CHAPTER 1

An introduction to river science: research and applications

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Introduction

River science is a rapidly developing interdisciplinary field of study focusing on interactions between the physical, chemical and biological components within riverine landscapes (Thoms, 2006; Dollar *et al.*, 2007) and how they influence and are influenced by human activities. These interactions are studied at multiple scales within both the riverscape (river channels, partially isolated backwaters and riparian zones) and adjacent floodscape (isolated oxbows, floodplain lakes, wetlands and periodically inundated flat lands). It is an exciting and robust field of study because of the integrative nature of its approach towards understanding complex natural phenomena and its application to the management of riverine landscapes.

The modern era of river science is a challenging one because climate, landscapes and societies are changing at an ever-increasing rate. Thus, our use, perceptions and values related to riverine landscapes are also changing. The twenty-first century will be different to the twentieth century both in terms of the way in which we undertake research and manage rivers. Increasing globalisation and data availability will allow unique opportunities for sharing of information and experiences, at unparalleled rates. Therefore, we can expect an exponential upward trajectory in societies' understanding of rivers and their appreciation of them as one of the globe's key ecosystems. This will be especially true as the goods and services that rivers provide, in particular the demand for water as the resource, becomes scarcer in many regions. Water security is predicted to become a key global issue in the twenty-first century (Gleick, 2003). Thus river ecosystems and their associated landscapes are likely to be viewed and valued by society in the same way that the importance of tropical rainforests, as a regulator of climate change, became evident in the twentieth century.

Rivers and their associated landscapes are ubiquitous global features, even in the driest and coldest regions of the world (Hattingh and Rust, 1999; Bull and Kirby, 2002; Doran *et al.*, 2010). The physical, geochemical and ecological characteristics of the world's riverine landscapes are as

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diverse as the peoples of the world and their cultural origins (Miller and Gupta, 1999; Cushing *et al.*, 2006). Many rivers meander slowly through lowland regions, with some never making their way to the sea, while those that do so often rush down steep rocky gorges or flow hidden beneath the ground within alluvial aquifers or limestone caves. Some rivers flow in multiple channels and others exist as a series of waterholes connected by intermittent channels for most of the time. Some rivers only flow after prolonged rainfall and some flow all year round with little variation in water levels.

Human societies and populations have been drawn to these landscapes for millennia because of the provision of important resources, like water for human survival, irrigation, power, navigation, food and timber. The flat fertile lands of river floodplains have drawn people to them for agriculture and have been used by them as important transport routes, even in contemporary societies where road, rail and air freight may be more rapid. However, rivers and their floodplains also present challenges to those that choose to inhabit these landscapes because of their propensity to flood, erode their banks as well as to contract and even become dry during extended periods of drought (Lake, 2009; Pennington and Cech, 2010). The prosperity of human societies is closely linked to natural variations in the character and behaviour of riverine landscapes both regionally and over time, in many parts of the world (cf. Petts *et al.*, 1989; Wohl, 2011). Past civilisations have waxed and waned, and even disappeared, as result of the unpredictable and highly variable nature of riverine landscapes (e.g., Schumm, 2005).

Riverine landscapes and their associated ecosystems are the foundation of our social, cultural and economic wellbeing. The degraded condition of many of the world's rivers and floodplains is a testament to our failure to understand these complex systems and manage them wisely. The exponential increase in the number of riverine studies, from various regions, highlights the growing stresses placed on river systems in response to demands made directly upon them and their surrounding catchments. A recent assessment of the worlds 100 most-populated river basins, by The World Resources Institute, found 34 of these basins displayed high to extreme levels of stress, while only 24 had minimal levels of stress. This was primarily a result of water related pressures in these basins. These rivers flow through countries with a collective GDP of $US 27 trillion (World Resources Institute, 2014). Similarly, other studies with a more regional focus, demonstrate the impact of inappropriate activities on the health and/or condition of river systems. The Sustainable Rivers Audit undertaken in the Murray Darling Basin, Australia, for example, found rivers in 21 of the 23 sub-basins were in poor to very poor condition in terms of their hydrology, physical form, vegetation, fish and macroinvertebrate communities, because of changes in hydrological regimes, land use and inappropriate channel management (Murray-Darling Basin Authority, 2013). River science is the interdisciplinary study of these complex biophysical systems and seeks to understand the drivers that influence pattern and process within these critically important systems. In order to minimise future river catastrophes and degradation, river science should underpin our approach to their management and the setting of policy regarding these landscape scale systems.

