decades, and since the United Nations Millennium Ecosystem Assessment (MEA, 2005) ecosystem services have entered the mainstream policy arena (e.g. the 2011 United Kingdom National Ecosystem Assessment; UKNEA, 2011). The ecosystem service concept resonates with river scientists as it emphasises the need for understanding both ecosystem structure and function, while at the same time concentrating attention on the value of rivers to modern human society (UKNEA, 2011).

In this paper, we follow the definition of Thorpe *et al.* (2010) where ecosystem services are defined as “quantifiable or qualitative benefits of ecosystem functioning to the overall environment, including the products, services and other benefits human receive from natural, regulated, or otherwise perturbed river ecosystems”. The principle of a ‘cascade’ running from ecosystems to functions, to ecosystem services resulting in multiple beneficial outcomes for people is also well-established and documented in the literature (for example Everard *et al.*, 2011; Haines-Young and Potschin, 2010) and subsequently has been taken up in policy-related approaches both internationally (e.g. MEA, 2005) and nationally (e.g. UKNEA, 2011). In the UKNEA (2011), the three tier cascade put forward by Potschin and Haines-Young (2010) was used to link ecosystem *processes* (e.g. water retention), and their role in driving *primary* ecosystem services (e.g. carbon sequestration) leading to a *final* ecosystem service (e.g. water quality regulation). The same authors have also indicated the need to apply the cascade model in a geographical context (Potschin and Haines-Young,

2011; Potschin and Haines-Young, 2013). In river systems world-wide, many primary ecosystem services are significantly degraded, and final benefits and ecosystem services are depleted or lost (Gilvear *et al.*, 2013). This loss is compounded by 'shifting baseline syndrome' (Pauly, 1995) whereby each successive generation has a different perception of what constitutes a 'natural' river system, due to negative (or in some cases positive) changes that have occurred over preceding decades. This loss of experience about previous boundary conditions has also been termed 'generational amnesia' (Papworth *et al.*, 2009). This 'amnesia' militates against definition of what ecosystem processes constitute a fully functioning river, what ecosystem services are required to achieve 'reference' condition/status, and indeed which ecosystem services are optimised under these reference conditions.

Patch-dominated river corridors

Recent approaches for examining bio-complexity in river systems have concentrated on hierarchical patch mosaic dynamics. A growing number of workers (e.g. Poole, 2002, 2010; Thorp *et al.*, 2006; 2008) describe how this provides 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. The river catchment ecosystem is made up of landscape patch mosaics with longitudinal, lateral and vertical connectivity; this connectivity governs fluxes of water, sediment and nutrients and (Ward *et al.*, 1999; Gilvear, 1999; Newson and Large, 2006; Vaughan *et al.* 2009; Poole *et al.*, 2010). Over time, conceptual views of the structure and functioning of the system has progressed through viewing of 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 (Winemiller *et al.* 2010; Sponseller *et al.*, 2013). These successive approaches all emphasise the value of heterogeneity, connectivity and dynamism in the landscape. The patch mosaics arising from heterogeneity, connectivity and dynamism are central to the theoretical link between 'riverscape' (*sensu stricto* Thorp *et al.*, 2006; 2008) fluvial features, attributes and land cover types, natural ecosystem functions and river ecosystem service delivery.

Google Earth and other 'virtual globes' as panoptic mapping tools

In recent years we have made significant advances *via* legislation that addresses whole-system health (e.g. European Union Water Framework Directive), as well as in

methodologies of quantifying what nature does for us in terms of a range of provisioning and regulating (as well as cultural and supporting) ecosystem services (Everard, 2011). Any methodology aimed at quantifying or even simply defining the ecosystem services that rivers provide clearly needs to be able to assess heterogeneity, connectivity and dynamism in both a meaningful way and at appropriate spatial and temporal scales (Wiens, 1989; Blösch and Sivapalan, 1995). This is particularly so when catchment-scale restoration (Brierley and Fryirs, 2009) or ecoregion-level assessment (Naidoo *et al.*, 2008) are desired outcomes. Increasingly these approaches incorporate remote sensing to map and monitor river status and health at multiple, often hierarchical, scales within whole catchments. These studies have demonstrated the value of remote sensing to river science, yet despite being free, easily accessible and offering global coverage, *Google Earth*, and other virtual globes (e.g. *Microsoft Virtual Earth*, *Skyline Globe*, the National Aeronautics and Space Administration's *NASA World Wind*), as panoptic mapping tools have been largely ignored in this arena. While the potential value of virtual globes and *Google Earth* in particular, has been well-recognised in other fields including geology (Lisle, 2006), geomorphology (Tooth, 2006), palaeontology (Conroy *et al.*, 2008), archaeology (Myers, 2011), biology (Janies *et al.*, 2007), ecology (Butler, 2006), water resource management (Silberbauer and Geldenhuys, 2009) and geohazard appraisal (Sato and Harp, 2009), there has been a paucity of studies exploring data retrieval for river science using *Google Earth* (Fisher *et al.*, 2013) in its various forms; namely *Google Earth Free*, *Google Earth Pro* and *Google Earth Enterprise*. In reviewing publications from 1999-2010, Schaich *et al.* (2010) highlight a similar issue in relation to cultural landscapes and ecosystem services in that no mainstream geomorphology or river science journals are mentioned.

