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Incorporating catchment to reach scale processes into hydromorphological assessment in the UK

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Abstract

Hydromorphological pressures and the measures undertaken to address them are an important element of the delivery of the WFD within the UK. While assessment procedures currently employed gather useful morphological information for river reaches and their immediate margins and some process information, crucial information on key processes is missing and information gathered on the riparian zone and floodplain is limited. This paper presents a newly developed framework that enables existing data to be placed within a multi-scale, process-based context. The framework has great promise for diagnosing hydromorphological pressures, identifying where and how natural recovery is likely to take place, and where more interventionist restoration techniques may be needed. The ability to consider trajectories of river channel adjustments could help us understand how watercourses are still responding to historic changes, improve our confidence in applying restoration measures and the likely hydromorphological consequences of future climate changes.

Key words: Geomorphology, European Directive, River, River Basin Management, Fluvial

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Introduction

The EU Water Framework Directive (WFD 2000/60/EC) is the major driver for achieving sustainable management of the water environment within the UK and across Europe. The requirement to improve ecological status is partly based on the condition of hydromorphological quality elements. The degradation of hydromorphological conditions has been identified as the main reason for waterbodies failing the WFD (European Environment Agency, 2012). Assessment of the hydromorphological condition is key to understanding where changes are having an impact and where action may be taken to improve the quality elements.

Recently, Belletti et al. (2015) reviewed hydromorphological assessment methods. From a total of 121 methods used in 25 different countries, Belletti et al. (2015) identified four main assessment types (physical habitat, riparian habitat, morphological, hydrological regime). While those of the last type incorporate an assessment of river flows and their changes, the first three focus mainly on land and vegetation forms and so have the potential to provide more comprehensive hydromorphological assessments. Belletti et al. (2014) concluded that the main gap in most of these three types of form-based methods is insufficient consideration of physical processes indicative of flow and sediment connectivity and continuity, and of local (e.g. river bank or bed erosion) and more integrated (e.g. migration, enlargement, shrinkage) river channel adjustments.

Within the UK, no formal riparian survey and assessment method is currently applied, precluding thorough assessment of process-form interactions between the river channel and riparian environments. However, a variety of reach-scale physical habitat and morphological assessment methods are applied by the different responsible agencies. The Environment Agency for England and Natural Resources Wales have employed the River Habitat Survey (RHS, Raven et al., 1997), the Northern Ireland Environment Agency (NIEA) use the River Hydromorphology Assessment Technique (RHAT, NIEA 2014) and the Scottish Environment Protection Agency use the River Morphological Impact Assessment System (MImAS, UK Technical Advisory Group on the WFD, 2008).

Overall, the conclusions of Belletti et al. (2014) regarding the first three types of assessment method (riparian, physical habitat, morphological) in general, can also be considered true of the methods currently utilised in the UK at the river reach-scale, since they take little explicit account of processes and, although they give some attention to the river channel margins, are not true riparian habitat surveys. However, additional more process-oriented techniques are applied on a relatively ad-hoc basis and at varying spatial scales to identify information on sediment sources-sinks-budgets and river sensitivity as well as the range of features present (Maas and Brookes, 2009). These include the Stream Reconnaissance Handbook method (SRH, Thorne, 1998); Fluvial Audit (FA, Environment Agency, 1998); and Geomorphological Assessment (GA, Sear et al., 2008).

In summary, the current physical habitat and morphological surveys employed for the WFD in the UK gather useful morphological information for river reaches and their immediate margins, and some process information but crucial information on key processes is missing and information gathered on the riparian zone and floodplain is limited. Nevertheless, the problem is not so much one of missing observations but of not using existing information in the most effective and integrated way. One remedy to this problem is to embed current reach-scale survey data into a broader, multi-scale framework that incorporates information from areas beyond the river reach up to the entire river catchment or region, and organises it in a way that allows integrated, process-based interpretation.

