Realising the value of fluvial geomorphology

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Abstract

Fluvial geomorphological forms and processes exert a fundamental influence on riverine processes and functions. They thereby contribute significantly to beneficial services for humanity, yet remain largely undervalued. Major ecosystem service studies to date tend overlook the contribution of geodiversity and geomorphological processes, particularly of fluvial geomorphology, to human wellbeing. Yet management of the water environment which overlooks fundamental driving processes, such as those encompassed by fluvial geomorphology, is inherently unsustainable. Inferences from the literature highlight a broad range of contributions of fluvial processes and forms to the four ecosystem service categories of the

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Millennium Ecosystem Assessment, contributing to system functioning, resilience and human wellbeing. Fluvial geomorphologists can help society better address sustainability challenges by raising the profile of fluvial forms and processes to continuing human wellbeing and system resilience. To achieve this, we identify three challenges: (1) cross-disciplinary collaboration, addressing interrelations between biodiversity and geodiversity as well as broader scientific disciplines; (2) quantification to an appropriate level and, where possible, mapping of service generation and benefit realisation; and (3) persuasive demonstration projects emphasising how investment in this aspect of the natural environment can enhance service provision and net human benefits. We explore lessons learned from case studies on river rehabilitation, floodplain management, and mapping ecosystem services. We contend that linking fluvial geomorphology to societal wellbeing outcomes via the language of ecosystem services provides a pathway towards social and economic recognition of relevance, influencing policy-makers about their importance and facilitating their 'mainstreaming' into decision-making processes. We also advance a prototype conceptual model, guiding fluvial geomorphologists better to articulate the contribution to a sustainable flow of services through better characterisation of: (1) interactions between anthropogenic pressures and geomorphology; (2) how forms and processes contribute to ecosystem services; and (3) guidance on better management reflecting implications for service provision.

Keywords

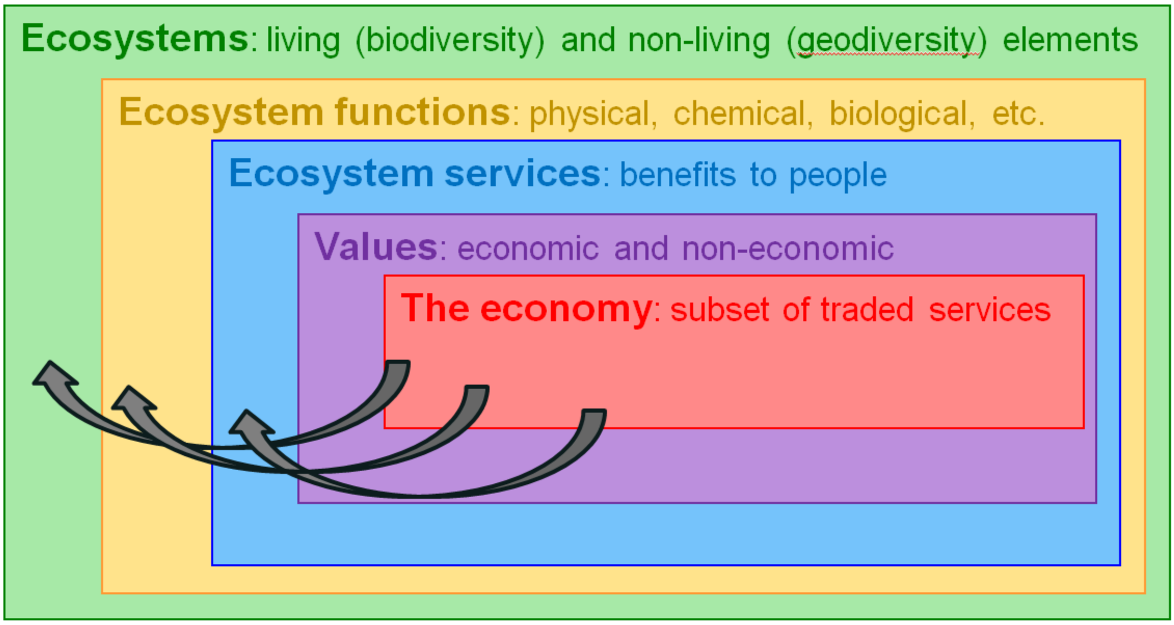
Ecosystem services, fluvial geomorphology, river restoration, ecosystem approach, ecosystem assessment

Introduction

Nature has substantial value to all dimensions of human interest, yet has been largely overlooked (Millennium Ecosystem Assessment, 2005; UK National Ecosystem Assessment, 2011; HM Government, 2011). Emerging recognition of the structure and functioning of nature in delivering ecosystem services in progressive regulation includes, for example, the EU Water Framework Directive (WFD) requirement to achieve 'good ecological status' as a strategic outcome superseding a former issue-by-issue ‘pressures’ focus. Ecosystem services concepts are receiving increasing critical attention from institutional and regulatory commentators in policy and law (Ruhl and Salzman, 2007; Kaime, 2013). However, there remains a substantial legacy of legislation, subsidies and other policy levers founded on narrowly focused disciplinary approaches. Framing ‘compliance’ as an end goal, rather than explicitly addressing consequent benefits to people and the integrity and resilience of ecosystems, hampers systemic practice despite clear policy pronouncements in international and national pronouncements. Even for emerging legal instruments with systemic intent like the WFD, entrenched assumptions have tended to reduce Member State implementation to compliance with sets of technical standards, perpetuating historic perceptions of ‘nature’ as a constraint on development rather that the primary asset supporting societal benefits (Everard, 2011). The basis of the Ecosystem Approach (http://www.cbd.int/ecosystem/principles.shtml) and policy statements seeking to embody it (such as HM Government, 2011 in a UK context) is recognition of multiple, substantial values flowing to society from ecosystems and their services.

The principle of a cascade running from ecosystems to functions, services and thence to multiple beneficial outcomes for people, including feedback loops, is established in the literature (Everard *et al*., 2009; Haines-Young and Potschin, 2010) and policy-related studies and positions both internationally (Millennium Ecosystem Assessment, 2005) and nationally (for example UK National Ecosystem Assessment, 2011). Everard (unpublished) favours representation as nested layers, emphasising systemic dependencies and adverse implications from feedback when valuation and trading includes only a subset of ecosystem services (Figure 1).