A Web of Science search of key terms (**Table 1**) shows the growth in scientific papers addressing *Google Earth* and ecosystem services since 2006, but also highlights the continued lack of use of this free, yet powerful remote sensing platform to river science and ecosystem services assessment. Only five papers between 2007 and 2013 came up in a search for '*Google Earth*' combined with either 'river ecosystem services' or 'floodplain ecosystem services'. While the value of *Google Earth* in terrestrial ecosystems is clear from the literature, internet searches evidence no systematic attempt to use the virtual globe to map river ecosystem services on a source to mouth basis. This paper presents a methodology to reach-based river ecosystem service assessment from source to mouth using remote sensing via *Google Earth*. The river corridor methodology defines eight key

ecosystem services based on fluvial feature and land cover recognition from *Google Earth*.

Specific objectives were:

- (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) above within the wider framework of Potschin and Haines-Young (2010) '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 model (**Figure 1**) 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) above, to devise a robust ecosystem services 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.

Figure 1. Adaptation of Potschin and Haines-Young's ecosystem service cascade model (2011), illustrating its applicability to riverscapes. The dashed line represents the boundary of the approach presented here, but the value of the cascade model to wider river management in terms of benefits and values is also seen as important

METHODOLOGY

Development of the approach to river ecosystem service assessment from remotely sensed data

There are three basic steps in our methodology for assessing river ecosystem services from the remotely sensed data freely available on virtual globes. The initial stage is the ability to identify relevant riverscape -scale features or attributes that in turn determine the type and level of ecosystem service. The second step is to develop a method and system for extracting the riverscape features/attributes from the remotely sensed data at appropriate scales, and the final deliverable is a protocol for assigning riverscape features/attributes to individual river ecosystem services along with a robust method for scoring/producing a metric.

Linking riverscape feature/attributes to ecosystem service provision

The 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). Under the Riverine Ecosystem Synthesis, attributes of rivers that positively enhance heterogeneity, connectivity and fluvial dynamics within river corridors positively enhance ecosystem service provisioning. The presence of an extensive floodplain relative to the river width, for example, has numerous benefits. It may attenuate flood peak discharges, enhancing floodwater retention, nutrient spiralling and storage, leading in turn to raised productivity and biodiversity. Floodplain forest on the floodplain will also help to slow the flow of water through increasing surface roughness leading to flood hydrograph attenuation and retention of sediments and nutrients. The presence of floodplain wetlands, palaeochannels and ponds increases lateral connectivity and water quality improves as phosphorous is adsorbed onto sediments and denitrification occurs as water flows through a varied mix of saturated and non-saturated floodplain soils. Conversely human modifications that simplify or degrade heterogeneity, connectivity and fluvial dynamics will reduce ecosystem complexity and, in turn, the ecosystem services dependant on system structure and function. In our assessment tool we recognise that ecologically degraded rivers still offer 'services' in terms of agriculture and forest products i.e. the 'societal trade-off'.

There is therefore a direct relationship between (1) fluvial features, morphological measures and land and cover types and (2) ecosystem processes and ecosystem services delivered. The UK National Ecosystem Assessment (UKNEA, 2011) has recently demonstrated the link between primary freshwater ecosystem processes (such as plant production, flood attenuation, nutrient and water storage), their associated final ecosystem services (crops, water supply, climate regulation, flood mitigation etc.) and goods and benefits that humans derive from them (including food, drinking water, and flood attenuation). While the assessment methodology we present here concentrates on eight widely-recognised ecosystem services derived from aquatic environments, a wide range of other ecosystem services can be derived from rivers depending upon biogeographical region and river type (**Table 2**). In this pilot project, eight was considered a suitable number to incorporate the three main ecosystem service categories - Provisioning, Regulating and Supporting – enhancing compatibility with other national-scale ecosystem service assessments (e.g. Egoh *et al.*, 2008). The number of riverscape features/attributes and land cover types needed to develop indices of provisioning of the eight ecosystem services of interest were kept to a minimum; eighteen features were identified and are described in **Table 3** and **Table 4**. The aim was to simplify data capture, but a second key objective was to minimise duplication/'double-counting' whereby more than one feature/attribute accounting for a single riverscape function might potentially produce a bias towards ecosystem services supported by those particular riverscape features and attributes.

As an illustrative example, channel sinuosity is the first of the eighteen riverscape feature/attributes we define in **Table 3** via *Google Earth*. From a hydromorphic point of view, sinuosity is associated with instream bar development, outer bank erosion, pool development, riffle formation, increased flow path length and reduction in slope. In turn, these features are instrumental in determining flow attenuation, hydraulic diversity and channel dynamism. Potential ecosystem services delivered as a result of these processes include fisheries, flood mitigation and biodiversity. In **Table 3** the theoretical linkages between riverscape features/attributes, driving processes and ecosystem services are specified for all 18 features/attributes used in the assessment tool.

