Characterizing geomorphological change to support sustainable river restoration and management

Robert C. Grabowski,[1,2*] Nicola Surian[3] and Angela M. Gurnell[1]

The hydrology and geomorphology of most rivers has been fundamentally altered through a long history of human interventions including modification of river channels, floodplains, and wider changes in the landscape that affect water and sediment delivery to the river. Resultant alterations in fluvial forms and processes have negatively impacted river ecology via the loss of physical habitat, disruption to the longitudinal continuity of the river, and lateral disconnection between aquatic, wetland, and terrestrial ecosystems. Through a characterization of geomorphological change, it is possible to peel back the layers of time to investigate how and why a river has changed. Process rates can be assessed, the historical condition of rivers can be determined, the trajectories of past changes can be reconstructed, and the role of specific human interventions in these geomorphological changes can be assessed. To achieve this, hydrological, geomorphological, and riparian vegetation characteristics are investigated within a hierarchy of spatial scales using a range of data sources. A temporal analysis of fluvial geomorphology supports process-based management that targets underlying problems. In this way, effective, sustainable management and restoration solutions can be developed that recognize the underlying drivers of geomorphological change, the constraints imposed on current fluvial processes, and the possible evolutionary trajectories and timelines of change under different future management scenarios. Catchment/river basin planning, natural flood risk management, the identification and appraisal of pressures, and the assessment of restoration needs and objectives would all benefit from a thorough temporal analysis of fluvial geomorphology. © 2014 Wiley Periodicals, Inc.

INTRODUCTION

In many countries, regulatory objectives now require rivers to be managed in a holistic manner that balances human use and modification with the preservation and improvement of aquatic and riparian

*Correspondence to: r.c.grabowski@gmail.com

[1]The School of Geography, Queen Mary, University of London, London, UK

[2]Cranfield Water Science Institute, Cranfield University, Cranfield, UK

[3]Department of Geosciences, University of Padova, Padova, Italy

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ecosystems. Implicit in these objectives is the acknowledgment that the hydrology and geomorphology of rivers has been fundamentally altered through a long history of direct intervention to river form and water flow as well as wider changes in the landscape that impact water and sediment delivery to the river.[1,2] These alterations in fluvial forms and processes have negatively impacted river ecology through the loss of physical habitat, disruption to the longitudinal continuity of the river, and a disconnection between aquatic, wetland, and terrestrial ecosystems.[3,4] However, the numerous demands on rivers (e.g., freshwater supply, navigation, flood protection) and dwindling financial resources to maintain current infrastructure and maintenance operations have placed an emphasis

on the identification of effective management and restoration approaches that yield sustainable solutions.[5,6] Working with the river's natural hydrological and geomorphological processes, as opposed to imposing form and behavior, offers the best opportunity to do so.[4,7,8] A process-based management approach requires an understanding of not only the current geomorphological condition a river, but also how this has changed over time. While from an ecological perspective, river restoration and broader management should target the measures and river reaches that would provide the greatest and most cost-effective impact in terms of reinstating and sustaining natural processes, it is critical that direct and indirect human interventions are factored into such an approach. Furthermore, although this paper emphasizes the understanding of processes and their direct relevance to restoration, this is only a small part of the many factors that are incorporated into river restoration in practice. Thus good science can contribute to the design of effective and sustainable restoration and management schemes, but the location(s), detailed design, and financing of such schemes are often more dependent upon a host of human-related issues that are beyond the scope of this review.[9]

Rivers change over time. This is an inherent property of rivers and floodplains, and is driven by forces operating within the channel (i.e., intrinsic) and as a result of changes in the wider catchment (i.e., extrinsic). Temporal changes in fluvial geomorphology can be expressed in a river in many different ways: the spatial location of the channel (e.g., lateral migration and avulsions); riverbed and floodplain levels (e.g., channel incision and floodplain sedimentation); channel planform and dimensions; bed sediment characteristics; and the frequency and diversity of geomorphic units in the channel and floodplain. Some of these changes may be natural for the river type, while others are induced by changes that have occurred elsewhere in the catchment. By recognizing that rivers are dynamic, a temporal analysis of fluvial geomorphology can support river management and restoration by providing information on:

- Rates of geomorphological, hydrological, and ecological processes (e.g., water flow, sediment transport, and riparian and aquatic plant growth and succession),
- The previous condition of the catchment, floodplain, and channel,
- Rates and trajectories of past change in channel and floodplain characteristics,

- Identification of human pressures and how they have changed over time,
- Channel response to past natural disturbances and human pressure.

While there is a growing recognition of the role of process-based management and restoration of rivers (e.g., the concept of 'Making space for water' promoted by the Department for Environment Food and Rural Affairs, in the UK), the identification, planning, and implementation of individual measures is often the best outcome of the complex interaction between various legal frameworks, regulatory drivers, policy initiatives, and stakeholder engagement which is compounded by the opportunistic nature of restoration projects (i.e., a willing landowner). Frequently, the result is piecemeal management that treats the symptoms of alterations to geomorphological processes rather than the causes, with the consequence that measures may not meet their intended objectives. The outcomes of a thorough temporal analysis provide managers with the information needed to develop a holistic understanding of their rivers and floodplains. It allows them to identify the nature, magnitude, and underlying causes of geomorphological change in a reach, the human constraints imposed on future restoration and management, and the possible evolutionary trajectories and timelines of change under different future management scenarios. This information can be used to develop effective and sustainable solutions with process-based objectives, regardless of whether they are integrated catchment-scale measures to tackle multiple pressures and improve ecological status, or reach-scale projects to improve physical stream habitat or local amenity.

The aim of this review is to provide guidelines and suggestions for the temporal analysis of geomorphological change in rivers which can inform process-based river management and restoration. The article is structured around a spatial hierarchical framework that nests the reach and its distinctive geomorphic forms and processes into a wider spatial context. A brief outline of the spatial scales is given, followed by an introduction to the types of approaches used in a temporal analysis and the timescales over which they are relevant. Then at each spatial scale, characteristics are identified that control critical fluvial processes or are indicative of channel adjustment, alteration, or artificiality. Recommendations are provided on the approaches for gaining information on each characteristic, the range of data that can be collected using those approaches, suitable analytical techniques and methods to assess data accuracy. Finally, the role of a temporal analysis of geomorphology in

the development of sustainable river restoration and management strategies is discussed.

SPATIAL AND TEMPORAL SCALES OF ANALYSIS

The geomorphological character of river reaches depends not only upon interventions and processes within the reach but also within the upstream (and sometimes the downstream) catchment. In addition, the character of river reaches responds in a delayed way to processes and interventions within the catchment. As a result, understanding geomorphology at the reach scale requires an understanding of current and past processes and interventions at larger spatial scales. Without such a multiscale understanding, management strategies are not fully informed and may not provide sustainable solutions.

Spatial hierarchical frameworks have been proposed in many forms in the literature, each developed with a particular application or set of applications in mind.[10–17] Addition of a formal temporal analysis to such frameworks is rare, although Ref 15 provides an excellent description of how this may be achieved. Nevertheless, many researchers acknowledge space and timescales over which processes may be influential and forms may persist[8,10,13,16]; while others consider scenarios of process dynamics and change.[11,12] This article complements these existing frameworks by providing guidance on the types of characteristics that should be investigated, the various data sources that can be assembled to investigate each characteristic, and data analysis techniques that can be used to support a scientifically rigorous interpretation of temporal change.

Spatial Scales of Analysis

For the present application, a hierarchy composed of four levels of spatial units is used, which is based on and coherent with earlier delineations.[10,11,15] Hydrological, geomorphological, and riparian vegetation properties are investigated within this hierarchy to develop a comprehensive picture of geomorphological process–form interactions and their changes over time (Figure 1; Table 1).

The *catchment* is an area of land that is drained by a river and its tributaries, and, for the purposes of this approach, can be delineated based on the topographic divide (watershed).

Landscape units, i.e., physiographic region/province, are portions of the catchment with similar geomorphological characteristics. The catchment is divided into landscape units that are broadly
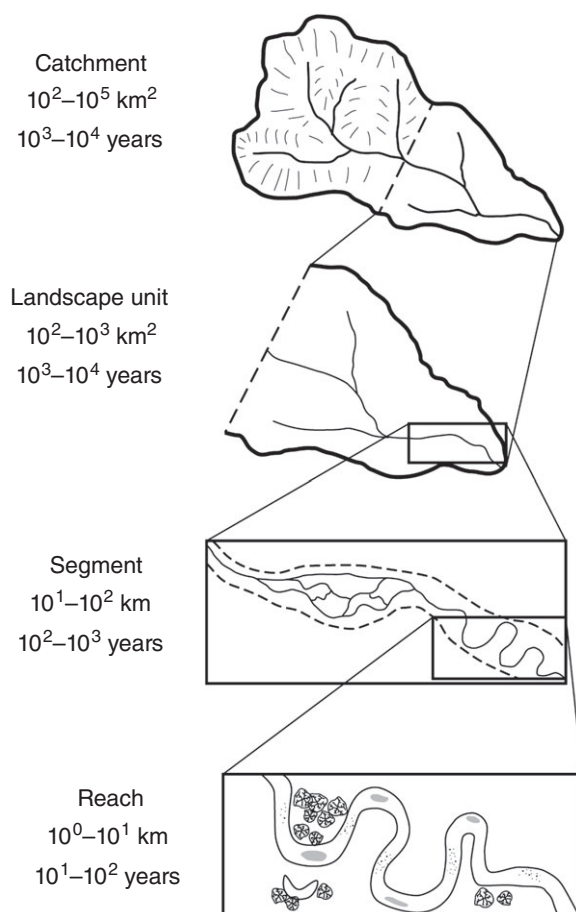

FIGURE 1 | Hierarchy of spatial scales for the assessment of river geomorphology with indicative spatial and time scales.

TABLE 1 | Temporal Change Is Investigated at Different Spatial Scales

Spatial Scale	Characteristics
Catchment	Land cover/land use (LCLU)
	Land topography
Landscape unit	LCLU and sediment production
	Land topography and sediment production
	Rainfall and groundwater
Segment	Valley setting
	Channel gradient
	River flows and levels
	Sediment delivery
	Riparian corridor and wood production
Reach	Channel planform, migration, and features
	Channel geometry
	Sediment transport
	Riparian vegetation, aquatic vegetation, wood

consistent in terms of their topography, geology, and land cover, as these factors determine the hydrological responsiveness of a catchment and the sources and delivery pathways of sediment to the river system.

River segments are sections of the river network that are subjected to similar valley-scale influences and flow energy conditions. Delineation is based on major changes in valley gradient, major tributary confluences, and valley confinement.

Geomorphologically speaking, a *reach* is a section of river along which boundary conditions are sufficiently uniform that the river maintains a near consistent set of process–form interactions, resulting in characteristic planform patterns and landforms in the channel and floodplain, such as meanders, gravel bars, and oxbow lakes.