Figure 1: nested model of connections from ecosystems and markets



Ecosystem services flow from the interaction of living (biodiversity) and non-living (geodiversity) ecosystem elements. Geodiversity, comprising the variety of geological and soil materials, the landforms they constitute and the processes which establish and alter them, is being increasingly recognised for its role in sustaining natural capital (Gordon and Barron, 2013; Gray *et al*., 2013). Fluvial geomorphology is a key element of geodiversity. Landforms and stream-related processes (primarily erosion, transportation and deposition of sediment) influence the evolution of fluvial forms and consequently the physical template of a riverscape, shaping the structure, ecology, functioning and diversity of ecosystems supported therein (Naiman *et al*., 2005; Stoffel and Wilford, 2012). Clearly then, geomorphological processes significantly influence the range of ecosystem services that river systems provide. Bergeron and Eyquem (2012) identify specific attributes of geomorphological systems instrumental in relation to ecosystem services (Table 1).

The contribution of geomorphological processes more generally to social sciences and philosophy is recognised by Downs and Gregory (2004). The role of fluvial geomorphology is also becoming progressively more strongly recognised in river management (Gregory *et al*. 2014; Wohl 2014). For example, the WFD includes hydrogeomorphological condition as a constituent of ecosystem quality, and certain geomorphological processes are recognised as significant for engineering concerns (for example scour of bridge supports: May *et al*., 2002). This repositions fluvial geomorphology in a more multidisciplinary context, Newson (2006, p.1606) suggesting that, “Fluvial geomorphology is rapidly becoming centrally involved in practical applications to support the agenda of sustainable river basin management”. Thorndycroft *et al*. (2008, p.2) adds, “A resurgence in fluvial geomorphology is taking place, fostered for example by its interaction with river engineering, and the availability of new analytical methods, instrumentation and techniques. These have enabled development of new applications in river management, landscape restoration, hazard studies, river history and geoarchaeology". More specifically in relation to ecosystem services, Bergeron and Eyquem (2012, p.242) suggest that fluvial geomorphologists have "…a key role to play in their identification and evaluation" and so should become "…more actively involved in this relatively new, yet rapidly expanding and increasingly important, area of applied research".

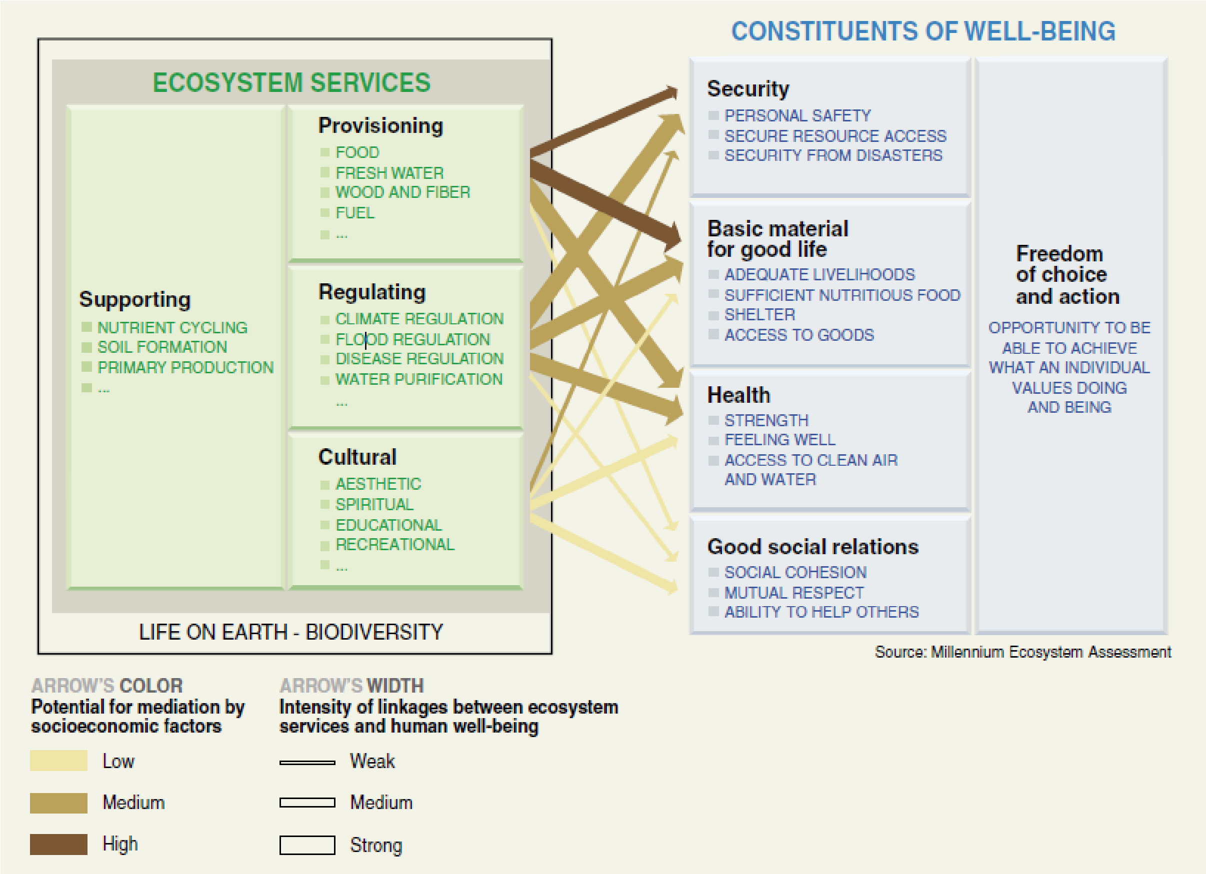
International commitment to the 12 principles of the Ecosystem Approach implicitly includes fluvial geomorphology under Principles 3 (effects on adjacent ecosystems), 5 (ecosystem structure and functioning), 6 (ecosystem functioning), 8 (lag and long-term effects) and 12 (involving all relevant scientific disciplines). The wide spectrum of human wellbeing end-points supported by fluvial geomorphology has not yet been explicitly recognised in policy and management frameworks, particularly for supporting, regulatory and other non-marketed services. Where fluvial geomorphological processes are overlooked, loss of societal wellbeing may ensue through direct costs (such as river bank erosion) or lost opportunities to benefit from natural processes (for example natural flood management solutions). Understanding systemic connections between ecosystem services provided by geomorphological forms and processes is therefore important if river management is to become optimally sustainable and societally beneficial, including avoiding unforeseen trade-offs (Morris *et al*., 2008).