This paper briefly describes an open-ended, flexible framework that has been developed within the EU FP7 funded REFORM project to aid the delivery of the WFD. The framework allows existing survey and other information relevant to catchment to reach scales, and from the past (typically up to 100 years) as well as the present, to be combined in a way that supports better understanding of processes, forms, and functions across space and time. The framework encourages not only integrated use of existing information but also an integrated way of thinking about river systems that can inform catchment and river management decision-making. Full details of the REFORM Framework are available in Gurnell et al. (2014, 2016), Rinaldi et al. (2016) and González del Tánago et al. (2016a). The aim of this paper is to briefly describe the framework in the context of its potential application to UK catchments and their river systems.

Space-time structure of the REFORM framework

The REFORM framework sets river reaches, the focus of most river management efforts, into a nested hierarchy of spatial units up to the catchment and region scales, so that segments of the river network are made up of one or more entire reaches, landscape units contain one or more entire segments, and catchments are comprised of one or more landscape units. Such spatial frameworks have been widely used internationally to underpin river assessment (see review by Gurnell et al., 2016) but the REFORM framework has been specifically developed to (a) provide a tool for use by river managers, (b) incorporate human pressures as well as natural processes and forms at all included spatial scales, (c) be flexible to the extent that users can incorporate their own data sets, methods and modelling tools, (d) and so maximize the potential for a process-based 'way of thinking' that is adapted to local circumstances to be widely adopted. Thus the framework can be used to assimilate the wide variety of river survey and other environmental data sets that are available within the UK.

The first stage in applying the framework is to delineate the spatial units. The units are defined and their delineation is briefly described in Figure 1. Although delineation approaches summarised in Figure 1 are based on interpreting natural breaks and transitions, spatial units can also conform to WFD catchment and water body boundaries.

The second stage is to gather information from existing surveys and other secondary sources in order to characterise spatial units that have been delineated and estimate indicators of key processes that cascade from catchment to reach scales and how these have changed over recent decades (Figure 2). Reaches are the key spatial units in the framework. Indicators for larger spatial units provide information on the sources and magnitude of fluvial processes arriving at individual reaches, whereas indicators for reaches and smaller (within-reach) spatial units provide information on the form and adjustments within river channel reaches and their margins (riparian zone and floodplain). Some examples of the numerous data sources that could support estimation of REFORM indicators at catchment to sub-reach scales for UK catchments are listed in Table 1.

The third stage is to consider the indicators in their spatial and temporal context in order to link causes and effects, which are often separated in space and lagged in time. Indicators such as those listed in Figure 2 represent processes of water and sediment production and delivery from catchment to reach; human pressures and interventions that may affect water and sediment production and longitudinal continuity through the river network; the abundance, structure and degree of human modification of riparian and aquatic vegetation within segments and reaches. At the reach and within-reach scales, indicators refer to flow energy, channel and floodplain dimensions and types, the assemblage of geomorphic units that is present, and the degree to which there are constraints on the lateral continuity of inundation, erosion and deposition of sediment and large wood. Multi-scale considerations of these indicators help to build a space-time understanding of how river reaches function and their adjustments to changes in processes. A particularly useful outcome is understanding how sensitive the river network and individual reaches are to changes in controlling processes and the specific likely responses that may occur in relation different types of process change and the time required for such responses to become apparent.

The fourth and final stage is to use the understanding developed through stages one to three to forecast possible outcomes of future scenarios of change. Such changes could relate, for example, to catchment to reach scale process responses to climate or land cover / management changes or reach scale adjustments to local management or restoration interventions.

The four stages of application of the REFORM framework provide a variety of insights into the morphology and function of river reaches and their governing processes, which are highly relevant to the assessment, planning and design of interventions, routine management and restoration of rivers.