Many animal and plant communities depend upon riverine landscapes and their associated ecosystems for some or all of their lifecycle. Most rely on riverine landscapes as a source of water and nutrients. The strong linkage between rivers, humans and biological communities is strongest where human societies are also heavily dependent upon riverine landscapes for food and where fish is a major component of their diet. In many of these locations the concept of a 'healthy river' was, or remains, culturally important and an intuitive component of human survival (Kelman, 2006). Given the dependency on rivers and their health or productivity by humans and organisms, it is surprising that the subject of river science as a discipline in its own right has only emerged in recent years. The journal *River Research and Applications* and its predecessor *Regulated Rivers: Research and Management*, the pre-eminent scientific publication devoted to river ecosystems, only commenced publishing in 1987. In part, this is a reflection and response to the distancing of many human societies from riverine landscapes and the ecosystem goods and services, and environmental hazards that are an inherent component of these natural landscapes. Historically a gulf between river scientists and river managers has existed resulting in a lag between the advancement of the science and improved river management (Cullen, 1996; Parsons *et al.*, Chapter 10 in this volume): this lag, in part, still exists today.

The development of the discipline of river science

River science is a relatively recent discipline compared to the traditional academic disciplines of biology, chemistry, geology, mathematics and physics. However, river science does have a recognisable lineage within some disciplines, most notably biology, geology, geomorphology, hydrology and limnology. One of the first to document interactions between humans and their environment was George Marsh in 1864 (Lowenthal, 2000). Marsh highlighted the links between the collapse of civilisations through environmental degradation, most notably catchment land-use changes and the resource condition of catchment ecosystems, including its soil and water resources. It is no exaggeration to say that *Man and Nature* (Marsh, 1864) helped launch the modern conservation movement and helped many to recognise the damage that societies across the globe were doing to the natural environment. It also challenged society to behave in more responsible ways toward the earth and its natural systems. *Man and Nature* (Marsh, 1864) stands next to *Silent Spring* (Carson, 1962) and *A Sand County Almanac* (Leopold, 1949) by any measure of historic significance within the modern conservation movement (Lowenthal, 2000).

Three merging paths of activity have advanced our understanding of rivers as ecosystems and their role within the broader landscape since the publication of Marsh (1864). The first path was the articulation of conceptual constructs of the study of rivers and their landscapes. This began with the seminal paper by Hynes (1975) 'The stream and its valley', which acknowledged that hill slopes and fluvial processes are primary drivers of lotic ecosystems. It also provided a frame of reference for adopting a catchment-scale approach to the study of lotic systems and the coupling of hydrology, geomorphology and ecology to advance our understanding of rivers as natural complex systems. Another catalyst for scientific coupling was publication of the *River Continuum Concept* – (RCC) (Vannote *et al.*, 1980) that elegantly if not explicitly, linked hydrological, geomorphological and ecological components of a river system within the context of the longitudinal profile of a river. This was notable in that it took a source to mouth perspective, and indirectly – via reference to the concept of stream ordering (Horton, 1945) – a stream network perspective. The RCC provided the impetus for a relatively rapid progression in the conceptual understanding of river ecosystems; with the publication of the *Serial Discontinuity Concept* (SDC) by Ward and Stanford (1983), the *Flood Pulse Concept* (FPC) by Junk *et al*. (1989) and the *Patch Dynamics Concept* (PDC) by Townsend (1989). The research of Stanford and Ward (1993) on *hyporehos-stream linkages* also reinvigorated research in the field of surface and sub-surface linkages pioneered in the 1970s (e.g., Williams and Hynes, 1974) and provided a clear vertical dimension to our conceptual understanding of lotic systems. Later, the *Fluvial Hydrosystem Concept* of Petts and Amoros (1996) provided one of the first larger scale frameworks with which to view riverine landscapes; an approach carried forward by Dollar *et al*. (2007) and others. Both Petts and Amoros (1996) and Dollar *et al*. (2007) sought to describe patterns in riverine landscape in four dimensions (sensu Ward 1989) and at different scales to establish relationships between the physical character of riverine landscapes and their ecological functioning. The spatial arrangement of both physical and ecological elements within riverine landscapes is largely determined by the flow and sediment (both organic and inorganic) regimes. Functional and genetic links between adjoining components of the riverine landscape often result in clinal patterns conceptualised as continua. However, the integrity of river systems depends on the dynamic interactions of hydrological, geomorphological and biological processes acting in longitudinal, lateral and vertical dimensions over a range of temporal scales. Thus, resultant interactions may also produce riverine landscape mosaics rather than a system solely characterised by gradients. This was one of the central themes explored in the *River Ecosystem Synthesis* (RES) of Thorp *et al.* (2008). As a collective, all of these concepts and theories highlight the need for cross-disciplinary thinking and the importance of multiple scales of investigation for the research and management of riverine landscapes.