This paper addresses the role of fluvial geomorphological processes and forms in the production of ecosystem services, how human activities affect them, suggested policy responses, as well as significant knowledge and policy gaps and research needs. Although we use many European examples, we emphasise the generic importance of fluvial geomorphology as a central thread in river management, constituting an integral consideration for the achievement of wider ecosystem service outcomes.

The impact of fluvial forms and processes on human wellbeing

The contribution of four broad categories of ecosystem services (provisioning, regulatory, cultural and supporting) to multiple constituents of human wellbeing is represented in the Millennium Ecosystem Assessment (2005) conceptual model (Figure 2).

Figure 2. Millennium Ecosystem Assessment (2005) conceptual model of linkages between ecosystem services and human wellbeing



Some commentators (Boyd and Banzhaf, 2007; Turner *et al*., 2008) contest consideration of supporting services in benefit assessment as they principally constitute functions underpinning more directly exploited and valued ecosystem services. This view influenced the conceptual valuation model underpinning the UK National Ecosystem Assessment (UK NEA, 2011), in which supporting services and some regulatory services are largely recognised as 'intermediate services' (such as soil formation) contributing to 'final services' (e.g. food production) and ‘goods’ (for example saleable food commodities). Everard and Waters (2013) contest this approach, highlighting that exclusion of non-marketed services, far from completely included in market values assigned to traded goods, underpins many current sustainability challenges. Supporting and regulatory services, to which fluvial geomorphological processes contribute significantly, are therefore explicitly considered here to ensure that potentially important mechanisms supporting human wellbeing are not overlooked.

Whilst geomorphological processes are explicitly recognised at both global scale (Millennium Ecosystem Assessment, 2005) and national scale (UK National Ecosystem Assessment, 2011), the role of geodiversity including its functional links with biodiversity is substantially overlooked in both studies (Gordon and Barron, 2013; Gray *et al*., 2013). As the role of specific fluvial processes and forms are not addressed, their contribution to ecosystem service outcomes therefore warrants further study.

Tables 2-5 describe respectively the four Millennium Ecosystem Assessment (2005) categories of ecosystem services, outlining specific services supported or maintained, whether directly or indirectly, by fluvial geomorphological processes.

Fluvial geomorphology and the flows of services it supports are also substantially shaped by anthropogenic pressures. Significant amongst these is rising global human population, exacerbated by escalating consumption pressures from a burgeoning middle class in the developing world imposing food and other supply chain pressures, and increasing urban densities. A wide literature addresses multiple anthropogenic pressures, including land conversion for agriculture and urbanisation, changes to river flows through surface resource and groundwater abstraction, modifications to river channels such as impoundments and channelization (Gurnell *et al*., 2007), and alteration of habitat structure through aggregate extraction and management for fishery, navigation and other purposes.

Further indirect effects of fluvial geomorphological processes and forms arise from cross-habitat interactions (e.g. see Stoffel and Wilford, 2012, for a review of hydrogeomorphic processes and vegetation in upland and geomorphological fan environments). Whilst fluvial forms and processes are most directly related to fresh waters, there are close interlinks between other habitat types (UK National Ecosystem Assessment, 2011). The reciprocal influences between linked habitat types and the services provided by fluvial forms and processes need to be better understood and systematised.

Degradation of ecosystems and their processes has the potential significantly to erode benefits, or create dis-benefits, of substantial cumulative detriment across the full suite of ecosystem services. Elosegi *et al*. (2010), for instance, synthesise relationships between channel form, biodiversity and river ecosystem functioning and human impact, while Elosegi and Sabater (2013) review the effects of common hydromorphological impacts (e.g. channel modification, river flow) on river ecosystem functioning. Disruption of fluvial geomorphological processes is likely to destabilise production of ecosystem services, and hence overall catchment system resilience. In particular, anthropogenic pressures upon fluvial forms and processes warrant further review both as discrete pressures but also how they introduce feedback loops affecting the cross-disciplinary flow of ecosystem services. For example, climate change affects the intensity, locality and frequency of rainfall differentially across regions, with secondary effects upon propensity for both drought and flooding (IPCC, 2013; Kendon *et al*., 2014).

Impacts on fluvial processes also raise distributional equity issues, for example in a dammed river (generally to harvest the provisioning services of *fresh water* and *energy* although sometimes also promoting the cultural services of *transport* and water-based *tourism*) that tends to profit an already privileged minority with often substantial overlooked losses at catchment-scale incurred by multiple, often marginalised or otherwise disempowered stakeholder groups (World Commission on Dams, 2000; Everard, 2013).

Consequently, river and catchment structure and processes need stronger recognition as major contributors to ecosystem service benefits and resilience of catchment systems.

Integrating fluvial geomorphology and ecosystem services: key challenges

We identify three principal challenges to be addressed to achieve integration of fluvial geomorphological science with ecosystem services, which collectively will elevate the profile of the contributions and importance of riverine processes and forms to human wellbeing.

Challenge 1: cross-disciplinary collaboration. The success of river management depends critically on improving understanding and explicit modelling of the relationships between hydrological regime (water, sediment), fluvial processes and the interrelated ecological processes and responses (Arthington *et al*., 2010) or, as Gordon and Barron (2013, p.54) put it, the "…functional links between biodiversity and geodiversity". We need to move beyond paradigms and principles to "…practical tools, methods, protocols and models accurately linking volumes and patterns of flow to biodiversity and ecological processes" (Arthington *et al*. 2010, p.3). This requires aquatic ecologists and fluvial geomorphologists to work together. Gordon and Barron (2013, p.54), for example, make a plea for "…the geodiversity and biodiversity communities to break down disciplinary barriers" and work towards integration.