Extraction of riverscape features/ attributes from the remotely sensed data

Table 4 presents a summary of the steps for observing and measuring riverscape features/attributes and land cover on the *Google Earth* platform. For example, channel sinuosity is observable quite obviously by river bends/inflexions in the channel planform. Reaches are measured using the Path and Link tool in *Google Earth*, and the resultant lines labelled consecutively (they can also be sequentially colour-coded to aid their identification). Once channel length and valley length for the reach length being investigated are measured, sinuosity is then calculated as the valley-to-river length ratio. Taking another example, riparian/river bank woodland is manifest in *Google Earth* imagery as narrow, linear strips of textured vegetation bordering channel edges, including on islands and bars. Measurement of this attribute is taken as a percentage length of woodland in relation to the length of river bank (both sides of the channel) in the reach under investigation. On very low order streams the presence of a highly wooded riparian zone may obscure some of the in-channel attributes; on such low order streams ubiquitous vegetation cover becomes the dominant driver of the ecosystem. All eighteen riverscape features were deliberately chosen so that the need for expert interpretation from the imagery is minimised. Obviously some element of training in landscape interpretation from imagery is a basic requirement for robust and repeatable results.

A key issue in extracting information from the *Google Earth* imagery is that of scale. Wiens (1989) asserts that ecologists often behave as if patterns and the processes that produce these are insensitive to scale and as a result have designed studies 'with little explicit attention to scale'. Too coarse a scale (extent) runs the 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. The assessment methodology we describe here is intended to be international in scope, applied equally to rivers and streams of varying orders of magnitude in size, and allow whole river-length comparative assessment of differing zones or extended reaches. The minimum reach length was set at 500 metres to allow correlation with other indices e.g. River Habitat Survey in the UK. While use of a varying reach scale aids interpretation, a potential issue is that, in 1st-order sections of large rivers, reach lengths will be disproportionately long in comparison to 1st-order sectors in smaller rivers. It was felt however that using a system rigidly based on a ratio of channel width to overall river length would lead to unequal levels of effort and emphasis in differing river basins, and undermine efforts to produce a comparative tool.

Scoring system for assigning riverscape features/attributes to individual river ecosystem services

An integer-based scoring system was adopted 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. Values of 1 and 2 were assigned for intermediate states in relation to potential delivery of ecosystem service benefits. A rule-based approach focused on the measured riverscape features/attributes was used to assign scores and these are summarised in **Table 5**. Similar scoring systems have been used elsewhere in the literature (e.g. Sear *et al.*, 2009) and UK Government also promotes a similar semi-quantitative valuation approach to ecosystem service valuation (Everard and McInnes, 2013).

All scores were input into Microsoft Excel as this software is universally available. Calculations of river indices were made using the simple mathematical tools component of the software. A matrix was set up listing the 18 river features/attributes and the reach scores for these determined from the *Google Earth* imagery using the scoring system outlined in **Table 5**. Using the summing feature in Excel a variety of indices was determined from the matrix: a 'feature/attribute' score, a 'number of benefiting ecosystem services' score, an 'individual ecosystem service' score (Sector IEES) and a 'total ecosystem services' score (Sector TESS). Two further indices were calculated at the whole-river scale: a total individual ecosystem system score (River TIESS) and total ecosystem services score (River TESS). Finally, given that (in addition to cultural aspects which are not considered here) individual ecosystem services are defined as either 'Provisioning', 'Regulating' and 'Supporting' (World Resources Institute, 2003), sector and river IEES scores can be classified into these three classes and statistics produced.

We deliberately apply equal weighting across all eight ecosystem services; in reality this becomes a societal decision depending on where elsewhere in the world the method might be applied. For example water supply in an arid zone will be a priority, while in a European river designated as a special area of conservation, water quality and biodiversity may have greater importance in the decision-making process. The advantage of equal weighting is that the method is made more portable between rivers of different ecoregions and climatic regime. It should be emphasised that this portability should not extend to direct comparison of rivers across biogeographical/ecoregion divides or between rivers of significantly different

size. Nonetheless the system is robust enough to allow rivers any where across the globe or of any size to be assessed for ecosystem service delivery using the fluvial attributes defined. To demonstrate this we take three rivers of contrasting character and size and apply the methodology equally to each.

CASE STUDIES AND RESULTS

In order to determine the robustness and wider geographical applicability of the methodology three rivers that encompassed differing scales, differing ecoregion regions, physical habitat character, and degrees and types of human modification were selected for scrutiny. The Yana River in northern Russia was selected as a large pristine river, the River Tyne in northeast England as a river impacted by industrial and urban development, and the River Allan in Scotland, impacted by floodplain agriculture. Two rivers were selected from the same ecoregion (UK), but with different land uses in the riverscape to ensure the methodology was suitably sensitive to this variable.