The reach is arguably the most important scale. It is the key spatial scale at which the mosaic of features found within river channels and floodplains (1) responds to the cascade of influences from larger spatial scales and (2) is influenced by interactions and feedbacks between geomorphic and hydraulic units and smaller elements such as plants, large wood, and sediment particles within the reach. The reach is also the scale at which people view and interact with a river, and the scale at which most management and restoration work is directed.

Approaches and Timescales of Analysis

A diverse array of techniques can be applied to investigate temporal changes in geomorphological forms and processes from the catchment down to the reach scale. These techniques can be broadly categorized according to the disciplines within which they have been developed, the data sources they utilize, and the temporal scale at which they can be applied (Table 2; Figure 2). For the present review, techniques are divided into four major approaches: field survey, remote sensing, historical, and palaeo approaches. Table 2 lists the methods and data sources included within each approach, the timescales over which they are typically applied, and their strengths and weakness for the characterization of geomorphological change.

The choice of approach for an analysis of temporal change is dependent on the data sources that are available for an area, the history of pressures in the catchment, and the responsiveness of the river to pressures. Some data sources are preferred, typically those that are scientifically derived, unbiased and are supported by metadata detailing methods and uncertainties/errors. However alternative data sources can be used when and where the preferred data are

unavailable, but this may impact on the level of detail or confidence of the resulting interpretation. A river situated in a region with a long history of human modifications may require a longer timescale of analysis if causal linkages are to be identified between pressures and channel change. Likewise, a river that responds slowly to external forces (e.g., a lowland, low energy river with cohesive banks) may require a longer timescale of analysis to fully capture the trajectory of change that is occurring.

Accuracy, error, and uncertainty are discussed in more detail in a later section, but it is important to bear in mind that the reliability of data to faithfully represent geomorphological forms, processes, and events varies considerably within and between data sources. All data sources should be checked to determine the original purpose of the data, the person or authority that recorded the data, when it was recorded and subsequently published, the methods or instruments used, and reported levels of accuracy (spatial, temporal, attribute) to determine its suitability for a particular analysis.

Integrating Data from Different Sources and Scales

One of the main challenges of a temporal analysis is to integrate data from a wide range of sources with varying levels of reliability in order to detect genuine changes in the catchment, floodplain, and river channel. This is where a geographical information system (GIS) becomes particularly useful. Once the datasets are correctly loaded into a GIS, they can be queried and analyzed using a veritable toolbox of techniques.

A chronology to visualize the changes that have occurred in the catchment, riparian corridor, and channel over time provides a useful way of synthesizing changes and their potential causes[18,19] (Figure 3). The chronology pulls together information on the characteristics that influence geomorphological processes and those that respond to changes in those processes. This allows changes in characteristics to be tracked over time (e.g., land cover, riparian vegetation, human interventions, river flow regime including major flood or drought events, channel planform pattern, channel width, etc.) and also allows the causal linkages between them to be explored.

CHARACTERISTICS INVESTIGATED AT EACH SPATIAL SCALE

This section outlines what characteristics should be examined at each spatial scale, which approaches and

TABLE 2 | Four Approaches to Investigate Temporal Change in Fluvial Geomorphology

Approach (*Timescale*)	Methods/Data Sources	Strengths	Weaknesses
Field survey (*n/a*)	River reconnaissance Morphological quality index (MQI) River styles framework	Quick and relatively inexpensive to conduct Detailed information on current channel/floodplain forms and processes Essential for reach scale analysis if data are unavailable from other approaches	Only applicable at the reach scale Can only indicate possible change Cannot estimate rates of change Requires an experienced geomorphologist
Remote sensing (*Decades*)	Platforms: satellite, airplane, remotely operated vehicles (kites, drones) Data: photography, multi/hyperspectral, altimetry (radar, light detection and ranging—LiDAR, terrestrial laser scanning, TLS)	Large variety of data types that are suitable for most characteristics at all spatial scales Aerial photography archives extend back up to 100 years Satellite data extend back up to 30 years, and have high temporal frequency	Most freely available multispectral satellite data have low spatial resolution, so only suitable for large spatial scales or for large, wide rivers at the reach scale High resolution photography and multispectral data good for segment and reach scale, but are expensive to purchase/commission. Data processing and interpretation requires specialist knowledge
Historical (*Centuries*)	Maps Land/tax surveys Agricultural censuses River topographic surveys Monitoring station records Documentary evidence (diaries, deeds, estate records, etc) Photography, paintings, etc.	Historical maps can extend the timescale of analysis to centuries, and be used to study many characteristics Topographic surveys and gauging station records are often the only data sources for bed level changes. Documentary evidence can corroborate evidence from other data sources	Information is captured and interpreted through the 'lens' of the observer Availability and reliability of sources is highly variable, and both generally decrease as the analysis is extended further back in time Scale and original purpose of a map limits its application
Palaeo (*Millennia*)	Sedimentology Stratigraphy Dating: radiocarbon, OSL, tree rings	Insight into the underlying processes Provides accurate dating. Well constrained layers can be dated to decadal or even annual resolution	Requires specialist knowledge Dating using OSL and radiocarbon is expensive

data sources are recommended to investigate them, and how they can be analyzed and interpreted to quantify temporal change. While we identify preferred approaches and data sources, we recognize that these may not be available for every location or time period being investigated. Therefore, a range of alternative data sources is presented for all characteristics to maximize the likelihood of finding information to support the characterization. Finally, some discussion of the limitations of data sources is presented, but readers are referred to Table 2 for a general overview

of the timescales of analysis, strengths, and weakness of different approaches.

Catchment/Landscape Unit Scale

The geomorphological characteristics investigated at the catchment and landscape unit scales relate to the underlying drivers of river change: water and sediment. This section explores temporal variations in land cover/land use (LCLU), land topography, and precipitation and groundwater. Some important
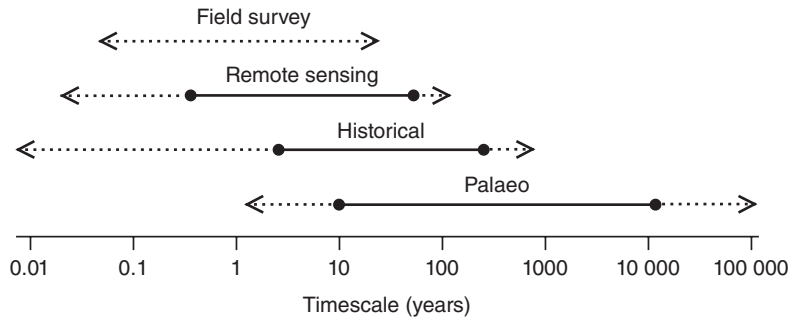
FIGURE 2 | Temporal scales over which different approaches may yield useful information (solid lines are the core temporal scales; dashed lines illustrate the potential range of temporal scales).
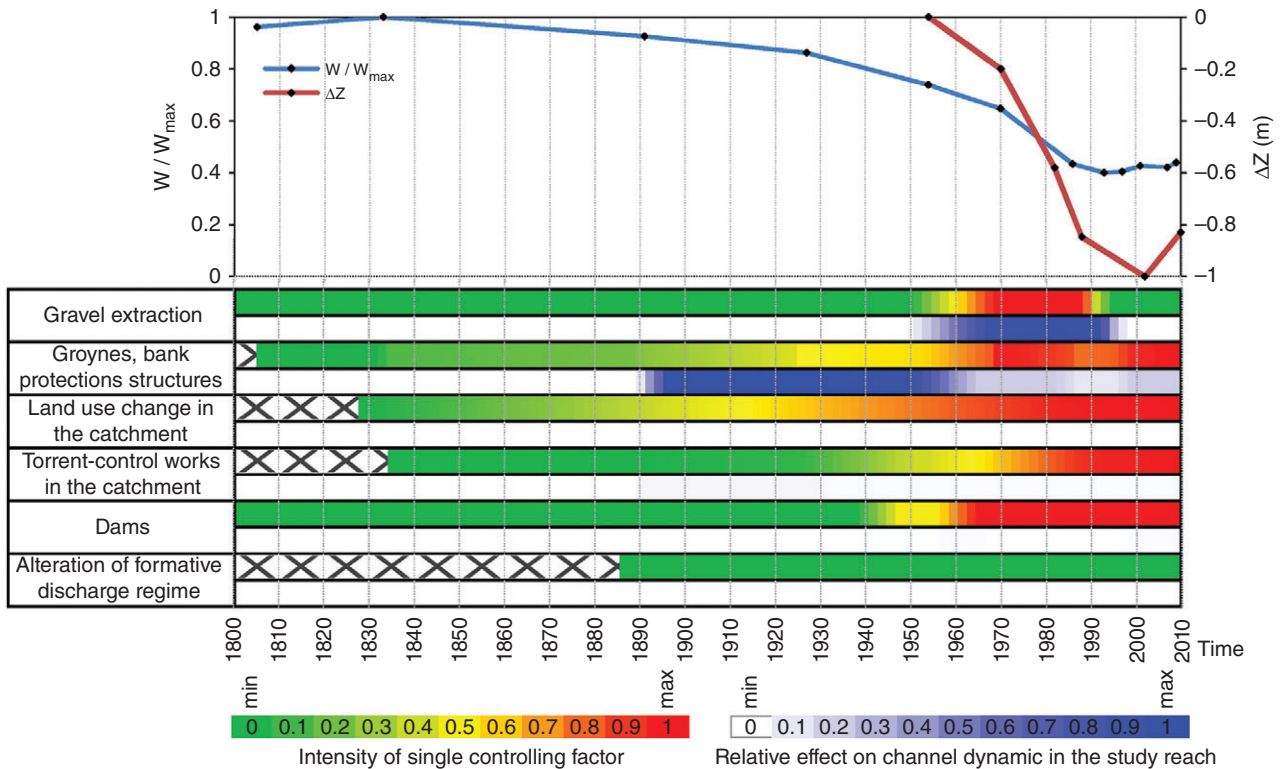
FIGURE 3 | A chronology is a valuable tool to integrate data sources, track changes in hydrological and geomorphological characteristics over time, and explore causal linkages. An example from the Tagliamento River that explores the impact of pressures on channel width (dimensionless, W/W_{max}) and bed level. (Reprinted with permission from Ref 20. Copyright 2001 Elsevier)

characteristics, most notably geology, are not included in this analysis, as they do not change substantially over the timescales under consideration. To facilitate presentation, the catchment and landscape unit spatial scales are combined here because characteristics and key processes that are subject to temporal change are similar at both scales (Table 1); however a higher level of detail would be expected for characteristics evaluated at the landscape unit rather than catchment scale.

Land Cover/Land Use

LCLU is a significant controlling factor on catchment hydrology and sediment production. Large-scale changes in LCLU can alter surface run-off and sediment production[21,22] and in severe cases even influence regional climate and precipitation patterns.[23] An analysis of temporal changes in LCLU relies principally on remote sensing and historical approaches, utilizing satellite imagery, aerial photography, and land/tax surveys.