An example of applying the framework to a UK groundwater-dominated catchment (River Frome, Dorset) has been published (Grabowski and Gurnell, 2016). The river was delineated into 3 landscape units based on elevation, geology and land cover/use, 6 segments based on valley setting and major tributary confluences and 17 reaches based on planform and longitudinal discontinuity. The application demonstrated how the framework can be applied to understand the pressure, particularly the morphological impacts, of fine sediment a commonly attributed cause of failure to achieve good ecological status within England (Environment Agency, 2015). Once the pressures have been evaluated the ecological response to these pressures can be assessed.

River Types

Reaches are the key spatial units within the REFORM framework. Furthermore, the 'river type' of each reach is central to implementation of the framework, and so we explain the REFORM river typology briefly here.

Each reach is allocated to a river type according to three simple criteria: valley confinement (confined, partly-confined, unconfined), planform (straight-sinuous, meandering, wandering, braided, high-energy anabranching, low-energy anabranching) and bed material size. There are 22 possible river types (Figure 3) and also a type '0', which is defined as artificial because of the presence of an artificial bed. Of the survey methods currently utilised by the UK regulatory agencies both RHAT and MimAS incorporate river types based upon the Montgomery and Buffington typology for mountain streams in North America (Montgomery and Buffington 1998). The REFORM framework extends this typology to incorporate more detailed river types found beyond mountain environments. This includes types 19 and 22, which are no longer found in a naturally-functioning state in the UK, although impacted rivers of this type do exist. Indeed many chalk rivers (excluded from MimAS) would be assigned to type 19, and naturally-functioning examples of both 19 and 22 were probably found in areas of very low gradient in the UK prior to extensive land drainage for agriculture and channel simplification for navigation and flood defence. A comparison of the river types employed by the REFORM framework, MimAS and RHAT is presented in Table 2.

It is also important to stress, that the REFORM types are based on simple criteria and aim (a) to ensure that any reach can easily be allocated to a type and, where bed material information is available (RHS data provide wide UK coverage), river type can be quickly estimated from existing map and image layers in a GIS, (b) to provide a simple and robust basis for identifying changes in type through time, and, most importantly, (c) to underpin assessment of observed / estimated forms and processes in the context of those that would be expected if the reach were functioning in a natural manner for its type.

The river typology is complemented by a floodplain typology, based on that proposed by Nanson and Croke (1992) (see Rinaldi et al., 2016 for further details), since floodplain types and their geomorphic features reflect the river types that build them.

The REFORM approach shows great practical advantages when combined with the current approach to typology applied within the UK. The UK adopted System A of the WFD for deriving a basic typology for natural rivers based on altitude, catchment size and dominant geology, with additional river types created for small catchments and one catchment in Cheshire where the dominant geology is rock salt (UK Technical Advisory Group on the WFD, 2003). System A is essentially a catchment or subcatchment typology, whereas the REFORM river and floodplain typologies apply to reaches of rivers within catchments.. The addition of the these factors together with consideration of trajectories of change within the REFORM approach matches the catchment based approach to improving the water environment promoted by the Department for Environment, Food and Rural Affairs (Department for food and rural affairs, 2013) and has been adopted in England within the second round of the River basin planning process. The addition of the REFORM river and floodplain typologies and framework ensures a stronger emphasis on process-form linkages across scales and within catchments..

Investigating the hydromorphological form and function of river reaches

Returning to the four stages of analysis described above following delineation (stage one), reaches are assigned to a river type as part of characterisation and estimation of indicators (stage two).