The Yana River (**Figure 2a**) is 872 km in length with a basin area of 238,000 km² and a mean annual discharge of 1090 m³s⁻¹ totalling 34 km³yr⁻¹ (Gordeev *et al.*, 1996). The River Yana catchment is located in a large near-wilderness area of the Russian Far East and drains from the Russian taiga through the forest tundra zone (Andreev and Klimanov, 2000) to the Arctic Ocean. The river itself is virtually pristine in form from source to mouth with the only human presence being some small mining communities close to the river in the lower catchment. While the Adycha, Bytantai and Olde rivers are the largest of the Yana River's 89 tributaries (Huh *et al.*, 1998), this case study concentrates on the main river corridor only.

The River Tyne (**Figure 2b**), has two main tributaries, the North and South Tyne and in total covers approximately 2933 km². The Tyne as a whole has a mean annual discharge of 34 m³s⁻¹ (Jones *et al.*, 2004), and is flanked by the North Pennines to the west, the Cheviot Hills to the north and the North Sea to the east (Environment Agency, 2000). The majority of the population live in the Lower Tyne valley, with the highest concentration in the urbanised east and coastal strip. Some two-thirds of the catchment area is agricultural and these activities have led to a mix of upland moor, forest, arable land and pasture. The River South Tyne and the Lower Tyne were focused on as part of this study (**Figure 1b**).

The River Allan, also known locally as the Allan Water (**Figure 2c**), is a tributary of the River Forth in central Scotland and has a predominantly upland catchment of approximately 216km² in area and a mean annual discharge of 7.01 m³s⁻¹ (Scottish Environmental Protection Agency, 2011). The upper catchment rising to 700 metres above sea level is dominated by moorland with sheep grazing. Rising in the Ochil Hills, it runs through the three small (< 10,000 population) settlements of Braco, Dunblane and Bridge of Allan before joining the tidal River Forth. Scattered farms also populate the catchment. The valley floor is predominately under pastoral land use with agricultural flood embankments. In Bridge of Allan, urban flood defences are also in place over a 500 metre length. Some channel straightening also occurred in the 1850s with the arrival of the railway to Scotland.

Figure 2. Location of the three rivers used as case study demonstrations of the river assessment methodology using Google Earth. (a) Yana River, northern Siberia; (b) river South Tyne, northeast England; and (c) river Allan, central Scotland

Sector scale river ecosystem scores and downstream patterns

Reach ecosystem scores (sector IESS and sector TESS) were plotted against distance downstream and are shown in **Figure 3**. The plots show the individual contributions of individual ecosystem services to the total score sector by sector. They demonstrate sector-to-sector scale variability but with a general pattern of higher ecosystem service scores in the mid-reaches. For example with regard to the Yana river (**Figure 3a**), TESS values peak at over 100 in sector 53 which equates to 530 kilometres downstream. The TESS values in sectors 47 to 65 are approximately triple those in the headwater reaches (sectors 1 to 26), due to the additional river features associated with floodplain development (e.g. floodplain forest) in the mid reaches and channel dynamics in the lateral dimension (e.g. palaeochannels, secondary channels). The notable drop in TESS value at sector 44 equates with 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 these sectors are potentially significant in terms of sediment delivery due to the presence of valley side bluffs. The dip in TESS value at sector 76 is associated with a small mining settlement.

Figure 3. 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.

In contrast to the Yana River, the River South Tyne in northeast England has a long cultural history of agriculture and mining. The river rises in the Pennine Hills and is predominantly

agricultural in the uplands. The form of the river corridor is an alternating sequence of constricted reaches separating wider sections with much higher rates of sediment reworking and channel activity. This is seen as an undulating form to the graphed scores in **Figure 3b**. Overprinted on this is a distinct 'saw-tooth' sequence reflecting sharp drops in ecosystem service score. These decreases in score are directly associated with human modification of the catchment in the form of small urban centres, engineering in close proximity to the channel for transport infrastructure and, importantly, the city of Newcastle upon Tyne at the downstream end of the main river (reaches 88-100). Timber and agricultural crop production occur throughout the catchment down to where the main urban section begins.

A similar pattern to the other two case studies is revealed for the River Allan (**Figure 3c**) with the mid reaches scoring highest in terms of sector IEES and TESS values of above 20 compared to between 5 and 15 upstream and downstream. The low scores through reaches 50 to 53 relate to a gorge section, as on the Yana River. Low IEES and TESS values for the most part are explained by human modifications to the river and floodplain. Thus reaches 18-30 are located on the river corridor where the floodplain is under agricultural land use with earthen flood embankments close to the river edge for most of its length. The natural tendency of the river to meander and create cut-offs has been lost by these embankments and bank reinforcement over the last two centuries of human hydromorphological modification. The low TESS values centred on reach 60 equate with a straightened and engineered river channel with flood embankments to help provide flood protection to the town of Bridge of Allan.