Satellite imagery is now the most commonly used data source for quantifying changes in LCLU over time at the catchment and landscape unit scales. A large range of datasets is currently available for this purpose, varying in the type of sensor used, spectral resolution and range, and the spatial resolution of the resulting data, and their applicability depends on the

TABLE 3 | The Minimum Spatial and Spectral Requirements for Satellite Data and Minimum Photographic Scale for Aerial Photograph for Identification of Land Cover and Attributes[24,26]

Land Cover/Use Attributes (USGS Levels)	Minimum Spatial Resolution Required for Identification from Satellite Data	Spectral Requirements[1]	Data Sources	Minimum Scale Required If Aerial Photos Are Used as the Main Data Source
Land cover (I)	20 m–1 km	VIS, IR, Radar	MODIS Orbview-1 NOAA AVHRR Landsat MSS EnviSat-1 (MERIS)	1:40,000
Cover types (II)	10–100 m	VIS, IR, Radar	Landsat TM 4-7 Landsat ETM 7 IRS (XS) ASTER RADARSAT	1:20,000
Species dominance (III)	1–30 m	VIS, IR, Panchromatic	IKONOS Spot 5 Quickbird	1:10,000
Species identification (IV)	0.1–2 m	Panchromatic	GeoEye-1 WorldView-1 OrbView-3 LiDAR	1:2400-1:1200

[1]Spectral bandwidths: VIS, visible (red, green, blue); IR, near- and middle-infrared; Radar, microwave; Panchromatic, grayscale images sensitive to the visible and ultraviolet spectra.

spatial scale and level of detailed needed[24,25] (Table 3). Aerial photography can be used to extend the temporal analysis of LCLU further back in time, in many countries to at least the mid-20th century. Other types of data from airborne sensors (e.g., LiDAR—light detecting and ranging, and hyperspectral) can be used to investigate land cover but the high spatial resolution of the data and the correspondingly low spatial coverage make them more suited to characterization at the segment scale.

Classification of LCLU from satellite data and aerial photographs can be done manually based on image characteristics (e.g., tone, color, texture, shape size, context), but is now more commonly achieved using image analysis software and semi-automated (i.e., supervised) or automated pixel-based or object oriented approaches.[27,26] Temporal change can be represented simply with catchment/landscape unit summaries of the areal cover of the land cover types or using a spatially explicit approach that detects change in the attributes of individual pixels. However caution must be exercised, particularly in relation to the latter option, to minimize errors associated with the position or classification of pixels. Many countries or regions have their own land survey data sets, often based on classification of satellite imagery, which are invaluable to LCLU change analysis and have the added benefit of harmonized LCLU classes (e.g., Corine Land Cover data for Europe[28]).

Finally, some countries have long histories of detailed land and tax surveying (e.g., cadastral surveys) that can provide an excellent source of information for the analysis of LCLU. Recent work from Germany[29] and Sweden[30,31] are good examples of this approach. The records should be checked prior to use to ensure they are spatially complete for the study region, and that LCLU classes are harmonized over time. Where maps were produced as a part of the land/tax surveying process, they were typically at a large-scale and can often be analyzed quantitatively in a GIS, following standard processing and georeferencing steps. For example, cadastral maps date back to the 17th century in Sweden and have been used to document transitions in LCLU over time.[30] Where records are in written format, additional map data, such as parcel locations on a more recent cadastral map, are needed to conduct a spatial analysis of change in a GIS.

Land Topography (Tectonics, Seismic Activity, and Mass Movements)

Changes in land topography over time will impact on both catchment hydrology and sediment production. However, over the timescales of interest to river restoration and management, they are primarily linked to changes in sediment production.[32] Tectonic movement, seismic activity, and mass movements triggered by a variety of processes (land cover change, climate variation, deglaciation, etc.) are major producers of coarse and fine sediment that can be delivered to the river channel. In this section, approaches are presented to assess changes in sediment production over time across the catchment or landscape units. The delivery of sediment to the river channel (i.e., hillslope-channel connectivity or coupling) is addressed at the segment scale and sediment transport at the reach scale.

Remote sensing is the preferred approach to assess changes in land topography and sediment production over time at the catchment and landscape unit scales, but historical maps and geomorphological surveys supported by stratigraphic and sedimentological data can help to lengthen the timescale of analysis and verify results from remote sensing.

The identification and quantification of mass movements has traditionally involved geomorphological field mapping and the manual interpretation of aerial photographs.[33] While these are valuable and time-tested methods, other remotely sensed datasets have the potential to reduce analytical cost and time, improve feature identification, and extend spatial and temporal coverage.[34,35] For example, recent studies have highlighted the possibility of automatic or semi-automatic extraction of mass movement features using high resolution LiDAR DEMs.[36,37] Likewise, the volumetric analysis of sediment mobilized during mass movements can now be easily calculated using remotely sensed data; a DEM of Difference (DoD) can be produced by comparing DEMs of the landscape prior to and following the event.[38] While many DEMs are now freely available online (e.g., SRTM, ASTER-G-DEM), the high spatial resolution of laser-derived DEMS (LiDAR and Terrestrial Laser Scanning—TLS) has expanded the types of processes that can be investigated and has markedly increased the precision of volumetric measurements. While only large mass movement events could have been realistically quantified in the past, aerial LiDAR and terrestrial laser scanning can resolve small changes in landscapes that yield detailed information on coarse and fine sediment production.[39]

Where they exist, historical topographic and landslide inventory maps can help to identify the location and extent of landslides in a region. An individual landslide map can indicate the level of landslide activity, but maps from different periods in time allow the calculation of landslide frequency and, if elevation is included on the maps, a rough estimation of sediment produced.[35,40] Documentary and photographic evidence can be used to support geomorphological and stratigraphic interpretations.[41] Landslide susceptibility datasets derived from an analysis of climate, slope, lithology, and land cover are also excellent resources to explore the likelihood of landslide activity and any spatial variations within a catchment[42] (e.g., European Landslide Susceptibility Map, Joint Research Centre, European Commission).

To lengthen the timeframe of the temporal analysis, palaeo-seismic and palaeo-landslide activity can be estimated from topographic, stratigraphic, and sedimentological evidence.[33,43,44] For example, palaeo-landslide work based on stratigraphy and radiocarbon dating has demonstrated links between landslide frequency and climate change[45] that are related to glacial erosion and debuttressing following glacial retreat,[46] anthropogenic land cover changes[41,47] and fluctuations in temperature and the timing, frequency, and magnitude of rainfall.[48]

Precipitation and Groundwater

Water drives rivers. Thus data on precipitation, surface hydrology, and groundwater are essential to studies of temporal change in geomorphology. The primary source of information is hydrological monitoring records, which are the focus of this short section, though remote-sensing is increasingly being used to characterize surface hydrology and detect change over time.[49]

Hydrological monitoring records are crucial to the investigation of temporal changes in precipitation or groundwater levels. A simple analysis of trends in average, maximum, and minimum annual and monthly precipitation or historical intensity–duration–frequency analyzes can be extracted from precipitation gauge records to examine general changes in the input of water to the catchment.[50,51] Similarly, spatial and temporal variations in groundwater levels from monitored boreholes can also be investigated.[52] Because of the complex patterns in time series data as well as the interactions between global climate oscillations and precipitation and groundwater levels, time series data may be better analyzed using a standardized procedure, such as the Standardized Precipitation Index[53] (SPI) or Standardized Groundwater level Index[54] (SGI) that were designed to identify periods of drought, or they can be investigated using non-stationary approaches like Fourier and wavelet analysis.[55] Where borehole

or piezometer data are unavailable, information on groundwater can be obtained from age dating, chemical proxies, or various hydrogeophysical techniques[56] (e.g., electrical/electromagnetic methods or land-based gravity surveying). If there is evidence of significant changes in climate, land use, or groundwater levels and the necessary data are available, a water budget can be assembled from current and historical data to explore changes in the amount of water delivered to the channel.[57,58]

Additional information on groundwater abstraction or inter-basin water transfers can be obtained from national scientific agencies, municipal water suppliers, or private water companies.

Segment

Geomorphological characteristics at the segment level relate to the boundary conditions that dictate channel form and processes: valley setting (gradient and width); river channel gradient; river flows and levels; sediment delivery to the channel; and natural riparian vegetation.

Valley Setting (Gradient and Width)

The valley setting is influenced by forces operating at vastly different timescales, from tectonic uplift acting over millennia to valley blockage by landslides and glacial surges inducing very rapid geomorphic response. These forces can alter the valley gradient, impacting upon river energy and sediment transport, and the valley width, which in turn impacts the planform and lateral mobility of the river as well as the extent of the active floodplain.

Methods from all four of the approaches (Table 2) are typically used in combination to identify, confirm, and date topographic features in the landscape that are indicative of changes in valley setting.[59–61] These features, such as river terraces and palaeo-landslides, are identified using geomorphological surveys and remote sensing techniques and may be depicted on historical topographic maps. Stratigraphic, sedimentological, and dating techniques are used to confirm the origin of the features and constrain the dates for their formation. Indicators of changes in valley setting, such as inset river terraces, can also be associated with rapid channel narrowing and incision caused by anthropogenic interventions.[62] These changes are discussed in more detail in the following sections, but it is important to point out here that in addition to the changes that occur in channel geometry and bed level, the floodplain width may be severely diminished, which can have significant implications for the conveyance of high flows and the distribution of riparian vegetation.

Anthropogenic structures that influence the valley gradient and effective valley width should also be studied. Large dams that span the width of the floodplain have a profound and immediate impact on the water surface slope, and cause significant changes in upstream bed elevation over time due to sediment deposition as well as profoundly influencing the flow regime and sediment delivery downstream. Extensive artificial levée networks associated with flood control structures or infrastructure (e.g., rail and road embankments) constrict the valley width, limiting the spatial extent of flood inundation and restricting the lateral mobility of the channel. Information on engineering structures can be obtained from maps, government records, or can be identified from aerial photographs and remotely sensed data. Semi-automated approaches have been developed to identify and classify earthworks in floodplains from DEMs, satellite multispectral data and aerial photography.[63] By linking the spatial representation of engineering structures with a timeline of their constructions and flood levels, it becomes possible to quantify changes in floodplain width over time.

Channel Gradient: Changes to Longitudinal Profile

Channel gradient is set initially by the valley setting, but is further controlled by planform pattern and geometry. Channel gradient will naturally adjust over time, in response to normal geological and geomorphological processes. Significant changes in channel gradient over short timescales, though, are often caused by anthropogenic modifications to the channel or catchment, such as changes to channel planform (i.e., channel realignment and meander cut-off), bed level (e.g., weirs, dams, and gravel mining), or sediment delivery from the catchment. Channel gradient is one of the fundamental properties that determine the amount of fluvial energy available to transport sediment within the river channel.