During stage three, the hydromorphological function, alteration / artificiality, and adjustment of each river reach and its riparian corridor function / artificiality are assessed at the reach scale under present and past conditions using reach-scale indicators. These reach-scale assessments are then interpreted in the light of past and present process indicators from catchment to reach scales to understand how processes at all scales cascade to river reaches to affect their form and function. These assessments are all made in the context of the specific river and floodplain types that are present and are fundamental to:

a. Identifying the most ‘naturally’ functioning reaches and river types that can provide local references within each landscape unit for restoration / rehabilitation design

b. Recognising the causes of restricted hydromorphological function
c. Estimating the sensitivity of individual reaches of different type to catchment – landscape unit – segment – reach-scale changes
d. Constructing trajectories of past to present adjustments within reaches and their causes, including changes in river type

By building understanding of space-time adjustments and reach sensitivity to changes within stage three, the impact of potential future scenarios on reaches of different type can be considered in stage four. In this way, the potential for inappropriate management, rehabilitation and restoration designs is minimised and a wide range of river types are considered, representative of the continuum of types that may exist in nature.

Conclusions

As stated in the introduction to this paper, full details of the framework are available elsewhere and so we have provided a brief overview relevant to a UK context. We have emphasised UK information sources to support application of the REFORM framework and suggested where it could be of benefit within the UK. In addition to the example of the River Frome (Grabowski and Gurnell, 2016), applications to a Spanish and Italian catchment illustrate how higher energy river systems with major human interventions have been successfully investigated (Belletti et al., 2016; González del Tánago et al., 2016b).

The REFORM framework helps to build knowledge of local hydromorphological functioning of reaches and also of those river types that show the most natural functioning and thus can guide restoration-rehabilitation of other, more impacted reaches. In this way appropriate local ‘reference’ conditions are identified for different river types. The framework is deliberately flexible, avoiding a heavily prescriptive approach but allowing local data sets and knowledge to be incorporated and local prescriptive applications to be devised. It can absorb and integrate information from all hydromorphological assessment methods in current use within the UK. Furthermore, the potential to incorporate both simple and sophisticated components into framework applications is enormous, as is the potential to use the framework adaptively as understanding of the functioning of local catchments and river systems increases. A major step change within the approach to assessing river types is consideration of trajectories of river channel change. This could provide a great advantage when considering the implications of catchment-scale land use changes for the hydromorphology of the river network as well as potential responses to climate change scenarios.

The policy framework to encourage the wider adoption of an integrated Catchment Based Approach to improving the quality of our water environment, which is promoted by Defra (Department for food and rural affairs, 2013), relies on the consideration of processes within a catchment context. We suggest that the REFORM framework could provide the basis for understanding the physical processes and incorporating this understanding within catchment management. We would encourage managers to apply this approach and share their results so that we can build on our understanding and ensure that we improve our confidence in applying restoration measures.

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Figure 1: Description and delineation criteria for spatial units within the REFORM framework