Challenge 2: quantification to an appropriate level and mapping. This addresses ecosystem services generated by rivers and floodplains, and links between them and supporting fluvial geomorphological and ecological processes (Arthington *et al*., 2010; Thorp *et al*., 2010). Others call for analysis and evaluation of the monetary and non-monetary contribution of geodiversity to "…ensure natural capital is not undervalued through its omission" (Gordon and Barron, 2013, p.54). Although ecosystem services supported by hydrological processes have received attention for some time (Ruhl, 1999; Postel, 2002; Postel, 2003; Braumann *et al*., 2007), case studies showing a continuum of predictive and functional understanding of geomorphological and ecosystem processes through to quantified ecosystem services are uncommon, and comparative evaluation of alternate approaches is rarer (Bagstad *et al*., 2014). Techniques for evaluating services underpinned by fluvial geomorphology are therefore under-developed (Thorp *et al*., 2010). Indeed, lack of practical tools and incentives to use ecosystem services concepts has been cited as a reason why some Australian catchment managers have not incorporated them into routine management and planning (Plant and Ryan, 2013). Although Plant and Prior (2014) propose a useful framework for incorporation of ecosystem services into statutory water allocation, this does not address the underlying needs referred to above. Everard and Waters (2013) provide a practical ecosystem services assessment method consistent with UK government guidance, emphasising that detailed monetised studies are not essential to illustrate the diversity of values provided by natural places and management schemes.

Challenge 3: demonstration. A third challenge is production of persuasive projects demonstrating how investment in the natural environment can result in enhanced benefits and service provision (Gordon and Barron, 2013).

The following sub-sections explore case studies illustrating how these three challenges might be met.

(i) River rehabilitation and ecosystem services

River rehabilitation has been seen as fundamental to improving biodiversity, emerging as a distinct discipline over recent decades and giving rise to projects across the globe seeking to demonstrate improvements in biota, habitat and/or cultural value. More recent attempts have been made to quantify the impact of these initiatives in terms of the quality and value of river-based ecosystem services. For example, dead wood is an important component of natural channels, so lack of it impacts nutrient and matter cycling, simplifies habitat and reduces biodiversity (Hofmann and Hering, 2000; Elosegi *et al*., 2007). A restoration project in Spain involving re-introduction of dead wood resulted in a 10- to 100-fold increase in stream-derived economic benefits, equating to an annual benefit of €1.8 per metre of restored river length with benefits exceeding costs over realistic time-frames (Acuña *et al*., 2013). These benefits arose due to improved fishing supported by improved habitat, better water quality consequent from increased water residence time, higher retention of organic and inorganic matter, and reduced erosion. Such case studies provide a framework for quantifying benefits, demonstrating how investing in the natural environment can deliver multiple ecosystem services.

Although ecosystem service enhancement can be used to justify investment in river restoration, Dufour *et al*. (2011) suggest that the concept can also reposition river restoration on a more objective-based footing, framing desired future state outcomes in terms of goals for natural system integrity and human well-being as components of a desired future state rather than more simply as change relative to a notional 'pre-disturbance' condition. Thorp *et al.* (2010, p.68) also acknowledge that "…a focus on ecosystem services may also promote alternative river management options, including river rehabilitation". Tailoring schemes to socially desired ecosystem services may optimise the benefits and inform the priorities for river rehabilitation.

Gilvear *et al*. (2013) demonstrate an innovative approach to optimising the outcomes of river rehabilitation in relation to delivery of multiple ecosystem services. Rather than quantifying them in monetary terms, levels of ecosystem services delivered are assessed on the basis of an expert-derived scoring system reflecting how the rehabilitation measure contributes to reinstating important geomorphological, hydrological and ecological processes and functions over time. The approach enables a long-term (>25 years) score to be calculated and provides a mechanism for discriminating between alternative proposals. Use of relative measures of ecosystem service rather than monetary values is interesting in relation to Plant and Ryan's (2013, p.44) observation that "…a well-facilitated process of group learning and reasoning about nature's values that is grounded in local knowledge and experience may ultimately better approximate the 'true' value of a region's natural capital that traditional positivist approaches aimed at comprehensive quantification and valuation of ecosystem services".

(ii) Floodplain management and ecosystem services

Posthumus *et al*. (2010) provide an example of the utility of using ecosystem services in floodplain management. Six floodplain management scenarios[2] were identified based on different priorities for land use in lowland floodplain areas. Fourteen goods or ecosystem services (column 2 of Table 6) arising from each land use were then semi-quantified on the basis of an indicator (Table 6), many of which are strongly supported by fluvial geomorphological processes. Results were normalised and depicted using radar plots, allowing the conflicts and synergies between the range of ecosystems services under the different land uses to be made explicit. This approach provides an example of how semi-quantitative methods can

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[2] (i) current use (ii) intensive agricultural production (iii) agri-environment (seeking to enhance biodiversity within predominantly agricultural land (iv) biodiversity (v) floodwater storage and (vi) income (seeking to maximise income derived from the land)

be used to support decisions, better internalising the contribution of fluvial geomorphology in operational practice.

(iii) Mapping ecosystem services

Mapping ecosystem services has value in that it identifies areas providing a high level of service, which therefore require targeted management strategies to retain this level of service provision (Maynard *et al*., 2010 and 2012; Martinez-Holmes and Balvanere, 2012).

Thorp *et al*. (2010) suggest the level of ecosystem service provided by river environments is directly related to their hydrogeomorphic complexity. They define functional process zones (FPZs) and describe a method for mapping them involving up to 15 catchment, valley and channel variables. Hydrogeomorphic complexity is thus related to habitat and niche complexity, influencing a river's biocomplexity and consequent ecosystem services. Thorp *et al*. (2010) acknowledge that research relating ecosystem services to hydrogeomorphic structure is still emerging, but provide an indication of the relationship between six contrasting types of FPZs and their potential level of ecosystem service provision (Table 7). Further development of mapping relationships between hydrogeomorphic zones and levels of ecosystem service provision is required.

Another influential case study was associated with end-of-life coastal defences in Wareham, Dorset (England), in which stakeholders developed consensus in tabular form about the ‘likelihood of impact’ in semi-quantitative terms for a range of ecosystem services likely to arise from different management options (Tinch and Provins, 2007). This example has been used by UK Government (Defra, 2007) as an example of where this form of mapping can avert the need for expensive, time-consuming and (in this case) unnecessary cost-benefit assessment to determine a favoured option.