The second path was the establishment of the series of symposia under the banner ‘International Symposium on Regulated Rivers’, formerly established in 1985 (cf. Craig and Kemper, 1987), although the original meeting was held in 1979 as a special symposium at the North American Benthological Society meeting in Erie, Pennsylvania, USA, and was called *The* [First] *International Symposium on Regulated Streams* (later referred to as FISORS). Subsequent successful meetings have been held in Australia, Europe and North America. The International Symposium on Regulated Rivers series ended in Stirling, Scotland in 2006 (Gilvear *et al*., 2008). After which it became the biennial conference of the *International Society for River Science* (ISRS). The inaugural meeting of the ISRS was held in Florida in 2009 with subsequent meetings in Berlin, Beijing and La Crosse, Wisconsin, USA in 2015. It was at the meeting in Florida that ISRS became a formal society, with its members focused on the interdisciplinary study of riverine landscapes and its applications to management and policy.

Closely associated with the symposium series was the launch of the journal *Regulated Rivers: Research and Management* in 1987; and this can be considered the third path of convergence in River Science. The journal changed its name in 2002 to *River Research and Applications* (RRA) and became the official journal of ISRS. This name change reflected the need for scientific coupling of traditional disciplines and marked the increased acceptance that River Science required contributions from hydrology, stream ecology, fluvial geomorphology and river engineering to be directed at the subject of understanding river ecosystems and their landscapes. Both ISRS and the journal have explicitly welcomed and encouraged interdisciplinary research and have resulted in an increase to the growing body of knowledge on river ecosystems.

The discipline of river science has in a relatively short period of time grown from its pioneering stage to become established within the community and has reached relative maturity. This is reflected in a meta-analysis of 1506 research publications within the journal *River Research and Applications* and its former iteration, *Regulated Rivers: Research and Management*, from herein termed *River Research and Applications* (RRA). Since the first publication in 1987, each manuscript was assessed in terms of its disciplinary focus. The nine disciplinary areas were: (i) catchment geomorphology; (ii) biology; (iii) chemistry; (iv) ecology; (v) engineering; (vi) fluvial geomorphology; (vii) hydrology; (viii) management; and (ix) policy. The spatial scale of each study was assigned to either the entire fluvial network, river zone, reach or site scale. In addition, the focus and approach of each study was determined as being in-channel, riparian, floodplain, drainage network or the entire system and if it was empirical, modelling or conceptual in nature.