An investigation of changes in channel gradient requires information on two variables at multiple points in time: (1) the length of the river in the segment and (2) the bed elevation at a minimum of two locations along the segment. In some situations, this information can be gathered from remote sensing sources, but the most reliable data come from historical sources, particularly systematic river topographic surveys. Accurate topographic surveying of rivers began in the mid-19th to early 20th century in Europe and North America due to the development of rivers for navigation, flood control, and water resources, and offers a wealth of data for historical analyzes of fluvial geomorphology.[64,65] For example, repeated
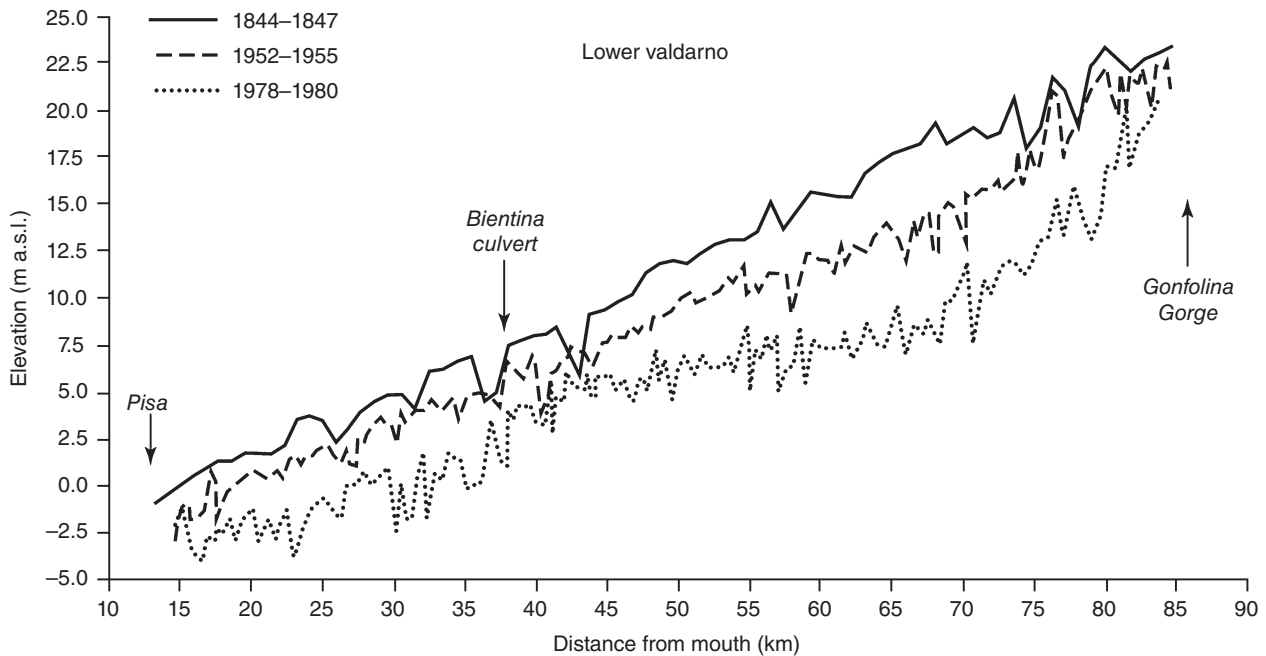
FIGURE 4 | Changes in bed level over time for the Arno River, Italy. (Reprinted with permission from Ref 67. Copyright 2007 Elsevier)

topographic surveys have been conducted in many European rivers and have been successfully used to quantify bed aggradation and incision associated with climate change and anthropogenic impacts[62,66–68] (Figure 4). Care must be exercised when comparing historical bed-levels as problems can arise due to differences in geographical reference systems, survey techniques, or in the attribute measured[65] (e.g., average bed, thalweg, or water surface level).

When systematic surveys are unavailable, channel gradient can be estimated by combining channel length and bed level estimates from different sources, or from gauging station records. Channel length can be derived from plan sources including maps, aerial photographs, and other remotely sensed datasets, while bed-level change can be derived from cross-sectional surveys conducted for other purposes, such as bridge construction and maintenance, flood risk management, or river restoration.[69–71] Changes in bed level can also be inferred from gauging station records in an approach known as specific gauge analysis, in which water surface levels at set discharges are compared over time using empirical ratings curves for each year of the analysis to reconstruct average bed elevation.[72]

If no quantitative information on historical bed levels is available, then some indication of bed level changes can be inferred from a field survey. For example, inset floodplain terraces, undercut bridge piers, and exposed bedrock/former floodplain layers in an alluvial river may all indicate incision.[73,74]

Conversely, buried engineering structures, large uncompacted point bars, and thick fine sediment deposits overlying a gravel bed may indicate aggradation. The occurrence of these properties varies depending on the catchment characteristics and the location of the segment within the catchment, so must be assessed by an experienced geomorphologist. Field surveys of bed level change should be conducted at multiple locations within a segment to ensure a reliable assessment. Stratigraphic, sedimentological, and botanical evidence can support conclusions drawn from a geomorphological survey and help to constrain the timing of bed level changes.[75,76]

River Flows and Levels

Information on spatial and temporal variations in river flow and level are vital to any analysis of temporal river change, because they are the primary control on sediment mobilization, transport, and deposition which in turn induce land form change. The most accurate and complete records come from river gauging stations, but some information can also be obtained from remotely sensed data and documentary sources.

Many indicators can be extracted from river flow records[77] (e.g., average and extreme flows and their timing) and can be used to estimate hydrological alteration.[78] Gauging station records spanning at least 20 years[79] are required for this type of analysis with a minimum temporal resolution of 1 day, or less if short-term events such as hydropeaking

are significant. The entire time series can be analyzed to investigate temporal trends, in magnitude, frequency, timing, duration, and rate of change in flow; divided into time periods related to significant changes in the flow regime (e.g., pre- and post-dam construction); or applied to observed and 'naturalized' flows, where the latter take account of modifications attributable to flow abstractions or additions. In the second and third options, indicators are extracted from the pre- or naturalized time series and compared to the post- or observed time series to assess hydrological alteration.[78] Different flow characteristics may be significant in different climatic regions and morphological settings.[77,80] Changes in any of these indicators through time or in comparison with natural or 'naturalized' conditions will be accompanied by hydromorphological changes within the segment and, in most cases will affect downstream segments as well. While small shifts may be attributable to climate change, major shifts usually reflect human interventions, with hydropeaking being a distinct indicator of artificiality in the flow regime. Figure 5 illustrates how dam construction and operation can impact maximum annual flow, monthly average flows, and daily flows.

Other useful geomorphological indicators are total and specific stream power. Total stream power (Ω) is the rate of energy dissipation per unit downstream length (W m^{-1}) and is calculated as

$$\Omega = \rho g Q S$$

where ρ is the density of water (1000 kg m^{-3}), g is acceleration due to gravity (9.8 m s^{-2}), Q is discharge (in m^3 s^{-1}), and S is slope (in m m^{-1}). A morphologically meaningful discharge indicative of, for example, bankfull conditions is most informative. Thus the median annual maximum flow (Qp$_{median}$) or the annual flood with a 2-, 5-, or 10-year return period have all been used for this purpose. Specific stream power is stream power per unit channel width (W m^{-2}) and is calculated by dividing total stream power by the average channel width for the segment. Stream power has been correlated to a wide range of geomorphological forms and processes, including channel size, planform pattern, sediment transport, and island formation.[83–88]

Where river gauging station records do not exist, modeling, remote sensing, historical records, and palaeo approaches can be used to estimate aspects of the flow regime. For example, the UK's 'Flood Estimation Handbook' presents methods to estimate flood indicators (e.g., Qp$_{median}$) for ungauged sites based on attributes of the catchment, river network, and precipitation in the UK.[51] Remote sensing can provide information on the spatial extent or elevation of the water surface that can be used, for example, to estimate flood levels and extent. River discharge cannot be directly quantified from remotely sensed data, but can be estimated from altimetry data by calibrating river level with gauging station records or through the use of hydraulic relationships.[49,89] Observations of flood levels and extents can also be obtained from documentary sources and combined with hydraulic modeling to reconstruct flood discharge, which can extend the analysis further back in time.[90] Lastly, palaeo-hydrological techniques can be used to estimate bankfull flow based on cross-section or planform geometry of palaeo-channels[91–93] and flood records based on fluvial sediment deposits.[94,95]

Finally, to assess the impacts of human intervention on the flow of water in the river, a chronology of anthropogenic changes in the segment should be constructed. Of particular interest are the dates of construction and the size of water flow impedances or storage structures, be they for water diversion, hydropower, flood management, or water consumption purposes. Information to complete the chronology can come from any number of historical sources, including maps, aerial photographs, and water company records.

Sediment Delivery

Sediment delivery refers to the transfer of sediment from the areas of production identified at the catchment/landscape scale to the river channel. The importance of coupling (i.e., connectivity) between channels and adjacent hillslopes has been long acknowledged.[96–98] Evaluation of the degree of coupling, and its change through time, is critical to drainage basin sediment dynamics as it controls in what proportion hillslope sediment flux contributes to drainage basin sediment storage and fluvial sediment yield, respectively.[99,100] Remote-sensing and field mapping are the most commonly used approaches for discrete sediment sources, whereas the palaeo approach is the preferred method for investigating diffuse sediment sources, particularly of fine sediment.