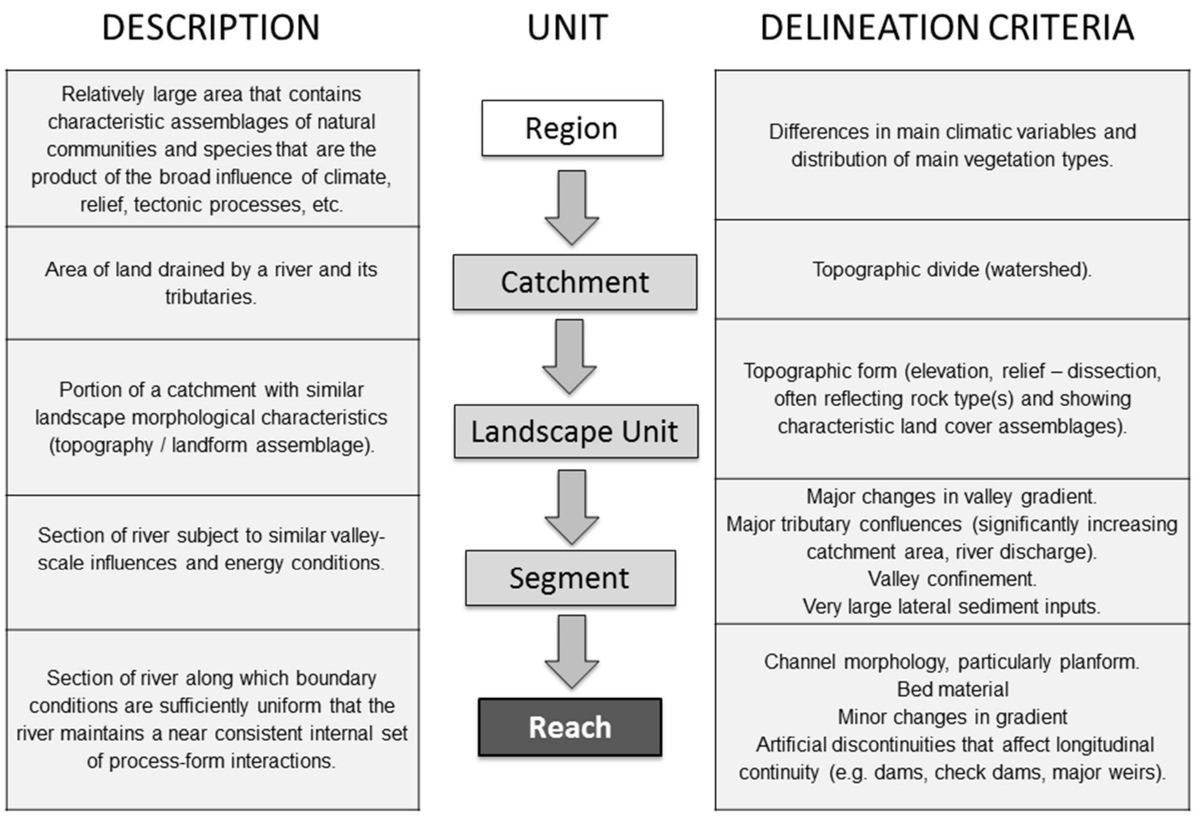

Figure 2: Examples of indicators of key processes at different spatial scales

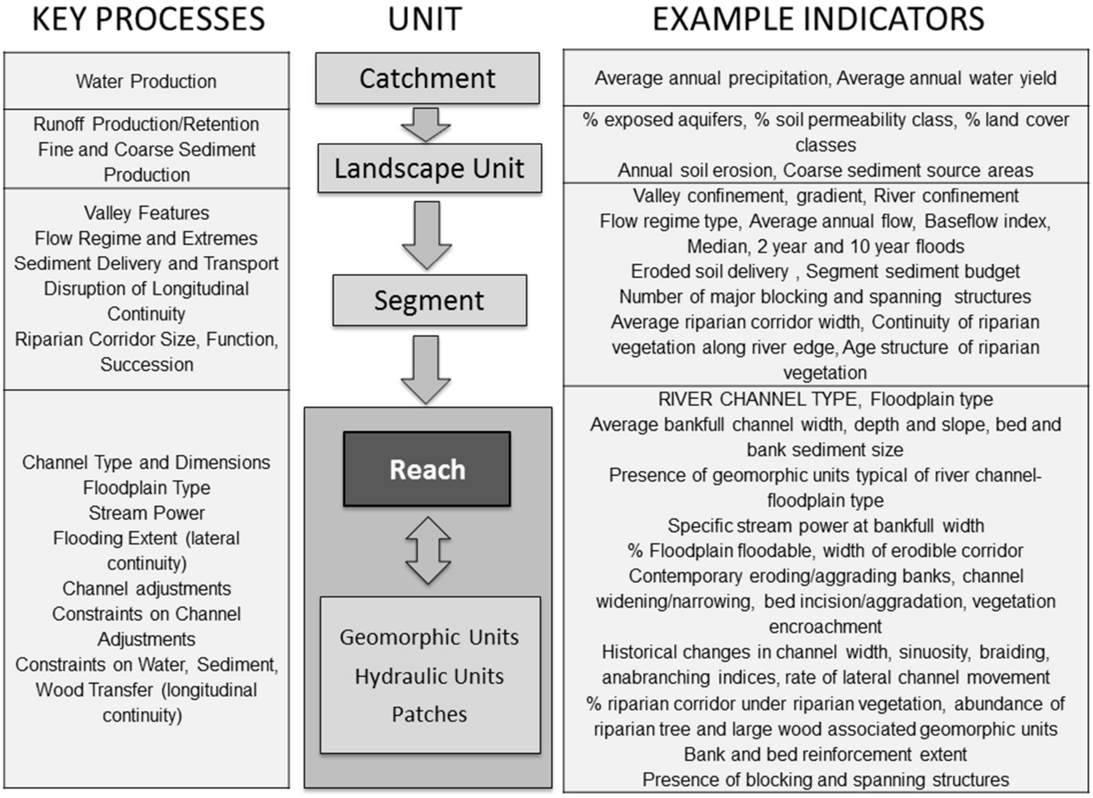

Figure 3: Sketches of the 22 REFORM river