RIVER SCIENCE

RESEARCH AND MANAGEMENT FOR THE 21ST CENTURY

Edited by
David J. Gilvear, Malcolm T. Greenwood,
Martin C. Thoms and Paul J. Wood

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Dedication

This volume is dedicated to Geoff Petts – vice chancellor, professor, river scientist, teacher, colleague and friend, whose inspiration and fortitude in bringing together the many elements fundamental to our understanding of river science have been a platform for many; without his visionary ideas river science would not be as advanced as it is today.

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Preface

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When I was appointed to the Chair of Physical Geography in the University of Southampton in 1976 I asked my Exeter research students if they wished to move with me or preferred to stay at the University of Exeter. The one research student who decided to move was Geoff Petts – surprising in some ways because he had already completed two years research so the move would be for his final writing-up year. Although I thought that it was a good idea to get experience of two universities, I had not influenced Geoff's decision, but later realised that this was typical of his subsequent career – the ability to see the potential as opportunities became available.

A foundation

Geoff had graduated from the University of Liverpool in 1974 with a joint honours degree in Physical Geography and Geology. The NERC studentship at the University of Exeter that we had obtained for research on river channel adjustments downstream from reservoirs was the second of a series awarded for investigations of river channel adjustments arising from a range of different causes. The empirical approach employed used field measurements of channel capacities downstream from dams in 13 areas throughout England and Wales to compare with the dimensions of unregulated channels. At that time there had been comparatively few such investigations, and indeed the effects of human activity on river channels had not been explicitly explored until classic papers by Wolman (1967a,b; see Gregory, 2011), although scour below dams had been surveyed by engineers as a necessary input to dam construction. The Tone had been investigated (Gregory and Park, 1974) but the results obtained by Geoff from a range of UK areas greatly extended understanding of changes that could occur. Areas studied included the Derbyshire Derwent where, in addition to comparing the size of channels downstream from reservoirs with channel size along unregulated rivers showing that capacities were reduced to c. 40% of the expected size, Geoff also demonstrated how a bench formed within the channel had produced the reduction in capacity and that dendrochronology could be used to date trees that had grown on the benches. This allowed confirmation that the reductions in capacity had occurred at dates corresponding to reservoir construction.

This research (Petts, 1978) was one of a series of NERC studentship investigations which deliberately focused on the national picture so that instead of concentrating on a single field area, then very popular with the growth of process-based investigations, the intention was to address large-scale problems by employing empirical measurements from several different areas of Britain. Such an approach was demanding for a research student, but Geoff demonstrated his ability to apply himself to the opportunity, assembling the literature context from the international publications, undertaking field surveys upstream and downstream from reservoirs in different areas of the country, then proceeding to identify the significance of event effectiveness, of sediment availability, of vegetation indicators, culminating in establishing the appropriate elements of a general model including relaxation paths of complex response. This resulted in an impressive array of papers dealing with the channel change effects downstream of the Derwent dams (Petts, 1977), with the application of complex response to channel morphology adjustments (Petts, 1979), with the range of channel changes in regulated rivers (Petts, 1982) and with implications for stream habitats (Petts, 1980a) introducing a link with aquatic ecology that was subsequently to feature throughout Geoff's later research. At a time when specific applications of research results were not often considered, he appreciated the potential significance of the research results for management (Petts, 1980b) which were considered in relation to long-term consequences (Petts, 1980c).

Having established his publication record so effectively, Geoff then had the vision to produce a book *Impounded Rivers* (Petts, 1984a) – which he described as the 'outcome of seven years of research and discussion with friends and professional colleagues'. This book was notable in that it contained hydrology, water quality, morphological effects, ecological aspects including vegetation and macroinvertebrates as well as fisheries, thus providing a truly multi-disciplinary approach to management problems and prospects that were the subject for the final chapter. This book demonstrated the value of providing a context and approach, which we would now refer to as holistic, to succeed the preceding engineering emphasis. In the final part of the preface to his book, Geoff made a plea for a long-term perspective in river management (Petts, 1984a, xv), a theme which he has pursued in much of his later work.