In the remote sensing approach, DEMs are used to track changes in the topography of sediment sources over time to estimate sediment delivery to the channel. For coarse sediment, the sources are typically discrete and in close proximity to the river channel (e.g., landslides), whereas for fine sediment they can be discrete (e.g., earth flows) or diffuse sources (e.g., soil sheet erosion). The DoD method works best with discrete events for which there are DEMs that characterize the topography before and after the event, preferably with multiple post-event DEMs to permit the calculation of delivery rates. DEMs derived
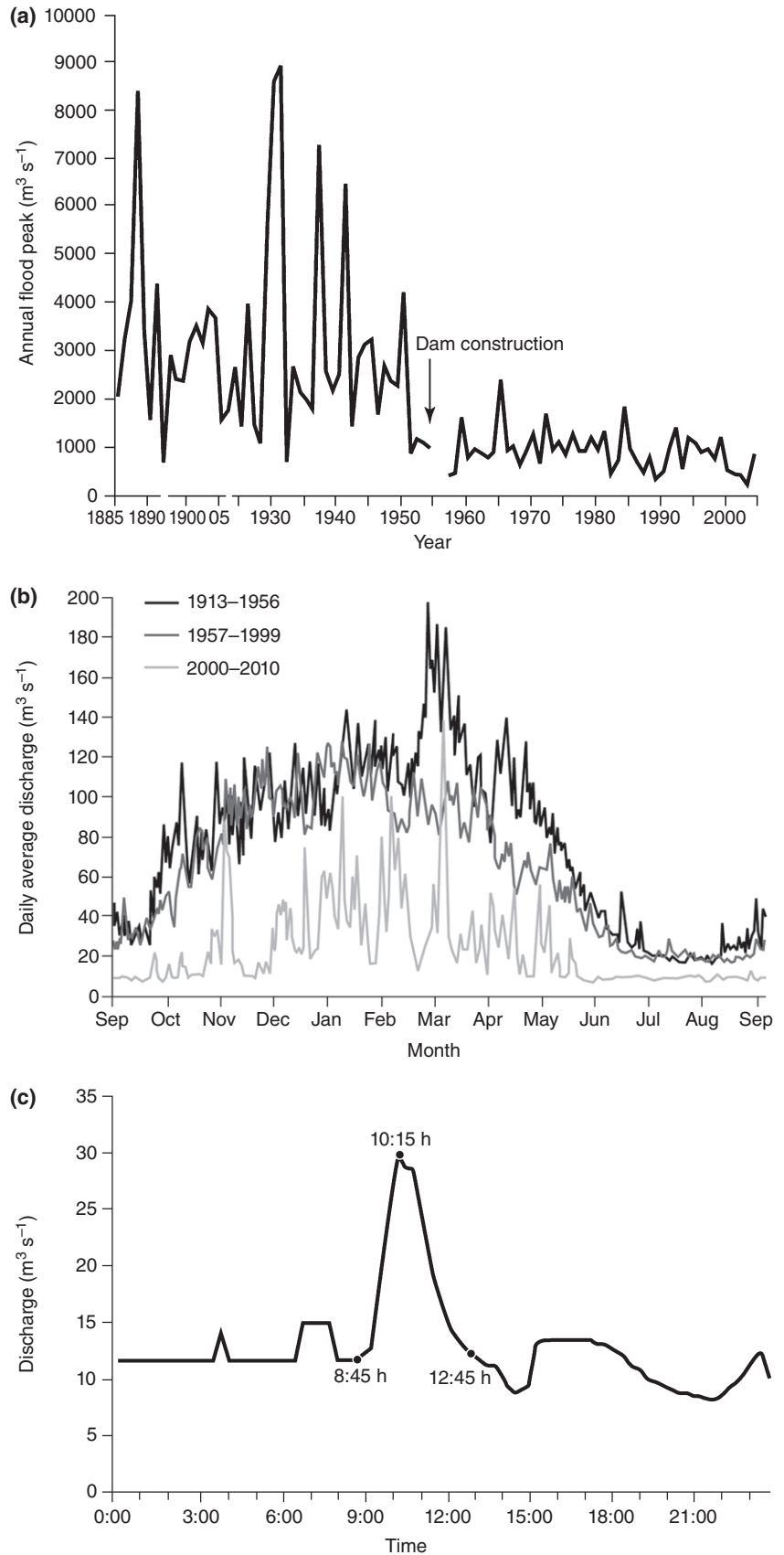
FIGURE 5 | Alteration of flow regime caused by dam construction and operation. (a) Annual floods on the Savannah River (USA), pre- and post-construction of the Thurmond Dam in 1942 (Modified with permission from the author[81]) (b) Changes to the annual hydrograph caused by construction of successive dams, and (c) changes to daily flows (i.e., hydropeaking) as a result of dam operation on the Aragón River (Spain). (Reprinted with permission from Ref 82. Copyright 1980 Springer)

from photogrammetry, field surveys, and LiDAR can all be used, but consideration must be given to the uncertainty in the topographic measurements and the amount of change being detected. For example, uncertainties in LiDAR-derived elevation measurements are still in the centimeter to decimeter range, so care must be exercised in interpreting topographic change over short time spans, or when the amount of change being detected is of similar magnitude to the positional accuracy.[101–103] A process-based geomorphological mapping method, which combines field surveying and remote sensing approaches, can be particularly useful for assessing coarse sediment connectivity and transfer.[104]

Palaeo approaches are the primary empirical methods for estimating the delivery of fine sediment to the river channel. Stratigraphic and sedimentological interpretation of sediment deposits from the channel bed, overbank deposits, fill deposits in cutoffs and avulsions, and reservoir/lake sediments can determine the amount, timing, and source of sediment.[94,95,105–108] Additional topographic and historical data (e.g., historical maps, diaries, photographs, legislation) can corroborate the evidence gathered from palaeo approaches, and can illustrate the impacts of altered sediment delivery on fluvial forms and processes.[109] Cosmogenic approaches are particularly useful for sediment budgeting,[101,110] but may only be feasible in areas with severe or complex fine sediment delivery problems due to the cost and expertise involved. Alternatively, soil erosion models can be combined with information on changes in LCLU, precipitation to predict changes in fine sediment delivery.[111–113]

Finally, temporal changes in sediment delivery may be identifiable in field surveys of the river channel.[18,114] For example, a decrease in coarse sediment supply may result in bed incision, bed armouring, a reduction in geomorphic features, or a change in river pattern (e.g., from braided to wandering). An increase in fine sediment delivery may result in the clogging or burial of a coarse-grained bed, bed aggradation, and the presence of fine sediment geomorphic features (e.g., silt bars and benches).

Riparian Vegetation and Wood

This section covers the analysis of riparian vegetation characteristics for both the segment and reach scales. Riparian vegetation is not only important from an ecological perspective, but its extent and structure can indicate past river dynamics and the potential character size and quantity of wood to the river. Wood delivery in turn has important influences on flow hydraulics, sediment retention, and landform

construction within the river channel and its margins, as does the extent and morphological structure of aquatic vegetation.[115,116] At the segment scale, the key characteristics include the size, width, and continuity of the riparian corridor and the potential for wood recruitment to the river. At the reach scale they relate to the structure, spatial distribution, and species composition of the riparian vegetation; the species, abundance, morphology (i.e., submerged/emergent) of aquatic vegetation; and the presence of large wood in the channel and its margins. Similar data sources and methods are used at each scale, but the level of detail required is higher for the reach scale. The primary sources of information come from remote sensing and ecological field surveys (not discussed here), although detailed land survey maps can contribute to the analysis.

Remotely sensed data is perhaps the best source of information to assess change in riparian vegetation over a decadal timescale, including aerial photographs; multi- and hyperspectral data from airborne or satellite-based platforms; and airborne LiDAR.[117–122] The choice of remotely sensed data for a particular river segment depends upon data availability and the spatial resolution of the data in comparison to the width of the riparian corridor and the amount of change being detected. For rivers with large and continuous riparian vegetation cover, small-scale aerial photography and freely available satellite imagery can be used to assess segment scale characteristics. For segments with narrow or patchy riparian vegetation and for all reach-level characteristics, higher resolution data is needed. For guidance on scale and resolution for vegetation identification and classification, see Table 3. Classification methods are similar to those presented earlier for LCLU, though additional supporting information is often needed (e.g., DEMs and floodplain extents).

Where available, LiDAR data is particularly useful for characterizing riparian vegetation structure and spatial distribution. The point cloud data that is generated by LiDAR provides information on the presence of vegetation, vegetation height and canopy structure, which can be used to interpret vegetation type, vegetation age, and ground topography.[119,123] LiDAR can also be combined with other remotely sensed data to more thoroughly characterize riparian vegetation structure.[119,124] Changes over time can be investigated using height frequency distributions, DoDs or areal coverage of vegetation classes (e.g., height or species).

Historical maps can be a valuable resource, particularly large-scale land and tax maps that have detailed land use information associated with them.
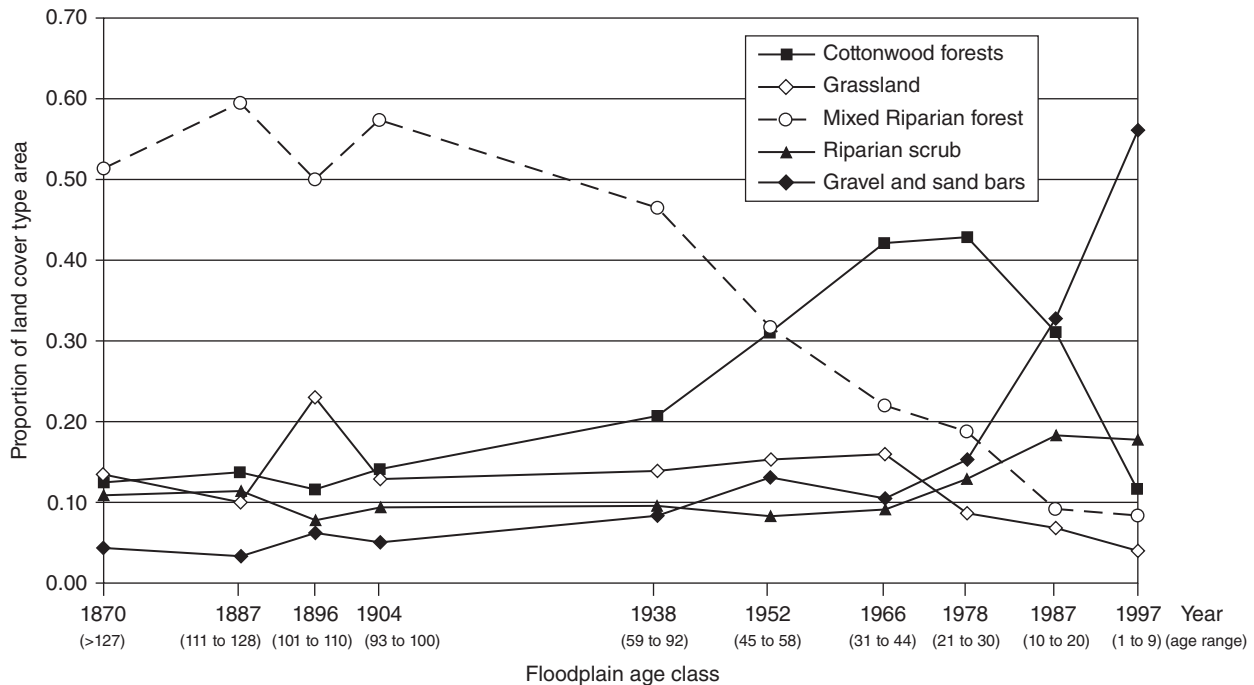
FIGURE 6 | Floodplain age and vegetation community in the Sacramento River. Floodplain age was determined from a historical analysis of planform changes using historical maps and aerial photographs. Note the shift from gravel bars to cottonwood forest to mixed riparian forest with increasing floodplain age. (Reprinted with permission from Ref 125. Copyright 2011 Elsevier)

Historical cadastral maps have been used to assess changes in the extent and composition of riparian vegetation.[118] This information can be paired with modern vegetation survey data to link historical channel change to current vegetation structure and species composition[125,126] (Figure 6) or to estimate changes in habitat type, age, and turnover.[127,128]

Changes in the distribution and frequency of large wood in the channel can be investigated effectively using remotely sensed data, including vertical and oblique aerial photography,[129] airborne hyperspectral data,[130] and a combination of LiDAR, oblique ground photographs and field surveys.[131] Structure from Motion (SfM) photogrammetry may be useful for this purpose, particularly using ground or low-altitude aerial photography[132,133] (e.g., a camera on a pole). SfM is a newly developed technique in geomorphology that can generate DEMs from any series of overlapping digital photographs with positional accuracies as good as LiDAR. This opens up the possibility of tracking volumetric changes in large wood using DoDs from historical photos.