A summary of the meta-analysis RRA research publications assessed is presented in Figure 1.1. There are three salient points emerging from this analysis. First, the number of papers appearing in RRA increased significantly between 1987 and 2013 (Figure 1.1a); (22 in 1987 to a maximum of 137 in 2012). This was also accompanied by increase in the number of RRA journal issues in 1987–2014 from four to ten. However, the number of manuscripts per volume also changed significantly in 2000; in that period the journal changed focus from largely managed and regulated rivers to a river science/river ecosystems focus. An average of 37 research manuscripts per volume were published in the 1987–99 period compared to 73 in 2000–13 (Figure 1.1a). Moreover, there was a steady increase of six additional published manuscripts per volume from 2000–13 contrasting with a relatively stable number of manuscripts per volume 1987–99. Second, a wide ranging set of disciplines has contributed to RRA but the relative contribution of the different disciplines has changed over time (Figure 1.1b). The disciplines of biology (31.8%), ecology (15.5%), geomorphology (15.6%) and hydrology (14.3%) were the major contributors to the journal, in terms of published articles, in 1987–99 compared to 2000–2013, where the disciplines of ecology (34.3%), geomorphology (22.7%) hydrology (14.5%) and management (15.9%) were the dominant contributors. Furthermore, multi-disciplinary studies became more prevalent, rising from 41.1% (1987–99) to 65.1% (2000–13). Third, the spatial scale, locational focus and research approach of the published studies also changed over the same period (Figure 1.1c). In terms of scale, the majority of published studies in 1987–13 were undertaken at the reach (63.8%) or site scales (21.8%). However, following 2000 there was an increase in the spatial scale at which researchers undertook stream and river studies. The number of studies conducted at larger river zone and network scales increased from 4.2% in 1987–99, to 17.7% in 2000–13 and from 1.7% in 1987–99 to 5.7% in 2000–13). Accompanying this was a decrease in site-based studies from 36.3% in 1987–99 to 7.3% in 2000–13. In addition, the number of studies undertaken over multiple spatial scales in 1987–13 increased steadily from a relative contribution of 2% in 1987 to 18% in 2013. Over the same period the locational