Explanation of the detail of his early research is necessary because it shows how these foundations were fundamental for the way in which he has been able to develop his career. After gaining his PhD he was first appointed in 1977 to the Dorset Institute of Higher Education (later to become part of the University of Bournemouth), but then in 1979 was appointed as lecturer in geography University of Loughborough where he remained until 1994, being senior lecturer (1986–89), Professor of Physical Geography (1989–94) and head of Geography (1991–94). In 1994 he was appointed Professor of Physical Geography University of Birmingham becoming Director of Environmental Science and Management (1994–97), he founded the University's Centre for Environmental Research and Training (CERT) in 1996, became Director of Environmental Science and Training in 1997, Head of the School of Geography and Environmental Science from 1998–2001, and then Pro-Vice Chancellor from 2001–07. With this background and progression it was perhaps inevitable that a move to lead an institution would follow, and in 2007 Geoff became Vice Chancellor and Rector of the University of Westminster. On taking up his post he said 'I am particularly looking forward to working in partnership with staff, students and other stakeholders to grow the University's contributions to the emerging economic, social and environmental demands of urban life in London and other cities across the globe'.

Research development and impacts

A career involving progressively greater amounts of administration, at Loughborough, Birmingham and Westminster, could have led to a decline of further research, publication and scientific impact, but Geoff has proved to be one of those individuals who maintains his academic contacts. His contributions can be encapsulated in terms of his developing research on flow regulation, the books and contributions in edited volumes that he has produced, and the establishment of the journal *Regulated Rivers*. Furthermore, by pursuing these three themes he has produced enlightening general perspectives, has established collaboration with many other scientists, including many international colleagues, especially European.

Research on flow regulation continued with investigations of a number of other areas leading to the context of flow regulation impacts, progressing research towards other themes. Further investigations of morphological change included the lowland English river Ter, Essex (Petts and Pratts, 1983) and the Rheidol in Wales (Petts and Greenwood, 1985). Whereas ecological changes had previously often been analysed independently from morphological changes, Geoff was involved in research combining the two (e.g., Petts and Greenwood, 1985) and also provided important dimensions such as timescales for ecological change (Petts, 1987). Although changes in water quality and reduced sediment transport downstream of dams had previously been investigated, Geoff was involved with analysis of monitored results from a controlled release from Kielder reservoir on the North Tyne (Petts *et al*., 1985), analysed sedimentation along the Rheidol (Petts, 1984) and bar development along the North Tyne (Petts and Thoms,1987). Although ecology and its relation to morphological changes had been major sections of his book (Petts, 1984) other aspects were subsequently explored including invertebrate faunas (Petts and Greenwood, 1985), the macroinvertebrate response and physical habitat change to river regulation on the River Rede (Petts, Armitage and Castella, 1993), and the effects of water abstractions on invertebrate communities in UK streams (Castella *et al*., 1995). Such specific investigations allowed elaboration of more general ecological concerns such as a perspective on the abiotic processes sustaining the ecological integrity of running waters (Petts, 2000), dams and geomorphology (Petts and Gurnell, 2005), a scientific basis for setting minimum ecological flows (Petts *et al*., 1995), and reservoir operating rules to sustain environmental flows in regulated rivers (Yin, Xin'an *et al*., 2011).

Flow regulation research led to evaluations of water resources such as the case of Lake Biwa, Japan (Petts, 1988), in turn leading naturally to concern for management problems such as the management of fish populations in Canada (Petts *et al*., 1989), advancing science for water resources management (Petts *et al*., 2006), linking hydrology and biology for assessing water needs for riverine ecosystems (Petts e*t al*., 2006), the role of ecotones in aquatic landscape management (Petts, 1990), and sustaining the ecological integrity of large floodplain rivers (Petts, 1996).

Such general themes inevitably meant that Geoff was able to make a very significant contribution in text books and edited volumes – both influential in shaping the development of a subject at a particular stage of its research development. Since *Regulated Rivers* (Petts, 1984a) Geoff has been involved in writing and editing more than 20 books. Texts contributing to the advancement of understanding of rivers include *Rivers and Landscape* (Petts and Foster, 1985), *The Rivers Handbook* Volume I (Calow and Petts, 1992), Volume II (Petts and Calow, 1994) and *Fluvial Hydrosystems* (Petts and Amoros, 1996). Such volumes demonstrated the benefits of multi-disciplinary approaches and Geoff Petts has galvanised the production of edited volumes that have been significant in bringing research results together at a time when branches of disciplines are evolving and hybrid approaches are being articulated. Thus *Regulated Rivers in the UK* (Petts and Wood, 1988) demonstrated the state of the art in relation to river regulation effects, *Historical Analysis of Large Alluvial Rivers in Western Europe* (Petts *et al*., 1989) achieved a similar result for channel changes in Europe, and *Global Perspectives on River Conservation* (Boon *et al*., 2000) provided a timely world approach to an inter-disciplinary field.