Finally, information on riparian vegetation and large wood can come from other historical sources such as travel accounts, ground photographs, and government policy/records.[64,134] For example, large wood may have been, and may still be, removed from channels by the local population for use as fuel or to improve drainage and reduce local flooding, and by governments to maintain channels and protect infrastructure. Any information on how the spatial extent and intensity of these practices has varied over time will help to develop an understanding of how large wood has influenced the current and past geomorphological condition of the river.

Reach

While the characteristics investigated at the larger spatial scales were largely associated with controls on geomorphology, those at the reach scale are primarily indicators of function, channel adjustment, or alteration/artificiality. Geomorphological characteristics are grouped into three categories: planform morphology and channel migration; channel geometry; and bed sediment caliber. Riparian vegetation, aquatic vegetation, and wood should also be assessed at the reach scale, but this has already been discussed in the segment-scale description above.

Planform Morphology and Channel Migration

This section addresses changes in the two-dimensional form of rivers over time, and includes river planform and associated characteristics (e.g., channel width and sinuosity, braiding, and anabranching indices); channel migration; and geomorphic units within the channel or floodplain. This encompasses a large variety of

characteristics, but they are united by the data sources and analytical techniques used to investigate temporal change.[135] Analysis of these characteristics (e.g., channel pattern, channel width) allows reconstruction of evolutionary trajectory of river morphology. This is crucial in river management for understanding present morphology and processes and predicting possible channel evolution in the near future.

The analysis of temporal change in planform relies primarily on remotely sensed data and historical maps. In fact, these sources are often used in combination. Aerial photographs or satellite data are frequently used to characterize recent planform, and historical maps to extend the analyzes further back in time. The basic premise of the analysis is to overlay images from multiple years and check to see if there has been a change in the position of a feature (e.g., bankline, Figure 7) or a change in the characteristics of a feature (e.g., channel width, Figure 3). Because this type of analysis is based on a comparison of geographical positions, it is crucial that the data sources are properly registered to a common coordinate system in a GIS and accuracy/uncertainty is estimated for each source and at each time point.

Maps, aerial photography, and satellite imagery can all be used to investigate temporal changes in rivers that cover the full range of sizes, patterns, and dynamics. The major consideration is the scale of the data sources in relation to the size of the feature being detected (e.g., channel width) and the amount of change being detected (e.g., lateral migration). Consequently, studies of temporal change in narrow or slowly adjusting rivers need large-scale maps and aerial photographs (minimum 1:10,000 scale) or high resolution satellite imagery.[136–139] Large and dynamic rivers can be studied with smaller-scale maps and aerial photographs[120,140,141,20] or with coarse-resolution satellite data.[142–144] Infrared bands of multispectral satellite data, e.g., MODIS band 2 or Landsat Thematic Mapper band 5, can be used to automatically segregate water and land based on a pixel threshold and so to differentiate banklines, particularly for large rivers with clear water.[145] In addition, well-tested band ratios can be used to discriminate vegetated from unvegetated surfaces (Normalized Difference Vegetation Index[146]), and wetter from drier surfaces (Modified Normalized Difference Water Index[147]). Maps, aerial photography, and satellite data can also be used to identify geomorphic features within the channel and track changes in their size, frequency, and location over time.[148–151]

Geomorphological surveys can provide insights into channel migration and changes in channel width,

particularly when combined with botanical, sedimentological, or stratigraphic evidence.[152,153] For example, channel narrowing can be identified from active accretion of sediment on opposite banks, particularly when such accretion is stabilized by vegetation encroachment. The species composition and age structure of riparian vegetation can also provide clues to the direction of channel change. For example, lateral banding in the height and ground cover of riparian vegetation due to vegetation succession can underpin estimates of lateral migration extent and rates[154,155] and modes of lateral floodplain construction,[156,157] whereas lateral and downstream changes in the species composition or morphological structure of riparian vegetation can be indicative of distinct geomorphic features, subject to contrasting inundation and soil moisture regimes.[158] Thus changes in vegetation structure and composition can reveal channel bed incision or aggradation[76] through their influence on moisture conditions within the geomorphic features.[159] To go further back in time, the planform configuration of palaeochannels can be investigated based on their topographic signature in the floodplain and supported by sedimentological and stratigraphic evidence.[160,161]

Finally, the chronology of physical pressures should be updated with the dates and extent of river realignment and channel bank and bed reinforcement. This information can come from maps, remote-sensing, and water agency records.

Channel Geometry

Channel geometry refers to the cross-sectional form or bed configuration of a channel. Changes in channel geometry over time can indicate changes in the flow or sediment regime or direct channel interventions such as sediment removal (mining). These are all important indicators of instability that need to be taken into account if any channel management or restoration is envisaged. They are also indicators of induced changes in other processes, for example, bank hydrology and flow hydraulics, that may in turn impact on riparian as well as the aquatic ecology. While information on channel width can be gained from maps and aerial photography, additional data are essential for a full characterization of channel geometry. The recommended data source for this analysis is topographic surveys, although several remote-sensing approaches are applicable in certain situations.

Cross-sectional surveys are the core data sources to examine changes in channel geometry over time. They are conducted across the river channel, perpendicular to the flow direction, and provide a wealth of morphometric information about the channel (bankfull and low flow channel width, bed-level,
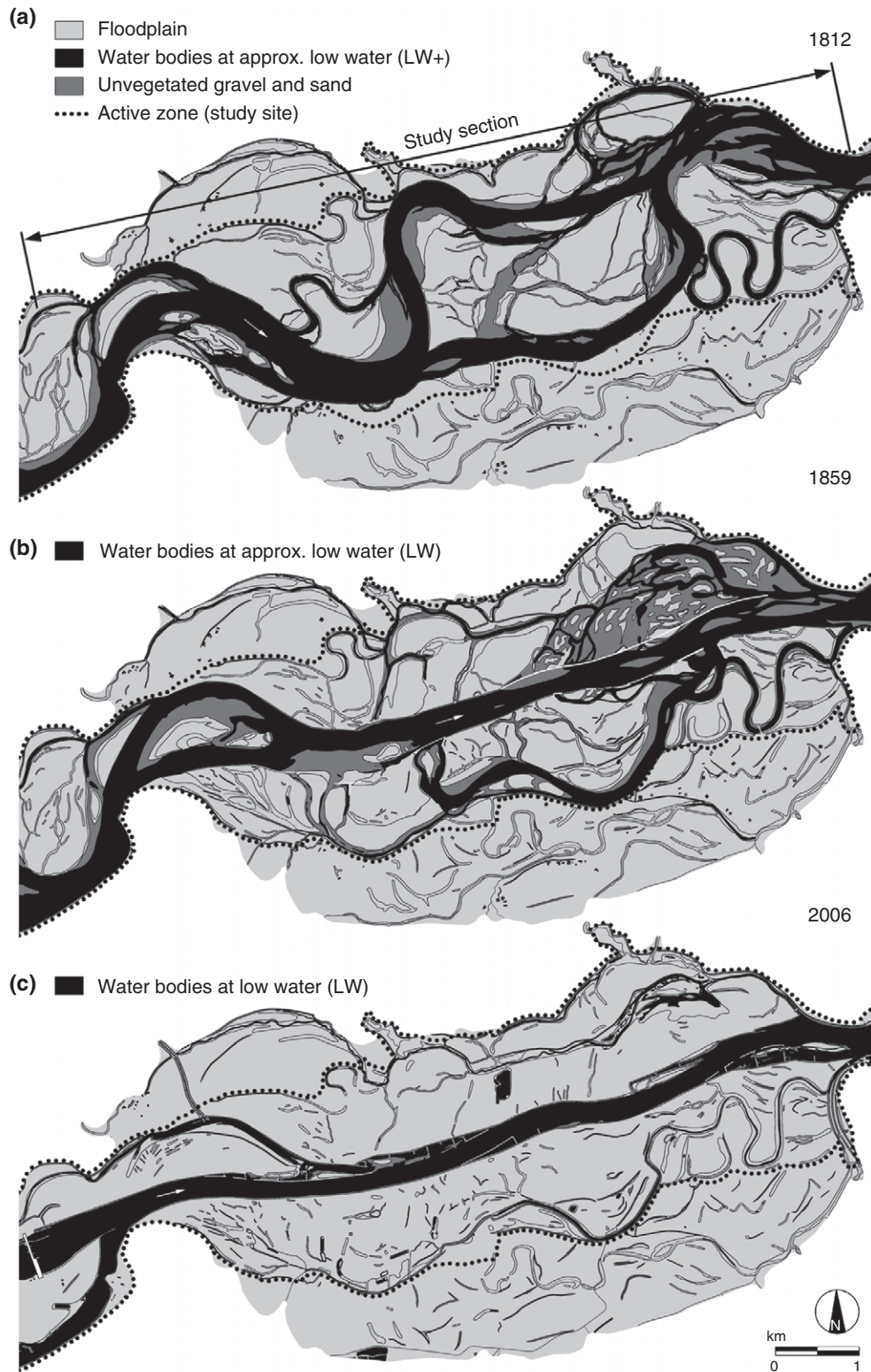
FIGURE 7 | An analysis of historical maps reveal significant anthropogenic alterations to the Danube River that have impacted its planform and the presence of geomorphic features within the channel and floodplain. (a) The Danube 'riverscape' prior to significant human alteration (1812), after an intensive channelization period (1859), and after the construction of a hydropower plant and further channelization (2006). (Reprinted with permission from Ref 128. Copyright 2013 John Wiley & Sons)
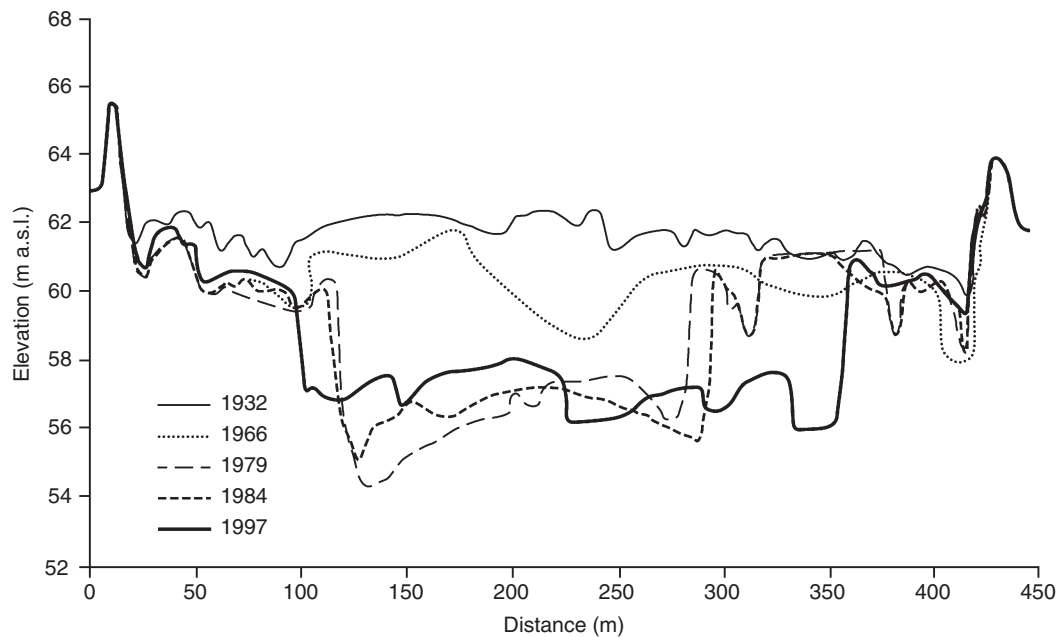
FIGURE 8 | Temporal changes in cross-section form and bed level for a reach in the Brenta River, Italy (1932–1997). (Reprinted with permission from Ref 68. Copyright 1997 Wiley)