types, indicating their association with level of confinement, planform and bed material calibre.

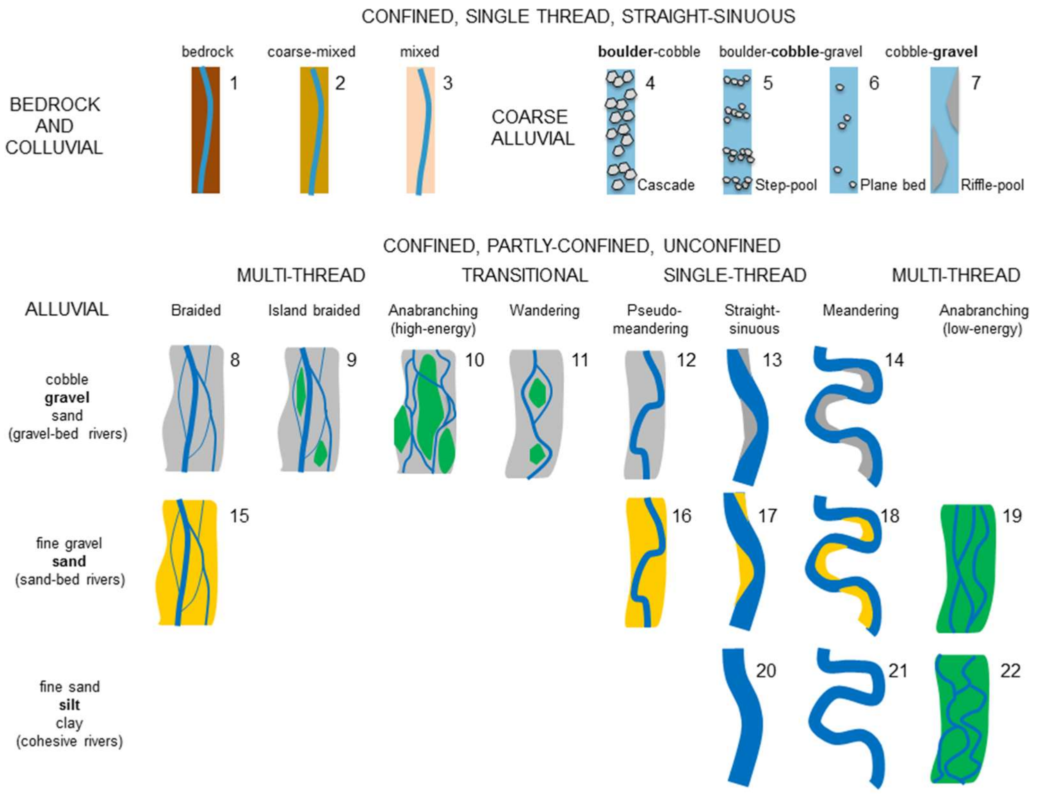

Table 1 A comparison of river types between REFORM, MImAS and RHAT.