A recurrent theme emerging from these publications has been the commitment that Geoff has shown to multi-disciplinary approaches, and an outstanding contribution was the way in which his idea for a journal led to *Regulated Rivers* – first published in 1987. This interdisciplinary journal, for which Geoff still continues as Managing Editor, evolved from *Regulated Rivers: Research and Management* (1987–2001) to *River Research and Applications*, having achieved its stated aim to become an international journal dedicated to the promotion of basic and applied scientific research on rivers. In 2010 it appeared as 10 issues with 1314 pages developing from the four issues per year with 375 pages in 1987. It is now an established international journal ranked second in the Science Watch list for Water Resources 1981–2009.

Such progress in publication and research has positioned Geoff to make significant general contributions including changing river channels: the geographical tradition in which he compared the geographical approach with the geological and engineering traditions and advocated a return to large rivers and linking geomorphology and ecology (Petts, 1995). Other position statements have included advancing science for water resources management (Petts *et al*., 2006), research progress and future directions for dams and geomorphology (Petts and Gurnell, 2005), instream-flow science for sustainable river management (Petts, 2009), and our collaborative proposal for restructuring physical geography (Gregory *et al*., 2002). The direction of Geoff's scientific contributions has necessitated collaborative work and multi-authored publications – a necessary characteristic of research publication since the days of Geoff's first research. Collaboration with research students, with research grant investigators and with associates from international organisations has been very beneficial and, for example, collaboration with Angela Gurnell has been reflected in publications in the fields of glacial geomorphology, fluvial geomorphology in Italy, including the Tagliamento – encompassing the intriguing paper on trees as riparian engineers (Gurnell and Petts, 2006). The substantial range of associates in the past is testified to by the authors of the chapters of this volume, combining intersection with the phases of his career and the range of disciplines transected in that career.

Recognition

With research output of more than 20 books and 100 scientific papers and as founder and Editor-in-Chief of the international journal *River Research and Applications* it is appropriate that there has already been significant acknowledgement and recognition of the contributions that Geoff has made. He has been a member of several scientific advisory committees including the

International Council for Science (ICSU) Scientific Committee on Water Research; UNESCO IHP Eco-Hydrology Programme; and US Department of the Interior, Fish and Wildlife Service, Long-term Monitoring Programme for the upper Mississippi River. He has been invited to give numerous keynote addresses, he was Director of the International Water Resources Association (1992–94), a Council Member of the Freshwater Biological Association (2000–03), and was appointed Vice President of the new International Society for River Science which was launched in 2006. In 2007, he was awarded the Busk Medal of the Royal Geographical Society for his contributions to inter-disciplinary research on river conservation; in conferring the award the President commended the way in which he had forged inter-disciplinary links between geographers, civil engineers, biologists, ecologists and conservationists. His track record makes it very appropriate that he received a Lifetime Achievement Award from the International Society for river science in 2009.

Following such recognition it is equally appropriate that this collection of essays is published to honour the contribution that Geoff has made, particularly when he has done much to influence the progress of river science with responsibility for founding the journal *Regulated Rivers*. His essential characteristics that have pervaded his academic career include dynamism, opportunism, vision and a multi-disciplinary focus. It is his particular combination of attributes and skills that have enabled him to make a lasting contribution. In his speech receiving the Busk Medal at the RGS in September 2007, Geoff acknowledged his parents giving him a subscription to the *Geographical Magazine* – which he said meant that his 'future was set by the excitement of the topics being reported'. He has managed to continue and convey that excitement throughout his work and it has spilled over in his other interests, particularly hockey and cricket later supplemented, (or succeeded?), by golf and fishing.

Geoff's research began with river regulation: careers such as his can include changes which are analogous to construction of a dam which retains most of the discharge so that relatively little research is published after administration and leadership begin to dominate. However, as Geoff's career has been regulated, he has continued to research and publish and to influence the development of river science in a variety of ways. It is therefore excellent that Geoff's contribution has provided the raison d'etre for this book and that the editors have been so effective in organising such an illustrious list of authors and managing the production of such a timely volume.