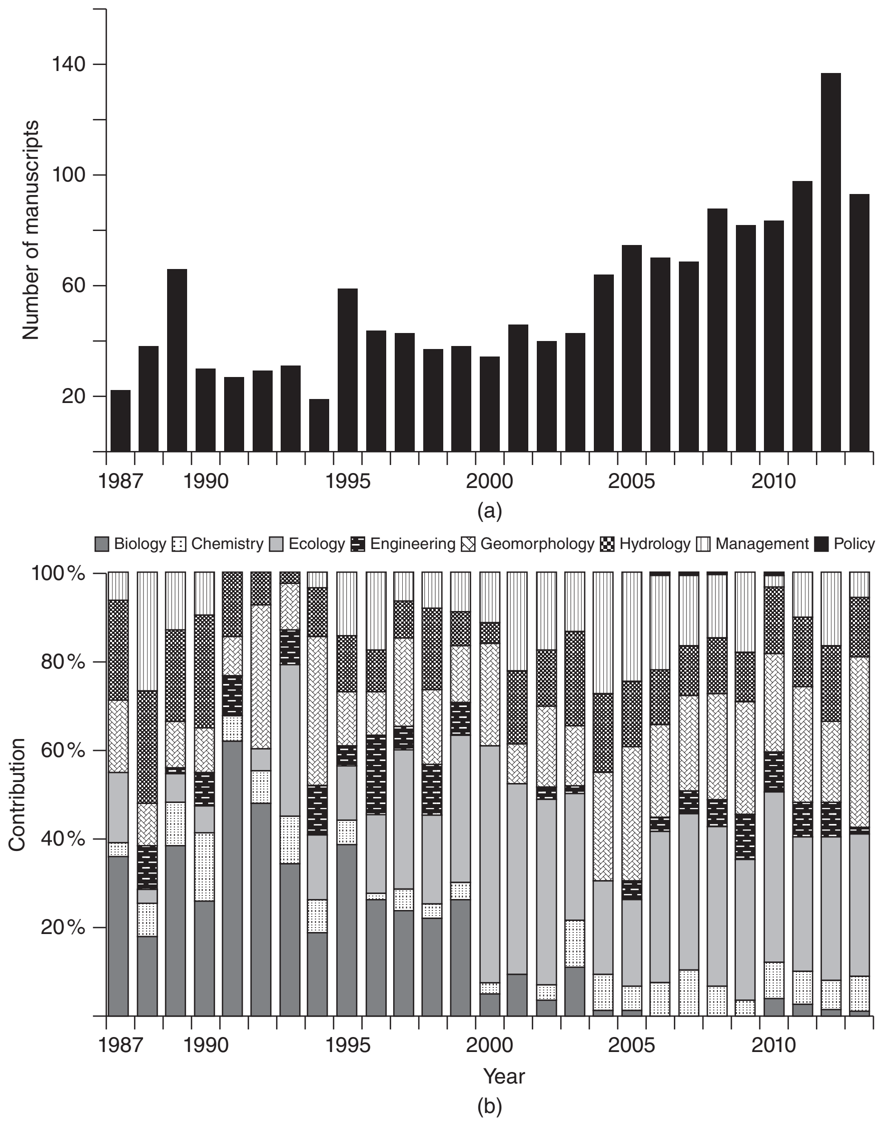

Figure 1.1 Meta-analysis of published research manuscripts in the journals *Regulated Rivers: Research and Management* and *River Research and Applications* for the period 1987–2013. (a) The annual number of publications; (b) the relative composition the various disciplinary foci; and (c) the scale of focus of the various published studies.

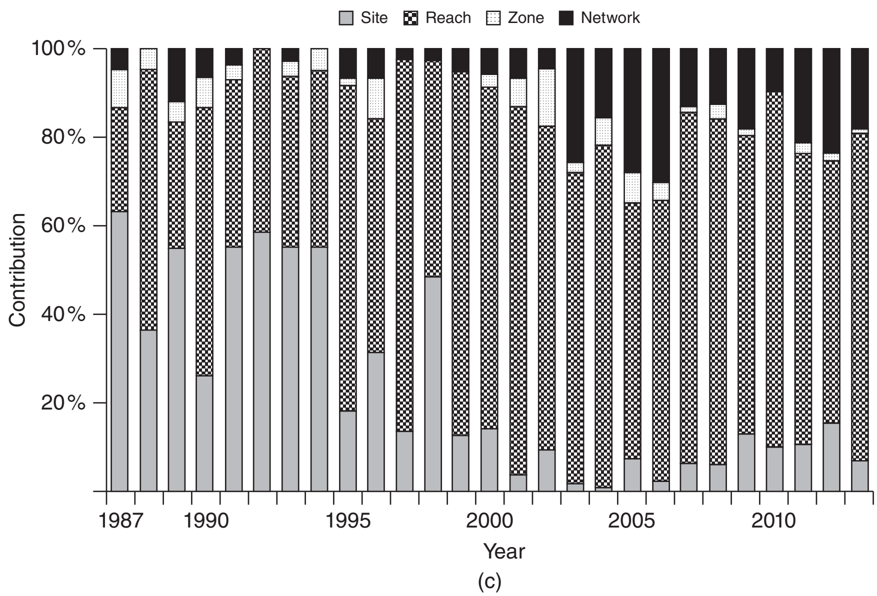

Figure 1.1 (*Continued*)

focus of the studies also changed from being dominated by in-channel focused (76% of studies in 1987–99 to 60% in 2000–13) to having a greater emphasis on entire systems, that is a combined in-channel, riparian and floodplain focus (6.9% of studies in 1987–99 compared to 20.5% in 2000–13). Finally, research publications in RRA are essentially empirical in nature, representing on average 91% of the published studies. This has only changed slightly with conceptual and modelling studies increasing in 2000–13 to contribute 13% of the total published papers.

River science continues to expand from descriptive studies of the physical or biological structure of river channels to a field which includes, among other things, biophysical processes involving conceptual and mathematical modelling, empirical investigations, remote sensing and experimental analysis of these complex process–response systems. These studies are being conducted at both greater (e.g., catchment – continental) and smaller (e.g., fine sediment biochemical processes) scales and more importantly span multiple scales. Through the emergence of a systems approach within science during the 1970s more broadly, an inevitable convergence of individual disciplines towards river science occurred; although the term *river science* would not come into contemporary use until the early twenty-first century.