Another benefit of mapping service provision is that it highlights discontinuities in supply and demand of ecosystem services. For example, Stürk *et al*. (2014) illustrate a pan-European spatial mapping approach comparing ecosystem service supply and demand focussing on flood regulation services. This approach could help identify priority areas for investment through conservation and land use planning. Based on the priorities of Pagella and Sinclair (2014), we suggest there are four key areas for development with respect to mapping ecosystem services underpinned by fluvial geomorphological processes: (i) maps at appropriate scales and resolutions connecting field scale management options and river ecosystem services; (ii) definition of landscape boundaries and flows and pathways from source to receptor; (iii) approaches to calculating and presenting synergies and trade-offs amongst and between services; and (iv) incorporating the stakeholder perspectives to help deepen understanding, bound uncertainty and improve legitimacy. However, at least in the UK, a consistent and generally accepted method of detailed mapping river attributes and functions is lacking, beyond the rapid assessment tool River Hydromorphology Assessment Technique (RHAT) devised for monitoring under the EU WFD (Water Framework Directive UK TAG). Other tools addressing at least a subset of relevant attributes of fluvial geomorphology are available and have been used in previous surveys, including for example fluvial audits for river conservation (Natural England, 2008), River Habitat Survey (http://www.riverhabitatsurvey.org/), River Corridor Survey (National Rivers Authority, 1992) and PHABSIM (Milhous and Waddle, 2012) as an example of habitat suitability modelling. An opportunity to map and extend awareness of ecosystem services generated by river geomorphology is presented by Large and Gilvear (2012) in the form of a methodology for reach-based river ecosystem service assessment of eight ecosystem functions using remote sensing using Google Earth remote sensing data, drawing theoretical linkages between 18 riverscape fluvial features, attributes and land cover types, observable and measurable on Google Earth, and resultant river ecosystem service delivery.

Learning from how the above case studies inform the three principal challenges is summarised in Table 8. Cumulatively, these highlight the importance of addressing the major contributions of fluvial geomorphology to multiple ecosystem service outcomes, which need to be represented transparently to affected stakeholder groups who need, in turn, to be involved in equitable and resilient governance.

Discussion

The change of paradigm towards ecosystems thinking requires the multiple societal values, both economic and non-economic, of nature and its processes to be better articulated and integrated into decision-making across policy areas, including recognition of the broader ecosystem service contributions of fluvial geomorphological and other significant processes at both local and distant spatial and temporal scales (Seppelt, 2011). Closer integration, in both science and policy, of the living (biodiversity) and non-living (geodiversity) elements of ecosystems is necessary to support decisions incorporating the resilience, functioning and capacities of the natural world that sustain human wellbeing. Connecting underlying natural forms and functions with wellbeing end-points is essential if the value of fluvial geomorphology is to be understood and mainstreamed into operational practice. Recognition of the value of ecosystem services provided by river forms and processes also helps overcome the historic perception of 'nature as threat' (flooding, disease, drowning) and its necessary transition into 'nature as fundamental capital' that is implicit in the Ecosystem Approach. Wohl (2014, p.278) voice concerns that fluvial geomorphology "…also faces some serious challenges, however, in maintaining societal relevance in a human-dominated environment", and by Gregory *et al*. (2014, p.479) that it "…needs to raise its profile in contributing to major questions in society and to living with environmental change". We contend that linking fluvial geomorphology to societal wellbeing outcomes via the language of ecosystem services provides a pathway towards social and economic recognition of relevance, influencing policy-makers about their importance and facilitating their 'mainstreaming' into decision-making processes. Furthermore, consideration of all interconnected ecosystem service end-points stemming from geomorphological processes and forms can lead to more robust, socially valuable and equitable outcomes, the language of benefits to people also constituting a more intuitive and systemic means for communicating across stakeholder groups.

Outcomes of this policy influence should include the framing of new regulatory instruments and subsidies in terms of systemic wellbeing outcomes. It should also promote reinterpretation of existing instruments, recognising their potential for to deliver broader societal values. Everard *et al*. (2012) and Everard and McInnes (2013) emphasise that refocusing on the purpose of legacy legislation, rather than slavish adherence to regulatory clauses in isolation, can lead to more systemic practice, especially if supported by government guidance. Examples relevant to fluvial geomorphology include refocusing on the wider societal values stemming from achieving 'good ecological status' in the WFD, broader societal benefits from cross-compliance requirements under UK, EU and other agri-environment agreements via their effects on fluvial geomorphology, and assessing the broader outcomes of in-channel and riparian construction projects. Distributional considerations are also important, for example where the beneficiaries of ecosystem services such as climate and flood regulation may be remote from the point of resource ownership, exploitation and service production. Everard *et al*. (2014) consequently call for greater coherence between higher-level international and national commitments to taking an Ecosystem Approach and their practical translation into compulsions and inducements within the diverse formal and informal policy environment that shapes the decisions of often private resource owners, which may make a significant contribution to optimising benefits across society.

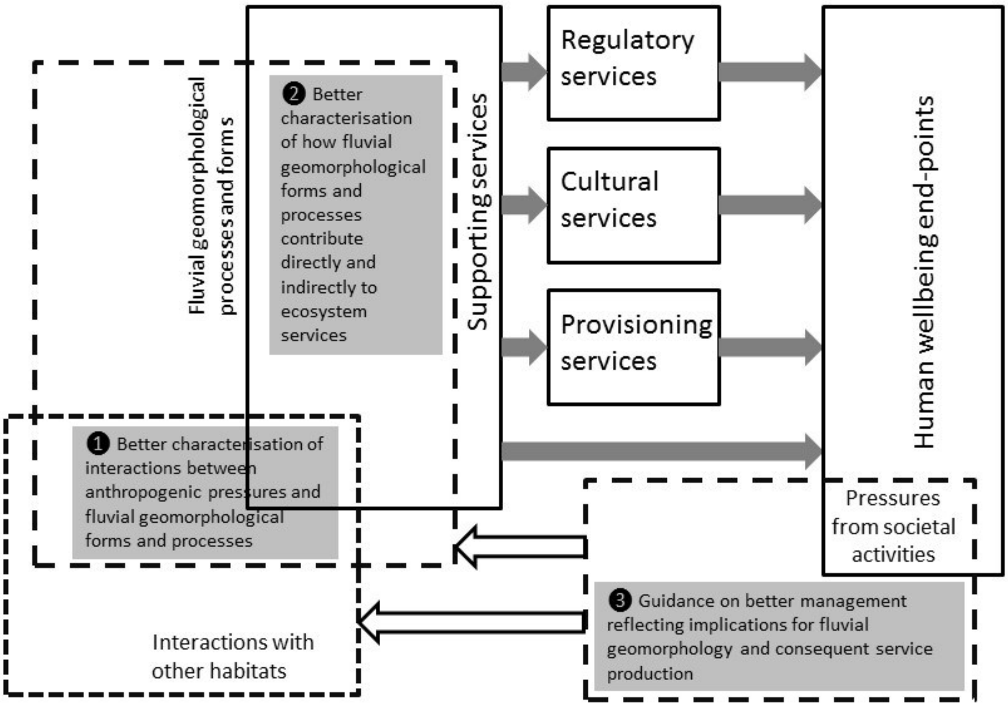
Clearly documented, if possible quantified, case studies would also promote better understanding and demonstration of the contribution of fluvial geomorphological forms and processes to beneficial end-points, and their integral interdependencies with biological processes. This necessarily entails assessing implications for the full spectrum of ecosystem services, importantly including hard-to-measure services which, if overlooked, may continue to generate negative unintended externalities eroding net societal value. Techniques to derive indicative values for all ecosystem services are reviewed by Everard (2012) and articulated by Everard and Waters (2013), including for example linkages to surrogate markets, travel cost analysis, and 'willingness to pay'. These methods may not provide market values for all, or perhaps most, services, but can be illustrative of relative significance (large or small, positive or negative) of services helping highlight potential unforeseen trade-offs and also supporting more inclusive, equitable and sustainable decisions.