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CHAPTER 1

An introduction to river science: research and applications

Martin C. Thoms[1], David J. Gilvear[2], Malcolm T. Greenwood[3] and Paul J. Wood[3]

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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

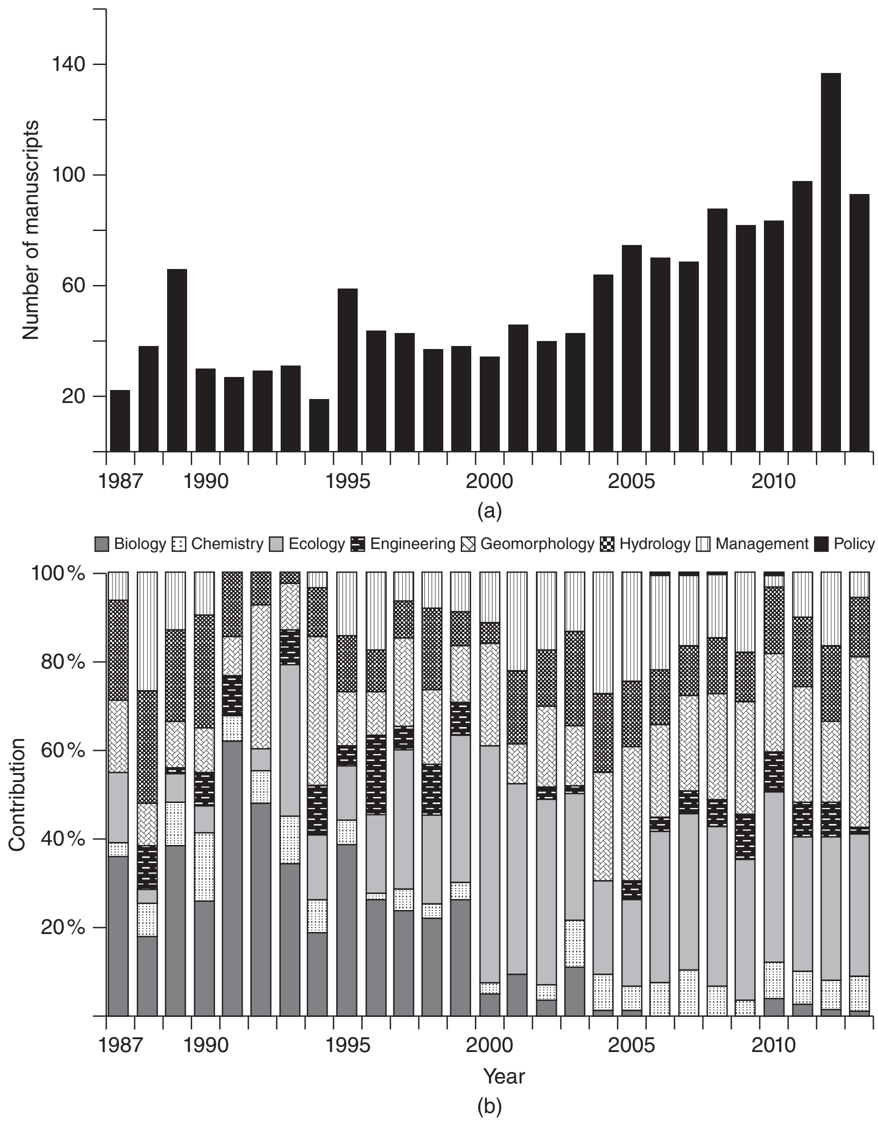

Figure 1.1 Meta-analysis of published research manuscripts in the journals *Regulated Rivers: Research and Management* and *River Research and Applications* for the period 1987–2013. (a) The annual number of publications; (b) the relative composition the various disciplinary foci; and (c) the scale of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