Figure 4 shows an alternative way of pictorially representing the downstream patterns observed above in the three case studies, this time subdividing of ecosystem services into Provisioning, Regulating and Supporting. Summary statistics for river scale IEES, TESS values and ecosystem service classification are shown in **Table 6**. These essentially quantify the ecosystem service value for individual ecosystem services and in totality for the whole river length surveyed. Since reach/sector length varies on rivers of differing size, for true cross river comparison total river scores need to be calculated per river kilometre. The Yana River is defined by TESS values per kilometre almost twice that of the North Tyne and four times that of the River Allan. This relates to the pristine nature of the River Yana at one extreme and at the other, the human-modified nature of the Allan Water's river corridor. **Table 7** expresses the river scale individual ecosystem service data as 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.

Sector scale ecosystem scores and scenario assessment

Comparison of **Figures 3c and 3d** demonstrate a modelled river rehabilitation envisaged as part of an engineering project, itself a component of a future natural flood management project within the catchment focusing on reaches 18-30. The proposal is to re-meander the river Allan along this sector reducing channel slope and improving physical habitat diversity by removing or setting the flood embankments back to allow inundation of the floodplain and storage of flood waters. This was visualised by means of photo montages of the proposed sector simulating re-engineered sinuosity and re-introduction of riverscape features/attributes. When these scenarios are incorporated in to the Excel-based matrix and the assessment tool applied, the outcome is current TESS values of between 2 and 15 being elevated to 27-34 with considerable ecosystem service benefit seen in the areas of flood mitigation and water quality. As with the actual scores, scenario assessment can also display the results in terms of Provisioning, Regulating and Supporting services (**Figure 4c, 4d**). At the river scale, this results in the River Allan TESS increasing from 713 to 1200 and the TESS per kilometre from 12.5 to 21.1 (**Table 6**) and associated changes in the percentage contribution to provisioning, regulating and supporting services (**Table 7**). That the methodology thus offers an innovative way of demonstrating and quantifying potential benefits of such restoration engineering in a form accessible to river managers and planners. Importantly it sets these multi-functional benefits within the wider catchment context.

Figure 4. Downstream patterns in ecosystem services (ES) displayed in terms of their Provisioning, Regulating or Supporting attributes for the three rivers assessed in this study. (a) Yana River, northern Russia; (b) river South Tyne, northeast England; (c) river Allan, central Scotland; and (d) river Allan, showing potential effects of restoration in reaches 18–30

DISCUSSION

Utility and appraisal of the approach

This study has demonstrated an approach to river ecosystem service assessment based on recognition that individual riverscape features/attributes and land cover types have an inherent set of properties. These drive environmental processes, thus leading to one or more ecosystem services. The vehicle for undertaking the assessment was the widely accessible virtual globe *Google Earth*. Given the approach showed equal applicability to three contrasting rivers in terms of their scale, ecoregion and extent of human modification, we can conclude that the overall assessment approach is robust. The scoring system allows individual reaches to be assessed and the spatial pattern of ecosystem delivery to be examined, 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 service delivery within river networks or across catchments obviously has great relevance as areas with lower ecosystem service delivery can be examined to ascertain whether this is a product of natural system characteristics or of environmental degradation. The approach is therefore of potential interest to managers and planners as it offers a useful tool for the assessment and visualisation of the effects of restoring sectors of channel or watershed, something that is been a persistent challenge, occurring as it does at the interface of hydrology, geomorphology, ecology and engineering (Clarke *et al.*, 2003; Palmer and Bernhardt, 2006). The value of river rehabilitation is also explored in the context of ecosystem service provision. Our approach was very much focussed on looking at multiple ecosystem services but where a particular ecosystem service was being assessed the basic protocol could be modified accordingly to give greater confidence in the outcomes.

Given the necessary data can be easily extracted from the widely available *Google Earth* platform, it has application globally. Identifying many of the features does require an element of training and experience particularly at finer landscape scales. Detecting features and attributes also requires an insight into geomorphological processes and vegetation-landform relationships. In the UK, and presumably elsewhere, undergraduates in geography and the environmental sciences receive basic training in landscape interpretation from aerial imagery. There are also a range of other virtual globes from which such data could be extracted (e.g. NASA's *World Wind* which also has the facility for dataset uploads by users). As such the method overcomes an issue identified by Langhans *et al.*, (2013): that of how to

deliver comparable river assessments across national and international boundaries. By its very nature, the virtual-globe assessment described here uses the river and its physical features and characteristics rather than geopolitical boundaries. Clearly though, on its own it still cannot get over the issue of how to apply management policies based on ecosystem service delivery where transboundary catchments are concerned.