Recognising the significance of fluvial geomorphology for all ecosystem services and their associated and equally interconnected beneficiaries is essential for reliable mapping, valuation and effective management of services. Novel policy instruments, including more systemically framed emerging legislation and market-based instruments, may better connect ecosystem resources and processes with their final beneficiaries. For example, payments for ecosystem services (PES) can create markets for formerly overlooked services, potentially opening novel funding routes wherein service beneficiaries who may not traditionally have recognised the benefits they receive from fluvial geomorphology, such as transport infrastructure managers, can invest cost-effectively in processes supporting their interests.

Assessment of gaps in the policy environment is an additional research need building on, for example, analysis of 'response options' within the UK National Ecosystem Assessment Follow-On programme (UK National Ecosystem Assessment, 2014) and highlighting opportunities for integration of fluvial geomorphological considerations into wider sectoral interests. Issues such as private rights on floodplains and other catchment land may constrain freedoms, or necessitate novel approaches, to protect important processes yielding public benefits. To promote more coherent policy formulation, we advance the conceptual model at Figure 3. This model clearly needs to be further developed to account for the full range of contributions of fluvial processes and forms to human wellbeing and the feedbacks from society, but serves to illustrate and communicate (based on already accepted systems models outlined in the Introduction to this paper) the specific place at which fluvial geomorphology needs to be considered as a contributor to the sustainable flow of services, namely:

1. Better characterisation of interactions between anthropogenic pressures and fluvial geomorphological forms and processes;
2. Better characterisation of how fluvial geomorphological forms and processes contribute directly and indirectly to ecosystem services; and
3. Guidance on better management reflecting implications for fluvial geomorphology and consequent service production.

Figure 3: Skeleton model of the influence of fluvial processes and forms on human wellbeing with feedback loops. Dotted boxes highlight areas of geomorphological interactions, and shaded boxes identify where further research and guidance is required by fluvial geomorphologists



Management of the water environment which overlooks fundamental driving processes, such as those encompassed by fluvial geomorphology, as well as their contributions to system resilience and human wellbeing, is by definition unlikely to be sustainable. Clarity about the connections between fluvial geomorphology and ecosystem service outcomes is crucial. This exploration of the benefits of linking fluvial geomorphology with the ecosystem services framework also serves to demonstrate the wider benefits of the Ecosystem Approach, to which many countries have been signatories since 1995, in recognising and integrating the many, long-overlooked values of natural systems centrally in decision-making.

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Table 1: Attributes of fluvial geomorphological systems important for generating or contributing to ecosystem services. Bergeron and Eyquem (2012) defined these as 'ecosystem services'; we re-define these as 'attributes', for example water quantity is an attribute that defines the ecosystem service of flow regulation.

ATTRIBUTE	DESCRIPTION
Water quantity (amount of flow)	Channel flow is a defining feature of fluvial systems, from which society derives the significant benefit of water supply.
Water delivery (timing of flow)	Fluvial geomorphology and catchment-scale geomorphological and hydrological processes play key roles in determining the timing of flow, including ameliorating flood impacts by attenuation and supplying baseflow during droughts.
Water quality	**Physical** Fluvial geomorphological processes determine water *velocity*, *turbulence*, *temperature*, *conductivity* and *clarity (suspended sediment)*, all of which influence other ecosystem processes, directly or indirectly contributing to various ecosystems services. **Chemical** Processes occurring in the fluvial environment contribute to maintaining *dissolved oxygen* as well as the *chemical character* and *odour* of river water. **Biological** Fluvial geomorphological processes involving the interaction of water and sediment with channel morphology generate a diversity of habitats supporting *microorganisms, plants*, *invertebrates*, *fish*, *wildlife* and their associated *genetic diversity,* all contributing to *ecosystem health* or *biotic integrity*.
Sediment	**Suspended sediment load**

characteristics	Fluvial geomorphological processes determine the *size fraction*, *amount* and *timing* of erosional and transport processes, influencing primary production in the water column and the re-distribution of sediment in the watercourse and floodplain. **Bed substrate** Fluvial geomorphological processes determine the *bed material size*, *amount, distribution* and *form* (bars and bedforms) determining the nature of benthic habitat, influencing the characteristics of water flowing over it.
Morphological characteristics	**Channel and floodplain morphology** Fluvial geomorphological processes determine the *channel gradient*, *dimensions*, *form, pattern* and associated *depositional* (e.g. point bar, floodplain) and *erosional (e.g. cut bank)* features: key attributes of the template of a river valley providing the physical basis for habitat and associated ecosystem services. **Bed stabilit**y Characteristics of the bed substrate, together with flow conditions and sediment load, determine bed stability. **Bank stability** Characteristics of the bank, together with flow conditions and sediment load, determine bank stability.