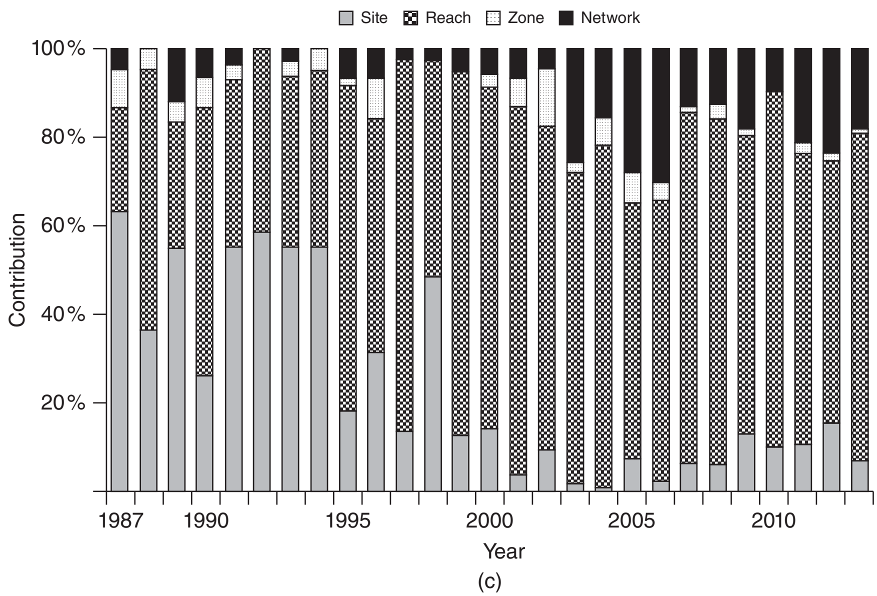

Figure 1.1 (*Continued*)

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

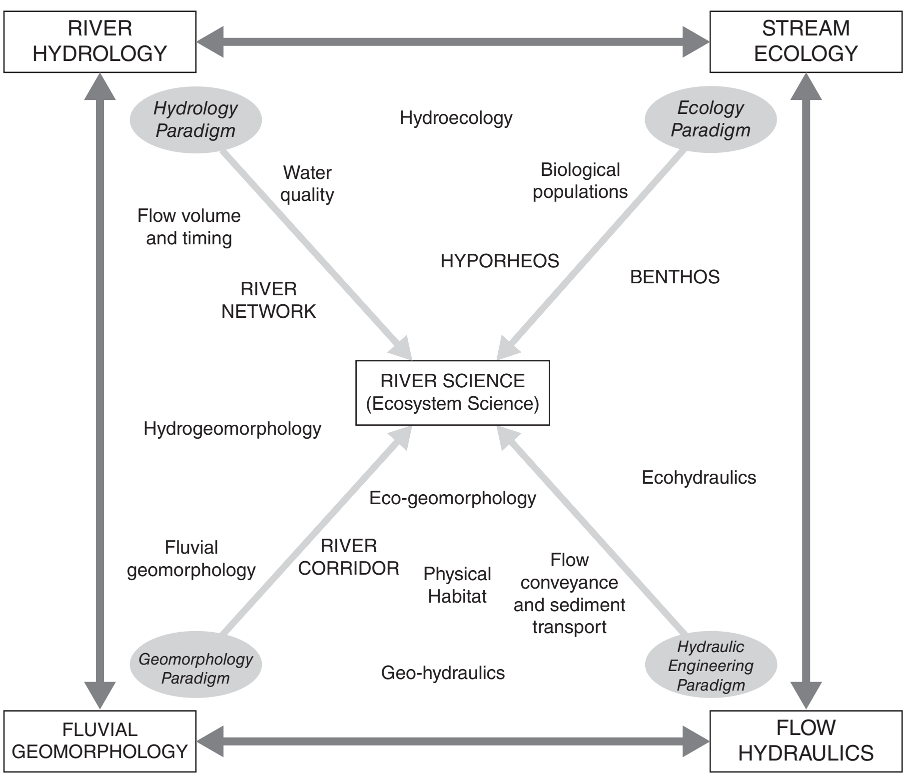

Figure 1.2 The evolution of river science over time from its foundations within river hydrology, fluvial geomorphology, flow hydraulics and stream ecology. The arrows that flow towards the centre of the page, from their subject specific paradigm, are conceptual timelines converging on the subject of 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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PART 1

Fundamental principles of river science

CHAPTER 2

An ecosystem framework for river science and management

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Introduction

River science, the interdisciplinary study of fluvial ecosystems, focuses on interactions between the physical, chemical and biological structure and function of lotic and lentic components within riverine landscapes (Thoms, 2006; Dollar *et al.*, 2007). These interactions are studied at multiple spatiotemporal scales within both the riverscape (river channels, partially isolated backwaters, and riparia of small streams to large rivers) and the surrounding floodscape (isolated oxbows, floodplain lakes, wetlands, and periodically inundated drylands). 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 and experimental analysis of these complex process–response systems. This emergence has also seen river scientists contributing effectively at the turbulent boundary of science, management and policy (Cullen, 1990, Parsons *et al.*, Chapter 10).