<table>
<tr><th>REFORM</th><th>MImAS</th><th>RHAT</th></tr>
<tr><td>1</td><td rowspan="2">A - Bedrock, cascade</td><td>Bedrock</td></tr>
<tr><td>4</td><td rowspan="2">Cascade, step-pool</td></tr>
<tr><td>5, 6</td><td>B – step-pool, plane bed</td></tr>
<tr><td>7-13, 15-17</td><td>C – plane-riffle, braided, wandering</td><td>Pool riffle glide</td></tr>
<tr><td>14, 18</td><td>D – active meandering</td><td rowspan="3">Lowland meandering</td></tr>
<tr><td></td><td>(E – groundwater dominated – not included in MImAS tool)</td></tr>
<tr><td>(18), 21</td><td>F – passive meandering</td></tr>
<tr><td>2, 3, 19, 20, 22</td><td colspan="2">Not included in MImAS or RHAT</td></tr>
</table>

Table 2: Example information sources to support application of the REFORM framework

Information type	Relevance (Delineation / Indicator(s))	Information *geographic extent*, source, web link
Biogeographic (sub)region	Region delineation	*EU* www.globalbioclimatics.org http://www.eea.europa.eu/data-and-maps/figures/biogeographical-regions-europe-2001
Digital Elevation/Terrain Model	C and LU: delineation and relief LU and S: sediment erosion, delivery estimation S: valley-floodplain width, valley-river confinement and gradient R: river slope	*England and Wales* Environment Agency Lidar Archive, 0.25, 0.5, 1 and 2 m resolution 'composite' DTM data and time-stamped tiles at 0.25 m resolution. https://data.gov.uk/publisher/environment-agency *Great Britain* OS Terrain 5 / 50, 5 m grid based on OS topographic data. https://www.ordnancesurvey.co.uk/ *EU* - EU-DEM 25 m grid based on ASTER GDEM
Land cover	LU: delineation and estimation of runoff, fine and coarse sediment production	*UK* Countryside Survey Land Cover Data / Maps for 1990, 2000, 2007 at 1km resolution (1990, 2000) and based on land parcels (2007). http://www.countrysidesurvey.org.uk/ *Great Britain* - Agricultural statistics, including county summaries from 1993, parish summaries from 1886. http://www.nationalarchives.gov.uk/ and http://nrscotland.gov.uk/research *EU* - Corine land cover data for 1990, 2000, 2006 at 100 m resolution. http://www.eea.europa.eu/data-and-maps
Soil and Rock Types and their Hydrological and Sediment Production Characteristics	LU: delineation and estimation of runoff, fine and coarse sediment production	*UK* Hydrology of Soil Types (HOST) 1km gridded data. http://www.ceh.ac.uk/services/hydrology-soil-types-1km-grid *Great Britain* surface geology. DigimapGB at 1:10000, 1:25000, 1: 50000, 1:625000 scales; parent material / superficial deposit type, thickness, permeability, water table depth at 1:50000 scale. http://www.bgs.ac.uk/products/home.html *EU* surface geology. http://www.onegeology.org / aquifers and soil properties (type, erodibility, topsoil - organic carbon, pH, bulk density, texture, water content at field capacity, soil water regime class, soil erosion - PESERA). http://eusoils.jrc.ec.europa.eu/library/Data/EFSA/ landslide susceptibility. http://eusoils.jrc.ec.europa.eu/library/themes/Land Slides/index.html#ELSUS Chalk Rivers https://data.gov.uk/dataset/chalk-rivers1