The domain of river science

To quote Burroughs (1886) and direct it to riverscapes: 'one goes to rivers only for hints and half-truths … their facts are often crude until you have observed them in many different ways and then absorbed and translated these'. Ultimately it is not so much what we see in rivers, rather what we see suggests. The discipline of river science allows those engaged with it to observe rivers, their associated landscapes and ecosystems through a multitude of lenses. Thus, it embraces a continuum of ideas, concepts and approaches, from those having a biotic focus (e.g., aquatic ecology, genetics, physiology) at one end of the spectrum to those with an abiotic focus, most notably hydrology, geomorphology and engineering at the other. Spanning these are those areas of landscape and community ecology and biogeography to mention but a few. Figure 1.2 schematically represents the development of River Science over time. Over the last 45 years, from its foundations in hydrology, geomorphology, ecology and engineering, new disciplines have emerged and coalesced to form the modern day science of rivers. During this time the focus of attention has also shifted to areas outside of the channel bed to the floodplain and hyporheos and from the reach scale to the river network. Closer to the corners of this conceptual diagram of river science are the more singular disciplinary foci, whilst those towards the central regions represent the greater inter-disciplinary elements. The content critical to the subject of river

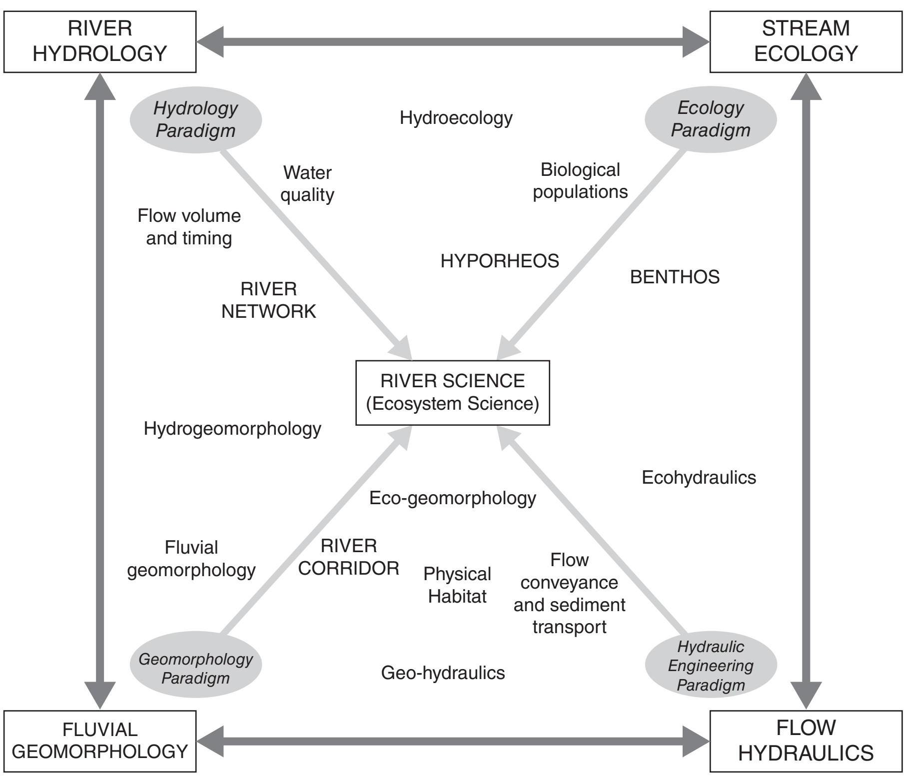

Figure 1.2 The evolution of river science over time from its foundations within river hydrology, fluvial geomorphology, flow hydraulics and stream ecology. The arrows that flow towards the centre of the page, from their subject specific paradigm, are conceptual timelines converging on the subject of river science and its focus on ecosystem science. In two-dimensional space a selection of disciplines and fields of enquiry (shown in lower case font) that emerged over time are shown to illustrate the conceptual development of river science as a subject. The widening of the focus of river science beyond the channel margins is illustrated in the diagram by differing components of river ecosystems (shown in upper case font) with their location reflecting the larger disciplinary area from which they emerged.

science, in terms of understanding river ecosystems, is clearly represented within the chapters in this volume.