Challenges and opportunities

The approach set out in this paper is viewed as providing a foundation upon which heuristic improvement and refinement should be a focus of the river science community. A number of assumptions, albeit based on river science knowledge, were made as to links between riverscape features and attributes with ecosystem service delivery. Even where these assumptions are scientifically valid there may be uncertainty in universal application. As such, critical assessment of the scores and patterns of scores will always be required. For example, floodplain wetlands in this approach have been deemed to be a carbon sink but, while many floodplain wetlands will sequester carbon, others may act as a net source of carbon to the aquatic and terrestrial system. Going forward, the river science community need to strive to reduce uncertainties in the linkages shown in **Table 2**. The riverscape features and attributes recorded, together with land cover types, were deemed the best selection based on our current understanding of river systems and with a view to offering ease of identification on virtual-globe imaging platforms. In all cases we make efforts to avoid double-counting but appreciate the difficulty in complex systems of ensuring this does not occur.

Our case studies examined the main river corridor from source to mouth. Accounting for delivery of ecosystem services at tributary junctions is required if this approach is to be extended to the whole drainage network. The approach also only scores reaches in terms of absence or presence of ecosystem service. There is the possibility that upstream river changes may degrade ecosystem service delivery downstream. Some reaches recorded as having zero ecosystem service potential may possibly adversely effect ecosystem services provision elsewhere along the river and, as such, influence scores elsewhere. Negative scoring may therefore be required in certain situations; e.g. point-source pollution, itself not covered in this methodology. In other words, the total cumulative ecosystem service benefit value may not always increase downstream but instead diminish in specific sectors due either to the natural characteristics of the river habitat or to environmental degradation.

The practical benefit of the method is that the effect of site-specific habitat fragmentation on whole-river systems to be assessed.

Although its potential is clear, and at the centre of this approach, *Google Earth* presents some issues. The first is that image and data quality is not universally good. This can create problems in certain areas in terms of feature recognition and measurement, especially in headwaters where stream width is small. However, with time, data quality is improving. In this study, the greatest difficulty experienced on the three case study rivers related to calculation of channel water slope. Channel water slope, as calculated using the *Google Earth* elevation data (derived from NASA's Shuttle Radar Topography mission: Farr et al., 2007) in some instances resulted in the slope value increasing. This issue can potentially be overcome as a free online tool exists for the extraction of elevation data from *Google Earth* imagery (Zonum Solutions 2010) allowing up to 5000 points to be easily extracted from a field of view. This can then be exported to ArcGIS or other software for more accurate georeferencing and surface representation. Wherever encountered negative water slopes were seen, this was interpreted as low/negligible channel water surface gradient for that reach. Another difficulty relating to this was accurate floodplain margin delineation. In most cases the valley floor/hillside delineation could be easily seen visually on the imagery but, in some instances, elevation data and oblique angle views needed to be used as supplementary evidence.. Differentiation between wetland and grassland land cover types on the imagery can also be a subject of debate, but here and elsewhere the availability of timelines of imagery facilitates interpretation.

Guralnick *et al.* (2007) highlight how visualisation tools like *Google Earth* bridge the gap between researchers and those who need most to be reached with the results of research - in particular policymakers and the public. They also highlight how *Google Earth* facilitates data analysis and communication of results due to its ability to embrace multiple data dimensions and multiple spatial scales. Using this *Google Earth* functionality to develop the ecosystem service framework provides a means of (i) highlighting unintended consequences of actions in river systems (Turner and Daily, 2008), (ii) evidencing shifting baselines for conservation management and restoration purposes (Papworth *et al.*, 2009) and (iii) demonstrating opportunities to seek win-win synergies between environmental management disciplines where optimisation rather than maximisation of services is the desired objective (Everard and McInnes, 2013). In Europe for example, framing Water

Framework Directive goals in terms of ecosystem service outcomes can potentially maximise societal outcomes by avoiding fragmented approaches to management across what are multiple-use river landscapes (Stanford and Poole, 1996; Everard, 2011). While the assessments in this exercise did not incorporate cultural ecosystem services, focusing instead on Provisioning, Regulating and Supporting services, the technique we outline here offers a way forward in terms of linking with cultural landscape research by providing a framework for examining system fluvial structure, landscape aesthetics ('naturalness') and historical infrastructure along the length of rivers. As part of the development process with regard to the approach to mapping river ecosystems services there is an on-going need to refine its approach and to identify research agendas that could usefully be taken forward by a working group with, for example, the International Society for River Science.

The future growth of 'virtual globes'

Google Earth and other 'virtual globes' are effectively 'geobrowsers' (Yu and Gong, 2012). At the current rate of progress, we will soon see the evolution of true 'digital earth' platforms with full GIS and image analysis capability incorporated. *Google Earth* arose from the high spatial resolution imagery provided by IKONOS (launched 1999) and *Quickbird* (launched 2001). Since then many more remote-sensing satellites have been launched and, with time, these will have improved spectral and spatial capability and transfer of data to virtual globes. This incorporation of multi-spectral and perhaps hyper-spectral imagery would facilitate discrimination of fluvial landforms, thus opening up the possibility of more sophisticated automated classification and mapping techniques and potentially improving accuracy.