water level at the time of survey, bank profiles, etc.) as well as indices used in hydraulic modeling (e.g., bankfull cross-section area and hydraulic radius). In regions where a network of cross-sections has been established for regular monitoring, cross sections from different points in time can be easily overlaid to investigate changes in channel geometry (Figure 8). However internal checks on the surveys should still be conducted to ensure that the same reference points and start/end locations have been used and that there has not been a change in the survey approach which would affect the way the survey was conducted, the accuracy of the measurements or the interpretation of landforms.

Remote sensing approaches to characterize channel morphology fall into two categories. The first uses altimetry data from photogrammetry, LiDAR, or TLS to create 3D models of the channel bed, i.e., DEMs. The DEMs are then used to identify features, detect changes in the morphology over time, and even calculate volumetric differences over time. This approach is mostly applicable to shallow, wide rivers for which a substantial portion of the bed is exposed. Large gravel-bed rivers have been studied extensively using this method.[162–166] However high resolution LiDAR and TLS have been applied to the study of bank and cliff erosion in meandering rivers in conjunction with aerial imagery,[167,168] and recent work has demonstrated the potential for automated extraction of channel networks and bank faces from

LiDAR.[36,169–171] LiDAR has an additional use in bathymetric data collection. Bathymetric LiDAR can measure the bed topography of water bodies up to ca. 60-m depth with high vertical accuracy. It does not suffer from problems associated with sun glint, shadows, or surface disturbances like the spectral approach described below, but its application is limited to waters with low suspended sediment concentrations and is not suitable for application to very shallow water[172,173] (<1.5 m deep). While the focus of discussion on remote sensing techniques throughout this review is on airborne and satellite approaches, it is worth pointing out that bathymetric sonar[174,175] and other related acoustic devices (e.g., sub-bed profiler[176]) can be used to map and detect changes in riverbed topography.

The second approach estimates water depths using the spectral signature of aerial photographs and multi/hyperspectral data.[173] This technique is well developed and has been used successfully to study changes in many types of water bodies, particularly coastal areas. It is used increasingly to characterize river bed topography (e.g., from aerial photography[164,166,177–179]; airborne multi- and hyperspectral data[130,177,180,181]; multispectral satellite data[182]). Although analysis of remotely sensed data can provide good characterization of spatial changes in water depth, the absolute accuracy of the depth estimates depends on calibration using synchronous water depth measurements. This has limited the use

of spectrally derived depth measurements in historical analyzes, but see Ref 164 for one solution to the problem of ground-truth data for historical aerial photographs. Furthermore, spectrally based bathymetry is limited not only to shallow water depths (typically a few meters) but also requires clear water conditions, substrate with bright and reflective surfaces, good illumination, and minimal atmospheric interference.[183]

In some circumstances, a geomorphological field survey may be the only available option to assess changes in channel geometry over time. This may be true for remote, narrow, or slowly adjusting streams which may not be represented on maps or may be subjected to high levels of uncertainty in spatial position which exceed the amount of change being detected. Channel widening can be evidenced by bank erosion or undercutting on opposite banks, whereas channel narrowing can be indicated by stabilizing, vegetated bars or benches on both banks. Field evidence of bed level changes was discussed earlier in the channel gradient section.

Sediment Transport and Bed Sediment Size

Information on bed and bank sediment size and sediment transport is crucial to understanding the geomorphological style and likely dynamics of rivers. Changes in the sediment regime, specifically in bedload transport, can cause channel instability that results in changes to channel planform, bed levels, and type, geomorphic features, etc. Therefore information on sediment transport is key for sustainable, process-based river management and restoration.

When available, long-term monitoring data for suspended sediment and bedload provide invaluable information on sediment transport within a reach. Suspended sediment is more commonly monitored than bedload transport, as it is an aspect of water quality that is typically measured by water companies and national environmental agencies. Bedload is more difficult to quantify, and consequently monitoring stations are usually located only in areas where bedload poses a very significant river management problem.[184] These sources can be readily analyzed and combined with river flow information to assess changes in sediment delivery and transport over time.[185]

Unfortunately, sediment transport is not monitored as commonly as water discharge, and many rivers have very limited or no sediment monitoring record. In this situation, changes in sediment delivery and transport associated with human disturbance to the system can be explored by creating a historical inventory of engineering structures that impact the lateral or longitudinal transport of sediment (i.e., sediment connectivity). For coarse sediment these structures can include dams, check dams, weirs, and torrent controls,[68,186] while for fine sediment they can also include drainage ditches in the catchment and artificial levées.[109] Depending on the catchment history, it may also be pertinent to acquire data for sediment-related activities within the channel, such as records detailing the quantity and location of sediment dredging or mining from the channel.[187,188] This inventory can be combined with information on land cover, topography, and sediment delivery collected at the catchment/landscape unit and segment scales to formulate an integrated chronology of sediment flux.

Remote sensing has enormous potential for use in sediment transport estimates and sediment budgets. This includes the detection and estimation of volumetric change in bed topography (i.e., the morphological approach) from aerial photos[189] or high resolution DEMs,[162] as well as monitoring fine sediment concentrations using aerial photography and multispectral satellite data.[190,191] The morphological approach to estimate bed-load has been successfully used in numerous studies,[189,192–194] in particular where direct measurements using samplers are difficult to carry out or where it is not possible to capture the wide spatial and temporal variability of sediment transport (e.g., in large gravel-bed rivers). Besides, it has been shown that morphological methods provide reasonably robust estimates of the time- and space-averaged bedload transport.[195] These approaches rely on morphological changes, requiring comparison of DEMs of river channels,[196] or cross-sections.[68] Considering the increasing availability of LiDAR data, but also the possibility of deriving DEMs from archival aerial photos,[164] there will be more and more opportunities to apply morphological approaches for sediment transport estimation. Even in the absence of favorable conditions for estimation of bed-load transport (the morphological approach requires that sediment transport is known at one cross-section within the study reach), comparison of DEMs represents the best tool for calculation of the sediment budget and, therefore, for assessing the evolutionary trend of channel morphology in a given reach.

Temporal changes in bed sediment caliber can be investigated using remote sensing, field surveying, and palaeo approaches. Techniques have been developed for the extraction of bed material size from aerial photography based on image texture.[197–201] For shallow rivers with non-turbid water, these techniques offer the possibility of extracting sediment sizes from archival aerial photos to assess change over time, particularly in light of recent analytical developments that allow for automated sediment size measurement without the need for field calibration.[202] If photography-based methods are not appropriate, a combination of field

survey, stratigraphy, and sedimentology can be used to identify morphological forms and structures that are indicative of a change in bed caliber (e.g., bed armouring or extensive fine sediment deposits in a gravel-bed river) and to quantify the timing and magnitude of change.

ACCURACY, UNCERTAINTY, AND ERROR

All data is subject to error, and so a careful appraisal of error is essential to scientific data analysis. Accuracy, uncertainty, and error are related, are frequently used interchangeably, and are all associated with the reliability of the data to represent the true form or process in nature.[203] The differences are subtle. When errors have been quantified for a particular data source, they are typically referred to as 'accuracy'; when they are unknown or not clearly defined, the term 'uncertainty' is used; and the term 'error' is used variously and often when it is quantified by the user. In this section, we use accuracy preferentially, and reserve uncertainty or error for the discussion of estimation methods when accuracy is not defined in advance for a dataset.

Types of Accuracy

Accuracy can by subdivided into three components: position, attribute, and time.[204] Positional accuracy refers to the location of a feature on a graphical representation (e.g., map, photograph, or remotely sensed dataset) in relation to other features (i.e., relative accuracy), or its true location in nature (i.e., absolute accuracy). It is influenced by the methods employed to collect, interpret, and display the data. For example, the absolute accuracy of a river drawn on a map is dependent on the accuracy of the original survey or the resolution of the aerial photographs it is derived from; the interpretation of a feature from those sources (e.g., banklines); the geographical projection used; and the purpose and scale of the map. Positional accuracy is routinely quoted for national/regional maps and satellite datasets. For example, a 1:10,000 scale UK Ordnance Survey map represents rivers at their true scale, with two banklines, when the river channel is at least 5-m wide. Average positional accuracy is quoted at ± 4 m (± 7 m, 95% confidence level), meaning that the channel's location on the map is on average 4 m off relative to its true position, and most points are within 7 m. Larger-scale maps typically have higher positional accuracy. A UK Ordnance Survey map at 1:2500 scale represents rivers to scale when they are 2-m wide, and has an absolute accuracy of ± 2.8 m.

When comparing maps over time in a diachronic analysis, a threshold for planform change detection must be set that incorporates the positional accuracy of each source.

Attribute accuracy relates to how the identification of a feature or the characteristics of a pixel compares to its true characteristics at that location. Some degree of interpretation, simplification, or classification is inherent when data is recorded, analyzed, and displayed graphically, whether this was done by the original surveyor and mapmaker of a historical map or a satellite-based sensor and a GIS technician, so attribute accuracy is always an issue. For example, for satellite-based multispectral data, the spectral signature of a feature is influenced by the spatial resolution of the data relative to the feature size, as well as by changes in illumination (e.g., sun angle), atmospheric conditions (e.g., clouds or haze), and viewing geometry.[27] The spectral signature is then processed, interpreted, and classified, all of which can affect attribute accuracy. If features are small relative to spatial resolution, pixels will represent more than one feature (i.e., mixed pixels), adding additional uncertainty to feature identification or classification. Techniques have been developed to help overcome this problem, e.g., classification of mixed pixels for land cover using fuzzy logic,[27,205] but in general it is best to consider the spatial scale of a feature *a priori* when selecting a data source.