Table 2: Direct and indirect contributions of fluvial geomorphological processes to specific supporting ecosystem services (Bolund and Hunhammar, 1999; Thorp *et al*., 2010; Dufour *et al*., 2011; Gordon and Barron 2013; Hill *et al*., 2014)

Supporting services comprise processes essential for maintaining the integrity and functioning of ecosystems and their capacity to supply other more directly exploited services (Millennium Ecosystem Assessment, 2005).	
ECOSYSTEM SERVICE	**CONTRIBUTION BY FLUVIAL GEOMORPHOLOGICAL PROCESSES**
Hydrological cycling	*Indirect*: continuous circulation of water through exchanges between the geosphere, atmosphere and living organisms supports ecosystem functioning and integrity, and production of ecosystem services.
Rock cycling and soil formation	*Indirect*: fluvial geomorphology contributes to rock cycling and to soil formation and fertility, through accretion processes on floodplains and depositional structures in rivers. This provides a physical template for habitat including the diversity of substratum and corresponding interaction with flow conditions, the water column and surface, and the riparian zone. Soil in turn constitutes a growing medium upon which many provisioning and other services depend.
Sediment supply	*Indirect:* fluvial processes result in the delivery of sediment to river habitats, deltas and estuaries, supplying nutrients and habitat to support commercially important fisheries.
Habitat creation and maintenance	*Indirect*: geodiversity provides the physical template supporting a diversity of habitats and species. Fluvial geomorphological processes support and maintain the diversity and dynamism of these habitats and related

	ecosystem services, including driving ecological succession and consequent vegetative and topographical complexity.
Photosynthesis and primary production	*Indirect*: photosynthesis provides oxygen, and primary production supports plant growth and the functioning and integrity of other ecosystem services.
Biogeochemical cycling	*Indirect*: continuous circulation of important elements (e.g. carbon, nitrogen) and nutrients through exchanges between the geosphere, atmosphere and living organisms supports the functioning and integrity of other ecosystem services.
Building platform	Floodplains and river terraces provide a platform for buildings and infrastructure (e.g. bridges), providing economic benefits.
Waste disposal and water storage	Rivers have historically provided a conduit for waste disposal, and remain important for water supply and wastewater treatment. River valleys provide suitable sites for water storage and hydroelectric power systems, usually facilitated by dams. More locally, short-cycle recycling of water within a diversity of habitats maintains water resources in landscapes.

Table 3: Direct and indirect contributions of fluvial geomorphological processes to specific regulatory ecosystem services (Bolund and Hunhammar, 1999; Thorp *et al*., 2010; Dufour *et al*., 2011; Gordon and Barron 2013; Hill *et al*., 2014)

Regulatory services include those processes moderating climate, air and water quality, and other facets of the natural environment (Millennium Ecosystem Assessment, 2005).	
ECOSYSTEM SERVICE	**CONTRIBUTION BY FLUVIAL GEOMORPHOLOGICAL PROCESSES**
Water regulation	*Direct*: structure of the geomorphological system influences magnitude and timing of flows, and habitat complexity can help avert damage to ecosystems and human benefits (Jones, 2013).
Water quality regulation and waste treatment	*Direct*: the geomorphological system influences water quality (e.g. oxygenation over riffles), and the medium provides dilution, improvement of runoff quality via processes in the riparian zone (e.g. denitrification and sediment trapping). Water purification (N and P sequestration and denitrification) in headwater catchments of the USA was valued at $13,414 /ha/yr (Hill *et al*., 2014). *Direct*: catchment habitat diversity influences the service of water regulation through moderation and buffering of water flows (Ruhl and Salzman, 2007), buffering flood peaks and droughts.
Natural hazard regulation	*Direct*: protection of people and property from flood impacts through floodplain attenuation of peaks by providing storage and slowing flow, and hence greater resilience against extreme and unpredictable events.
Pollination, disease	*Indirect*: riparian vegetation, a secondary effect of

regulation and pest regulation	geomorphological diversity, provides habitat for pollinators and many host important pest predators. They can also attenuate disease-causing organisms, though may host some disease vectors.
Air quality and climate	*Indirect:* carbon sequestration by riparian vegetation makes an important contribution to climate regulation. Carbon sequestration in headwater catchments of the USA was valued at $278 /ha/yr (Hill *et al*., 2014). *Indirect*: riparian vegetation supported by valley and floodplain soils ameliorates locate climate, especially in cities (Bolund and Hunhammar, 1999). *Indirect*: topographic effects from gemorphological features and associated vegetation play a role in regulating air quality.
Erosion regulation	*Direct*: geomorphological structures and processes influence sediment erosion and accretion patterns, averting loss of habitat, preventing siltation of downstream infrastructure and maintaining important sediment feed processes, modified by the stabilisation effects of vegetation.

Table 4: Direct and indirect contributions of fluvial geomorphological processes to specific cultural ecosystem services (Bolund and Hunhammar, 1999; Thorp *et al*., 2010; Dufour *et al*., 2011; Gordon and Barron 2013; Hill *et al*., 2014)

Cultural services comprise the recreational, aesthetic and spiritual benefits that people derive from ecosystems (Millennium Ecosystem Assessment, 2005).	
ECOSYSTEM SERVICE	**CONTRIBUTION BY FLUVIAL GEOMORPHOLOGICAL PROCESSES**
Recreation and tourism	*Direct*: river systems support multiple recreation and tourism opportunities, some strongly linked to fluvial geomorphology (e.g. white-water rafting, kayaking). In a survey of these users in Colorado, USA, Loomis and McTernan (2013) found that willingness to pay and number of likely visits over the season depended strongly on river discharge (e.g. $55 per person per day and 1.63 trips at 300CFS vs. USD$97 and 14 trips at 1900CFS). Maximum marginal value in the area exceeded that for irrigation. In cities, rivers can be an accessible setting for recreation (Bolund and Hunhammar, 1999)
Spiritual and religious values and cultural meanings	*Direct*: river systems have featured strongly in folklore and legend throughout time. Many cultures ascribe spiritual or religious values to rivers, or specific locations or geomorphological characteristics (e.g. confluences, springs, waterfalls, pools)
Sense of place and aesthetic values	*Direct*: river systems are considered special and beautiful places; geomorphological features or processes often contribute to this sense of place (e.g. waterfalls, cascades)
Educational values	*Direct*: river systems provide an opportunity for formal and informal education, offering personal and life-long learning

	advantages and improved societal knowledge, skills and understanding.
Social relations	*Direct*: social groups can be organised around river systems (e.g. river restoration groups, hikers, youth groups, birdwatchers, anglers), providing opportunities for social interaction offering health and welfare benefits (to individuals and communities).
Artistic inspiration	*Direct*: river valleys, river scenery and waterscapes provide inspiration, featuring prominently in art, literature and music.
Cultural diversity, cultural heritage and geoheritage values	*Direct*: ecosystem diversity influences cultural diversity; the physical environment of rivers and associated natural features influences poetry, art and music, with corresponding health and welfare benefits to individuals. In cities, rivers can be an accessible focus for communities (Bolund and Hunhammar, 1999)
Knowledge systems/knowledge capital	*Direct*: society benefits from knowledge of fluvial geomorphology through applied engineering and river management. Records of past climatic and environmental changes (e.g. flood histories, heavy metal contamination) are archived in floodplain deposits (Gray, 2011).