In *Google Earth*, automated image classification is currently not fully possible due to radiometric distortion (Yu and Gong 2012), but this could potentially be circumvented by using river networks where multi or hyper-spectral imagery is available. Based on the rates of evolution of 'virtual globe' technology it is anticipated that the next significant advance will be development of global imaging platforms using high resolution spectral and spatial data providing the capacity to apply automated image analysis techniques to whole river networks. Validation will always be needed *via* ground truthing to ensure overambitious claims as to accuracy are not made. Some progress here is already being made with regard to *Google Earth* in terms of image analysis (Bernabe and Plaza, 2010); ESRI, the Environmental Systems Research Institute's ArcGIS Explorer also comes equipped with

analytical tools. Thus it is likely that the robust approach we advocate here, together with improvements in the capability of virtual globes, can be developed into a more sophisticated yet user-friendly tool for river ecosystem assessment in the near future. Such refinements could result in this river ecosystem service assessment approach becoming an important tool for river managers. Another benefit from including the remote sensing community within the process would be improved automation of riverscape feature/attribute/land cover recognition and measurement. This would help to eliminate operator variance ('the curse of expert knowledge') and speed up the process allowing longer lengths including tributaries to be assessed. Some of the methodology described above can already be automated but further work, for example on riverscape land cover classifications, is needed.

CONCLUSIONS

This paper uses current understanding of river ecosystem functioning as encapsulated in the Riverine Ecosystem Synthesis (Thorpe et al, 2008) to establish theoretical links between eighteen riverscape fluvial features, attributes and land cover types, natural ecosystem functions and eight river ecosystem services. It is accepted that there will be uncertainties in the linkages but the defined cascade from the features, attributes and land cover types to ecosystem services reflects the current state of river science knowledge. We set this theoretical relationship within the wider framework of the Potschin and Haines-Young (2010) 'cascade model' to allow assessment of river ecosystem service delivery from source to mouth. Using *Google Earth* and by adapting the Potschin and Haines-Young model we develop a rules-based ecosystem service scoring approach for rivers and apply it at the reach scale from source to mouth for three case study rivers. This exercise showed the tool to be applicable across ecoregions and to rivers of varying size, level of human modification and character.

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Search phrase(s)									
Year	'Google Earth'	'Ecosystem services'	'Google Earth' and 'river'	'Google Earth' and 'ecosystem services'	'Google Earth' and 'river restoration'	'Google Earth' and 'river assessment'	'Google Earth' and 'river ecosystem services'	'Google Earth' and 'floodplain ecosystem services'	
2006–2007	8840	11 200	1780	66	16	1	1	0	0
2007–2008	1470	1480	320	1580	27	0	1	0	0
2008–2009	20 300	19 400	4830	259	41	5	0	0	0
2009–2010	16 100	16 700	6270	354	50	8	0	0	0
2010–2011	22 700	25 700	7510	486	65	6	1	0	0
2011–2012	16 000	18 100	8530	660	73	9	1	0	0
2012–2013	20 300	23 300	6850	590	54	8	1	0	0

Table 1. A Web of Knowledge analysis of the use of Google Earth in river and ecosystem service assessments.

Ecosystem service	Feature/attribute determined from <i>Google Earth</i>																	
	Sinuosity	Secondary channels	No. of tributaries	Active channel complexity	Slope	Valley side connectivity	River/river corridor ratio	Riparian/bank woodland	Floodplain habitat mosaic	Palaeochannels	Wetlands	Floodplain forest	Floodplain lakes	Agriculture	Woodland plantation	Urban	Embankments	Instability / naturalness
Provisioning																		
Fisheries																		8
Agricultural crops																		1
Timber																		1
Water supply																		4
Regulating																		
Flood mitigation																		8
Carbon sequestration																		6
Water quality																		7
Supporting																		
Biodiversity																		13
Number of services provided by feature	3	3	3	3	2	1	3	2	1	3	4	5	5	1	3	0	0	6

Table 2. 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

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	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

Table 3. Linkage between riverscape feature/attributes or land cover type, fluvial processes and characteristics, natural ecosystem functions and ecosystem services delivered.

Riverscape features/attributes or land cover type	Observable evidence	Delineation and measurement of riverscape features/ attributes or land cover types
Sinuosity	River with bends	Use Path and Line tool to calculate Valley length to river length ratio
Secondary channels or 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
Tributaries	River channels originating from the valley sides	Count number of rivers that actively flow onto the valley floor
Active channel 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
Slope	<i>Google Earth</i> georeferenced elevation data	Use cursor elevation indicator to obtain top minus bottom altitude and divide by sector length
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
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
Riparian/river bank woodland	Narrow, linear strip of textured vegetation bordering channel edges, including on islands and bars	Estimate length bordering channel
Floodplain physical habitat mosaic	Frequency of separately coloured patches and/or tone variability	Estimate number of separately coloured patches
Palaeochannel	Presence of scroll bars and linear depressions	Estimate percentage area of linear channel-like features often not containing water
Wetlands	Discrete usually darker tones (imagery specific)	Estimate percentage area of darker, non-textured vegetation with diffuse edges, often bordering water bodies
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
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
Agriculture	Uniform vegetation/soil colour, presence of field patterns, straight drainage channels etc.	Estimate percentage area
Woodland plantation	Uniform textured vegetation often with straight edges	Estimate percentage area. At high magnification, individual trees or canopy details can sometimes be seen
Urban areas	Uniform areas of settlement, straightened boundaries, regulated reaches	Estimate percentage area
Embankments	Narrow linear, clearly artificial features paralleling channel	Estimate length
Channel dynamism/ 'naturalness'	Absence of human influence on land cover and channel form	Presence of exposed bars, scroll meanders, multiple thalwegs, backwaters and palaeochannels