Chapters in this volume and book structure

This volume is a reflection of, and a tribute to, the emergence of the discipline of river science and the recognition that it helps to provide an holistic approach through which to study, manage and conserve lotic ecosystems in the contemporary social, political and environmental landscape. Our aim for this edited book was to produce a volume which brings together the multiple strands of research that represent this rapidly developing arena of research (natural science, social sciences, engineering and environmental policy), that would provide a benchmark text for those familiar and new to the concept of river science. In addition, the volume represents a resource that will be valuable to researchers, practitioners, environmental regulators and those engaged in the development or implementation of policy. The volume was also specifically prepared as an acknowledgement of the ongoing commitment to river science provided by Professor Geoffrey Petts, editor in chief of *River Research and Application* over 30 years. To achieve this goal, recognised international research leaders within the field of river science were asked to position their contributions within the context of the historical development of the field, identify key research challenges for the future and highlight the wider societal implications of the research. The volume encompasses a range of chapters illustrating the dynamic nature of riverine processes (Gangi *et al.*, Chapter 14; Gurnell, Chapter 7; Milner *et al.*, Chapter 8; Nestler *et al.*, Chapter 5; Scown *et al.*, Chapter 6; Walling and Collins, Chapter 3) how riverine landscapes support natural ecosystem functioning (Delong and Thoms, Chapter 2; Milner, Chapter 12; Stanford *et al.*, Chapter 13) and how this knowledge can be used to inform policy and management practices (Foster and Greenwood, Chapter 4; Gilvear *et al.*, Chapter 9; Gore *et al.*, Chapter 15; Mant *et al.*, Chapter 16; Wilby, Chapter 18). The chapters clearly illustrate the relevance of river science to all parts of contemporary society, from the scientific community through to those living alongside rivers, of the physical, economic, cultural and spiritual benefits and risks associated with our ongoing relationship with rivers (Parsons *et al.*, Chapter 10; Wood *et al.*, Chapter 11; Yeakley *et al.*, Chapter 17). Collectively, the chapters demonstrate the growing maturity of river science and its central place in the management and conservation of rivers across the globe.

The book is comprised of two sections: Part 1 provides an overview of some fundamental principles of river science (Chapters 2–10), from its early development within the confines of traditional academic disciplines through to contemporary interdisciplinary research, which transcends traditional disciplinary boundaries and addresses research questions at multiple spatial (site through to catchment) and temporal scales (days to millennia) and also within the context of an ecosystems framework. Part 2 (Chapters 11–18) comprises a range of case studies, which illustrate how contemporary river science continues to address fundamental research questions regarding the organisation and functioning of river systems, how anthropogenic activities modify these systems and how we may ultimately manage, conserve and restore riverine ecosystems to sustain natural functioning and ecosystem health, and also to support the needs of an ever thirsty society for water, energy and the services that rivers provide.

We realise that a book of this nature could never realistically hope to cover all aspects of contemporary river science. Indeed, we are conscious that this volume only touches on the burgeoning body of research centred on the biogeochemistry of riverine ecosystems, such as nutrient spiralling (von Schiller *et al.*, 2015) and the processing, storage and transport of dissolved organic matter (DOM) and dissolved organic carbon (Singh *et al.*, 2014). We also recognise that the current volume only touches on issues associated with the impacts of, and future threats posed by, invasive/non-native species on lotic ecosystems across the globe (Scott *et al.*, 2012). In addition, the chapters exclusively address the upper and middle reaches of riverine catchments and they do not consider the interface between what many consider the end of the river, the brackish/estuarine system (Jarvie *et al.*, 2012). It is hoped that by following both the themes and topics illustrated in this volume, together with new initiative ideas, an in-depth and broadening knowledge of river science will be established.

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