Temporal accuracy relates to the reported date for the observations or data. This is primarily a concern for historical data sources, such as maps and documentary evidence. For example, the time lag between the initial field survey and the publication of a map can vary substantially. Often with historical maps, a single publication date is listed for the entire map collection, even though locations were surveyed and map sheets produced at different times. An additional problem with maps is partial resurveying, in which only a portion of an earlier map is updated and labeled with the new date. These resurveys introduce significant temporal uncertainty if the extent of the resurvey is not indicated. Temporal accuracy is less of an issue for remotely sensed datasets, which are typically time/date stamped at collection or processing, but can be a problem for archival aerial photographs.

Assessing Accuracy/Uncertainty

A wide range of data sources can be used in the analysis of temporal change in river form and processes. These sources differ substantially in their inherent reliability and it is extremely important that sources are assessed prior to inclusion into a study. Assessment involves a series of internal and external checks that

verify the positional, attribute, and temporal accuracy of a source.[206] For example, a historical map can be checked to see if it is a partial resurvey by examining accompanying records, comparing the map against earlier or later ones from the same source, or comparing the map to other sources from the same time period (e.g., land survey records, aerial photograph). If the data sources are judged to be sufficiently reliable for the analysis, the accuracy or uncertainty of the data can be estimated and integrated with the other sources in the temporal analysis to support change detection. In the remainder of this section, further information is provided on estimating positional and attribute accuracy/uncertainty.

When not reported for a data source, positional accuracy can be estimated by comparing positions on the graphical representation with their true location (e.g., ground control points) or with locations on a map or digital product with higher accuracy. When using a GIS, this process takes place when the data source is registered to a geographical projection (i.e., georeferencing). To illustrate this, we provide an example using historical maps. A similar procedure would be conducted with aerial photographs, however there are additional steps that should be taken to correct for image distortion or perspective, i.e., orthorectification (for an introduction see a relevant textbook[207]). A historical map is typically registered to a coordinate system by identifying common landmarks on a modern large-scale map.[208] Landmarks should be stable in space and time (e.g., a building), as precise as possible (e.g., the corner of a building), and evenly distributed over the map. Geometric transformations are then used to alter the scale, displacement, and rotation of the historical map.[209] For most maps, a first-order transformation should be used unless there is significant evidence of shrinkage and distortion of the paper map.[136] The output of this process is an average displacement of positions on the historical map, which is typically represented as a root mean square error (RMSE) and often used to assess positional accuracy.[210] However, methods to estimate positional error and how it propagates through data analysis have advanced significantly, and recent work provides further details on methods and underlying assumptions.[165,203,209,211]

Attribute accuracy/uncertainty is discussed here with a focus on raster datasets. Numerous techniques are available to assess uncertainty and detect change, and the choice is dependent on the data and type of change being detected.[212,213] For land cover, error mis-classification matrices are commonly used post-classification to estimate attribute accuracy and detect change.[214,215] A fuzzy logic approach is particularly appropriate when attribute classes are not standardized over time or between sources,[205,216] and a multilayer (GIS-based) approach can be useful when multiple data sources are integrated for the classification.[212,213,215] A direct comparison of pixels between years can be used, but this approach is more sensitive to positional and attribute errors.

An attribute that deserves special attention is elevation. DEMs are datasets with elevation as an attribute, and a characterization of uncertainty in these measurements is essential for detecting changes in topography over time using DoDs. Similar to the discussion of 2D change detection, volumetric change detection can use a single threshold of change or a more advanced spatially distributed approach.[162,217]

APPLYING THE TEMPORAL ANALYSIS OF GEOMORPHOLOGICAL CHANGE TO RIVER RESTORATION AND MANAGEMENT

A temporal analysis allows us to peel back the layers of time to explore what a channel and its floodplain looked like in the past, how they have changed over time, how quickly these changes have occurred, and what the role of human interventions is in these changes. In other words, it supports holistic, sustainable river restoration and management by permitting the quantification of hydrological and geomorphological processes (e.g., water flow, sediment transport, riparian, and aquatic plant growth and succession), the identification of natural and human-induced alterations to these processes, and the estimation of the impacts of alteration on geomorphological process rates and forms within a reach. This information allows managers to identify the root causes of geomorphological change in river-floodplain ecosystems, identify constraints on restoration potential, and assess the possible trajectories and timelines of change under different management scenarios[141] (Figure 9).

Geomorphological degradation of a reach is caused by changes that have occurred both within the reach itself and at larger spatial scales. The loss of physical habitat over time may be related to direct physical alteration of the reach in the past or current management practices, but equally it may be the symptom of hydrological and geomorphological changes that have occurred upstream (or downstream) of the reach or in the wider landscape in the past. For example, changes in LCLU will alter water and sediment production at the catchment/landscape scale, which impacts the delivery of water and sediment to
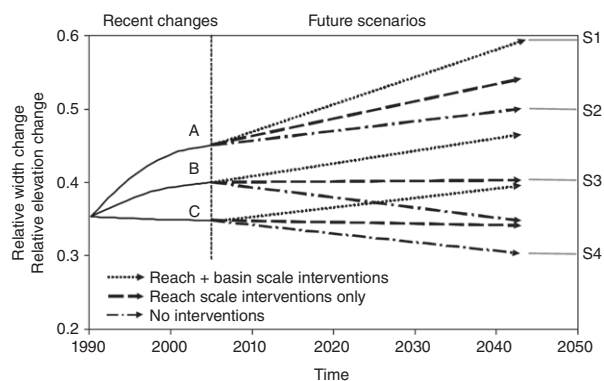
FIGURE 9 | Possible evolutionary trajectories for the (line A) upper Piave, (line B) lower Brenta, and (line C) Cellina rivers (Italy) based on different sediment management strategies (no interventions, reach scale interventions, or reach + basin scale interventions). (Reprinted with permission from Ref 141. Copyright 2013 Wiley)

the channel and floodplain at the segment scale, and which ultimately affects channel planform, dimensions, bed levels, bed sediment size and transport, and the creation of the hydraulic and geomorphic features that support aquatic and riparian ecosystems at the reach scale. Urbanization of a catchment is an excellent example of this cascade. Numerous studies have shown how changes to sediment and water delivery, flow regimes, and riparian vegetation associated with urbanization can cause reach-scale problems such as channel incision, widening, bed armouring, and a decrease in the diversity and frequency of geomorphic features.[21,218] In this example, a temporal analysis of geomorphology would allow practitioners to quantify changes in land use, channel gradient, channel cross-sectional form/width and the extent and type of riparian vegetation, and to determine how the key geomorphic processes have been altered (e.g., runoff generation, sediment delivery, river flows, sediment transport, etc.). By identifying these root causes of temporal changes at reach scale, restoration and management strategies can be developed to target the underlying processes to allow for a better geomorphological functioning of the channel-floodplain ecosystem or to support a comprehensive restoration plan, rather than simply tackling the symptoms of the degradation.

Once the underlying causes of geomorphological degradation are identified, the potential for restoration of those processes can be appraised. In heavily modified catchments or those that support large human populations, industries, or services, it is unlikely that all of the processes will be restorable and some human constraints on geomorphological processes will have to persist. In these situations, an

assessment is needed on how the impacts of these constraints can be minimized. For example, hydropower dams may be required in the headwaters of a river for the medium- to long-term to provide electricity for urban or industrial areas further downstream. While a disruption to bedload transport may be unavoidable for a large dam, changes to the dam operation can minimize the impacts on the flow regime by mimicking natural flow magnitude, timing, duration, and frequency.[81] In this example, the temporal analysis of river flows allows practitioners to identify what the natural flows would have been prior to human interventions and to establish patterns of flow (daily, seasonal, and annual) that are as close as possible to the natural ones. Other impediments to coarse sediment delivery downstream of the dam can be identified, and, if appropriate, removed to reconnect the coarse sediment supply to the channel. If the major alterations to geomorphology cannot be remedied, then it becomes necessary to target the reach-scale symptoms in light of the current altered processes in order to increase geomorphological diversity and maximize ecological benefits.

Finally, with an understanding of the hydrological and geomorphological processes and human constraints, we can begin to predict the evolutionary trajectories of the river and floodplain under different management scenarios, set management end goals, and estimate timescales for change.[7,219] Previous conditions of the river and the direction and rates of change that resulted from alterations to hydrological and geomorphological processes in the past give an indication of how a channel and floodplain will respond to future changes. Practitioners are referred to a range of approaches that can aid the development of evolutionary trajectories: assessment frameworks[15]; conceptual and empirical models of channel evolution[220–222] and channel and floodplain morphologies[84,223]; and numerical models of morphodynamics and sediment transport.[224,225] It is important to stress that past condition does not mean reference condition. Human interventions to rivers and catchments extend back centuries to millennia depending on the region, and historical condition is instead an image of what the river and floodplain looked like under those boundary conditions and how it changed when those conditions were altered. Restoration should aim to restore geomorphological function or work within the current boundary conditions (water flows, sediment fluxes, etc.) to develop obtainable and sustainable targets. The rates of change in the system provide an indication of the potential and timescale for natural channel evolution. Dynamic rivers that adjust rapidly and respond rapidly to

extrinsic factors have the best prospects for renaturalization. A high energy, gravel-bed river that has incised, narrowed, or shifted to wandering planform because of sediment control and exploitation has a good potential to reach a good geomorphological condition in a short period of time once processes are naturalized, because rates of hydrological and geomorphological processes are high. Conversely, a formerly anastomosing river in a lowland setting that was simplified, channelized, straightened, and widened may take considerably longer to recover a good condition because process rates are much slower. In these situations, a temporal analysis can provide a guiding principle with which to develop restoration measures.

CONCLUSION

The aim of holistic river basin management is to balance the demands of human use and modification of rivers with the preservation and improvement of physical structure and condition to support natural and diverse ecological communities. A process-based approach to holistic river management works with river processes (ecological, chemical, hydrological, geomorphological) to facilitate the development of sustainable management and restoration strategies. An analysis of change in fluvial geomorphology supports this approach through a quantification of the key processes at multiple scales that structure the river and floodplain at the reach scale, an identification of alterations to these processes, and an assessment of how past alterations to the processes have affected and continue to affect the geomorphology of the river and floodplain. This information allows managers to identify the underlying causes of geomorphological change in river-floodplain systems, identify constraints on restoration potential, and assess the possible trajectories and timelines of change under different management scenarios. The recommendations on hydrological and geomorphological characteristics, data sources, and analysis provided in this review form a flexible framework with which to conduct a temporal analysis that develops an improved understanding of how a river functions in response to temporal changes in the spatial hierarchy of processes that influence it and so provides a foundation on which to base holistic and sustainable river restoration and management decisions.

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FURTHER READING/RESOURCES

REFORM (Restoring Rivers for Effective River Management) website and wiki, http://www.reformrivers.eu, http://www.wiki.reformrivers.eu.