Table 4. Riverscape features/attributes or land cover types and their observable evidence in Google Earth together with their method of delineation and measurement

Riverscape feature/attribute or land cover	Score			
	0	1	2	3
Sinuosity	Straight (1:1)	Sinuuous (<1.5)	Highly sinuous (1.5–2.5)	Tortuous (>2.5)
Averaged number of secondary channels	None	<2	2–3	>3
Tributaries along sector/reach	None	1	2–3	>3
Active channel complexity (ratio of bend apices to exposed bars and backwaters)	>3	2:1–3:1	1:1–2:1	<1:1
Sector/reach slope	>2%	0.5–2%	0.1–0.5%	<0.1%
Valley side connectivity	Absent–trace (<5%)	Low (5–25%)	Medium (25–50%)	High (>50%)
River : corridor width ratio	1:1	1:11–1:5	1:51–1:10	>1:10
Riparian/riverbank woodland	Absent–trace (<5%)	Low (6–25%)	Medium (26–50%)	High (>50%)
Corridor physical habitat mosaic	Simple/uniform (mosaic absent)	Low patch variability	Moderate patch variability	Highly heterogeneous
Palaeochannels	Absent–trace (<5%)	Low (6–25%)	Medium (26–50%)	High (>50%)
Wetlands	Absent–trace (<5%)	Low (6–25%)	Medium (26–50%)	High (>50%)
Floodplain forest	Absent–trace (<5%)	Low (6–25%)	Medium (26–50%)	High (>50%)
Lakes/ponds/open water bodies	None	1–2	3–10	>10
Agriculture	Absent–trace (<5%)	Low (6–25%)	Medium (26–50%)	High (>50%)
Woodland plantation	Absent–trace (<5%)	Low (6–25%)	Medium (26–50%)	High (>50%)
Urban/paved areas/mining	Absent–trace (<5%)	Low (6–25%)	Medium (26–50%)	High (>50%)
Embankments along sector/reach	Absent	Locally present	Discontinuous but extensive	Fully embanked on both sides
Active channel dynamism/ 'naturalness'	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

Table 5: Rules relating to attributing riverscape features/attributes or land cover types to potential ecosystem service score

Summary statistic							
River	Surveyed length of river (km)	Number of reaches/sectors	Reach/sector length (km)	Feature score (range over surveyed length)	Total feature score per river length (and per km)	ES score (range over surveyed length)	Total ecosystem score (for surveyed length of river) ^a
Yana River	750	75	10	<i>Min.</i> 10 <i>Max.</i> 38	15 720 (21.0)	<i>Min.</i> 16 <i>Max.</i> 106	39 890
River South Tyne	100	100	1	4 28	1722 (17.2)	3 43	2916
River Allan	28.5	53	0.5	3 19	553 (19.4)	2 38	713
River Allan (incl. restoration scenario)	28.5	53	0.5	3 29	653 (22.9)	2 38	1200

^aValues not directly comparable between rivers because of differing sector lengths.

Table 6. Summary statistics for reach/sector survey output, riverscape feature/attributes and total ecosystem services scores (TESS) for the three rivers surveyed using the ecosystem service assessment tool, together with the river Allan restoration scenario

Ecosystem service	River			
	Yana	South Tyne	Allan	Allan (<i>incl. restoration scenario</i>)
Fisheries [P]	18.7	15.1	16.7	15.4
Water supply [P]	4.8	2.0	3.5	2.3
Timber [P]	0	2.4	0.4	0.1
Agricultural crops [P]	0	4.4	4.8	4.8
Flood mitigation [R]	18.6	21.0	23.0	20.0
Carbon sequestration [R]	8.1	2.3	0.6	0.4
Water quality [R]	20.5	18.7	15.4	20.8
Biodiversity [S]	29.3	34.0	32.4	36.3
<i>Total</i>	<i>100</i>	<i>100</i>	<i>100</i>	<i>100</i>
Provisioning ecosystem services	23.5	23.9	28.6	22.9
Regulating ecosystem services	47.2	42.1	39.0	42.0
Supporting ecosystem services	29.3	34.0	32.4	37.0

Table 7. Summary statistics for individual ecosystem service scores and Provisioning, Regulating and Supporting services at the river scale (river IESS). Values are expressed as percentage contributions for the three rivers surveyed using the ecosystem service assessment tool, together with the river Allan rehabilitation scenario. IESS, individual ecosystem service score