Information type	Relevance (Delineation / Indicator(s))	Information *geographic extent*, source, web link
Land Form and Vegetation Structure	S and R: river channel and floodplain width, planform, microtopography and geomorphic features, Riparian corridor dimensions, Riparian vegetation height-density.	*England and Wales* Environment Agency Lidar Archive, 0.25, 0.5, 1 and 2 m resolution 'composite' Digital Surface Model data and time-stamped tiles at 0.25 m resolution. https://data.gov.uk/publisher/environment-agency Riparian Shade Explorer http://theriverstrust.maps.arcgis.com/apps/MapTools/index.html?appid=3b87d2c8795b49b7bcf841db01e4f5d4 Flood Maps http://www.geostore.com/environment-agency/WebStore?xml=environment-agency/xml/ogcDataDownload.xml
River Network	S and R: delineation and river planform.	*Great Britain* OS Open Rivers (generalised water network) and OS MasterMap Water Network (detailed water network with flow direction, gradient, length and width). https://www.ordnancesurvey.co.uk/ https://data.gov.uk/dataset/os-open-rivers *EU* Ecrins Inferred channel network from DEM, catchment boundaries, lakes. http://www.eea.europa.eu/data-and-maps/data/european-catchments-and-rivers-network
Rainfall	C: rainfall component of water budget	*UK* CEH-GEAR daily and monthly, 1 km gridded rainfall data from 1890. https://eip.ceh.ac.uk/rainfall
Runoff	C: runoff component of water budget S: flow regime and extremes R: stream power	*UK* National River Flow Archive, daily, monthly, flood peak data for 1400 gauging stations. http://nrfa.ceh.ac.uk/ *EU* European Water Archive, daily, monthly flow data for 3800 gauging stations. http://www.bafg.de/GRDC/EN/04_spcldtbss/42_EWA/ewa.html
Sediment dynamics	S: sediment sources, transport, budget	*UK* Catchment baseline surveys, fluvial audits, river reconnaisance surveys etc. Obtained from various sources including Open data https://data.gov.uk/data/search Large scale (1:10560, 1:10000, 1:2500) historical Ordnance Survey maps, The National Archives http://www.nationalarchives.gov.uk/help-with-your-research/research-guides/ordnance-survey/ The British Library http://www.bl.uk/subjects/maps aerial imagery http://www.britainfromabove.org.uk/ https://historicengland.org.uk/images-books/aerial-photos/ *EU* aerial imagery (various sources, e.g. https://www.google.co.uk/)

Information type	**Relevance (Delineation / Indicator(s))**	**Information *geographic extent*, source, web link**
River channel dimensions	R: delineation and channel width, planform, slope	*UK* Bathymetic surveys - various sources including Open data https://data.gov.uk/data/search *Great Britain* OS MasterMap Water Network (detailed water network with flow direction, gradient, length and width). https://www.ordnancesurvey.co.uk / historical large scale (1:10560, 1:10000, 1:2500) Ordnance Survey Maps, The National Archives http://www.nationalarchives.gov.uk/help-with-your-research/research-guides/ordnance-survey The British Library http://www.bl.uk/subjects/maps aerial imagery http://www.britainfromabove.org.uk/ https://historicengland.org.uk/images-books/aerial-photos/ *EU* aerial imagery (various sources, e.g. https://www.google.co.uk/)
River channel sediments and features	R: delineation and bed material size, geomorphic features, vegetation features	*UK* Catchment baseline surveys, fluvial audits, river reconnaisance surveys etc. Obtained from various sources including Open data https://data.gov.uk/data/search *Great Britain* River Habitat Survey, https://data.gov.uk/dataset/river-habitat-survey-survey-details-and-summary-results1 http://www.riverhabitatsurvey.org/ Urban River Survey, http://urbanriversurvey.org/
River channel interventions	R: delineation and blocking-spanning structures, reinforcement	*Great Britain* River Habitat Survey, http://www.riverhabitatsurvey.org / Urban River Survey, http://urbanriversurvey.org / Environment Agency Flood defence structures https://data.gov.uk/dataset/flood-asset-register-points Environment Agency Canal and River Trust structures http://www.geostore.com/environment-agency/WebStore?xml=environment-agency/xml/ogcDataDownload.xml Catchment data explorer http://environment.data.gov.uk/catchment-planning/