Table 5: Direct and indirect contributions of fluvial geomorphological processes to specific provisioning ecosystem services (Bolund and Hunhammar, 1999; Thorp *et al*., 2010; Dufour *et al*., 2011; Gordon and Barron 2013; Hill *et al*., 2014)

Provisioning services comprise material and energy produced by ecosystems that are consumed by society (Millennium Ecosystem Assessment, 2005).	
ECOSYSTEM SERVICE	**CONTRIBUTION BY FLUVIAL GEOMORPHOLOGICAL PROCESSES**
Fresh water	*Direct*: water in rivers and streams enables extraction. Water supply in headwater catchments of the USA was valued at $245 /ha/yr (Hill *et al*., 2014). *Indirect*: a source supporting water-dependant habitats, biota and ecosystem processes.
Renewable energy	*Direct*: channel flow and hydraulic head enable hydropower development.
Mineral resources	*Direct*: extraction of building and industrial materials (e.g. sands, gravels and clays).
Food, fibre and fuel	*Indirect*: supply of biodiversity products generated in river and riparian habitats including floodplains (e.g. commercial or recreational fish, reeds, vegetables grown on floodplains). In many situations river and riparian ecosystems have higher productivity than surrounding areas (Dufour *et al*., 2011). Arthington *et al*. (2010, p.2) suggest the biochemical and fibres from wetland and riparian systems are "…critically important to human welfare and livelihoods in many parts of the world".
Genetic resources	
Biochemicals & medicines	
Transport	*Direct*: Water channels are directly exploited for transport, including by vessels and for floating logs and other goods.

	However, geomorphological processes also result in siltation, necessitating dredging.

Table 6: Indicators used to assess ecosystems services provided by a lowland floodplain (*after* Posthumus *et al*., 2010).

FUNCTION	**GOOD OR SERVICE**	**INDICATOR**	**UNIT**
Production	Agricultural production	**Gross output:** total agricultural production (arable and livestock)	£/ha/yr
	Financial return	**Net margin**: financial returns from different land-based options, estimates of fixed and variable costs. Net margins included payments under the Environmental Stewardship scheme and Common Agricultural Policy	£/ha/yr
	Employment	**Labour**: annual labour requirements for each land use type	man hours/ha/yr
	Soil quality	**Soil carbon stock**: estimated at equilibrium for each scenario	kg C/ha
Regulation	Floodwater storage	**Time-to-fill capacity**: ratio of storage volume of the floodplain to discharge in the river	Days
	Water quality	**Nutrient leaching**: estimates of negative impact of nutrients leaching from floodplains associated with agricultural production	kg NO_3/ha/yr

	Greenhouse gas balance	**Greenhouse gas emissions**: accounts for the release of carbon dioxide and methane	kg CO_2 equiv. ha/yr
Habitat	Habitat provision	**Habitat conservation value**: based on regional and national importance of habitat created	score
	Wildlife	**Species conservation value**: based on the value of habitats to species listed in the UK Biodiversity Action Plan	score
Carrier	Transport	**Risk exposure road infrastructure**: costs associated with transport disruption due to flooding	£/ha/yr
	Settlement	**Risk exposure residential properties**: costs associated with damage to residential properties	£/ha/yr
	Space for water	**Proportion of area annually inundated by fluvial flood**: area of the indicative floodplain/ total area of the floodplain x annual flood probability	proportion
Information	Recreation	**Potential recreation use**: based on density of public rights of way, cultural value of land uses, proximity of alternative similar sites, relative to	score

		population within 3km of the site	
	Landscape	**Landscape value**: based on consistency of alternative land use with the vision statement for designated Joint Character Areas (JCAs)	score

Table 7: Levels of ecosystem service associated with attributes for six functional process zones (FPZs) (*after* Thorp *et al*., 2010, merging their 'Natural ecosystem benefits' and 'Anthropogenic services' categories) (H=high, M=medium, L=low).

	Constricted	Meandering	Braided	Anastomosting	Leveed	Reservoir
Ecosystem Services						
Food and fibre production (excl. agricultural crops)	L	M	L	H	L	M
Water supply	MH	M	L	M	H	H
Recreation	LM	LM	L	H	L	H
Disturbance and natural hazard mitigation	L	M	L	H	H	H
Transportation	H	M	L	M	H	H
Primary and secondary productivity	L	M	M	H	L	H
Nutrient cycling and carbon sequestration	L	LM	LM	H	L	H
Water storage	L	LM	L	H	L	H
Sediment storage	L	M	M	H	L	H
Habitat for wildlife (indicated by biodiversity)	L	M	L	H	L	M
Hydrogeomorphic attributes						
Shoreline	L	LM	H	H	L	M

complexity ratio (shoreline length/downstream length)						
Relative number of channels	L	L	H	HM	L	L
Functional habitats within channels	L	LM	M	H	L	LM
Channel/island permanence	M	M	L	H	M	H
Floodplain size and connectivity with main channel	L	MH	M	H	L	L

Table 8: Lessons learned about the three principal challenges from case studies

Case studies	Challenge 1: understanding, collaboration and tools	Challenge 2: appropriate quantification and mapping	Challenge 3: demonstration
(i)_River rehabilitation and ecosystem services	Greater resilience, acceptability and net benefits arise from rehabilitation addressing multiple ecosystem services	Articulation of multiple benefits to stakeholder communities need not be quantitative, but needs to be representative of likely outcomes	Case studies need to be accessible and communicated to promote mainstreaming of good practice
(ii)_Floodplain management and ecosystem services	Effective management of floodplains can produce trade-offs and synergies between multiple ecosystem service outcomes, demonstrating the importance of stakeholder involvement	Metrics of ecosystem service outcomes are necessary to inform decision-making	Case studies of different ecosystem service outcomes resulting from alternative floodplain management can inform better decision-making
(iii)_Mapping	Mapping ecosystem	Spatial	Mapping of both

ecosystem services	services supply and demand can inform collaborative decision-making	representation of ecosystem service outcomes can lead to better-informed governance	conflicts and synergistic outcomes can be useful in supporting participatory decisions