Successful interdisciplinary science requires the merger of two or more areas of understanding into a single conceptual–empirical structure (Pickett *et al.,* 1994; Thoms, 2006). Implicit to this process is the development, testing and application of new ideas, as well as the continued integration of concepts, paradigms and information from emerging sub-disciplines and other scientific fields that operate across a range of domains, scales and locations. The progression of science is a dynamic process influenced by current and historical developments, with the accumulation of knowledge within formal logical frameworks. Such frameworks are often built from direct observations which are synthesised within hypotheses and then empirically tested (Graham and Dayton, 2002). Frameworks are useful tools for achieving integration of different disciplines and have been used in many areas of endeavour. A framework is neither a model nor a theory; models describe how things work, theories explain phenomena, whereas frameworks show how facts, hypotheses and models may be linked (Pickett *et al.*, 1999) Frameworks, therefore, provide a way

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of ordering phenomena, thereby revealing patterns of structure and function (Rapport, 1985). The continued development of river science and the exchange of its endeavours with management require a diversity of frameworks, study designs and research questions and a commitment to the dual process of developing and testing theories and their application into the domain of management. While these steps are important to any field of enquiry, it is also crucial to challenge concepts and the prevailing 'wisdom' so as to: avoid stasis; accurately integrate fundamental knowledge within applied policies; and to ensure transfer of reliable information to future generations of scientists.

There is an intimidating array of 'models', 'concepts' and 'theories' on the nature of fluvial ecosystems to consider when developing a framework for research, rehabilitation or management. As the chapter title implies, a critical element of developing a viable framework is the incorporation of an ecosystem approach, the value of which has been described as having three dimensions of influence (Pickett and Cadenasso, 2002). First is that its basic definition is inclusive and free of limiting assumptions; second, its ability to be expressed in a range of models that articulate the components, interactions, extent and boundaries of the ecosystem under investigation; and, finally the powerful influence it can have in social discourse through its metaphorical strengths.

An ecosystem is a spatially explicit unit of the Earth that includes all of the organisms, along with all of the abiotic components within its boundaries (Tansley, 1935). This definition establishes that there is a clear spatial (and temporal) dimension to an ecosystem. Moreover, 'spatially explicit' and 'within its boundaries' infer that an ecosystem approach is not just limited to the ecosystem level of organisation; it can be used consider biotic–abiotic interactions across many levels of organisation. From this perspective, a river basin, a lateral channel or a single rock can be viewed as an ecosystem if appropriate boundaries and scale are applied (sensu Likens 1992). An ecosystem approach allows for examination of form and processes across different disciplines through consideration of both biotic and abiotic interactions, thereby providing the holistic approach needed for an applicable framework.

To understand the behaviour and begin to manage rivers as ecosystems requires a holistic, interdisciplinary approach that simultaneously considers their physical, chemical and biological components (Dollar *et al.*, 2007; Thoms, 2002; Thorp *et al.*, 2008). Interdisciplinary research is fraught with many problems including different approaches and conceptual tools, hence disciplinary paradigms lose their usefulness in the interdisciplinary arena. Development and use of common frameworks can alleviate this. The objectives of this chapter are to:

- provide a historical overview of different models of river ecosystems, including their genesis, strengths, limitations and potential to aid in interdisciplinary science and management of river ecosystems;
- outline a conceptual framework for use in the research and management of river ecosystems; and,
- highlight the use of such a framework in the research and management of riverine landscapes.

To accomplish these objectives, we propose a shift in how river networks are viewed for research and management. To truly continue forward, it is essential that we look where we have been by examining past models and, from there, ascertain the best approach for achieving a framework that fits the criteria described previously in this chapter.

A brief history of models that have contributed to our understanding river ecosystems

Fish and biocoenotic zones

One of the earliest efforts toward a general model of the structure and function of river ecosystems emanated from Europe during the latter part of the nineteenth century. Its focus was on the classification of river networks with the division of the network into five 'fish zones' (Hynes, 1970; Hawkes, 1975). These zones, which were named for dominant species of fish within a given river, were fixed in their longitudinal location and had abrupt transitions from one zone to the next. In addition, locations of these non-repeatable sections were considered highly predictable from upstream to downstream. This was later modified to include physical and chemical characteristics of each zone (e.g., Huet, 1959; Aarts and Nienhuis, 2003). Testing this model outside the region of its development highlighted several limitations to the zonation of river networks by fish zones (Aarts and Nienhuis, 2003). The primary limitation was that discontinuities in river basin geomorphology interfered with the expected pattern of fish zones, often resulting in the repeated occurrence of zones throughout a river (e.g., Tittizer and Krebs, 1996). Fish zones were later represented as biocoenotic zones, where the intent was to consider all aquatic organisms (Illies and Botosaneaunu, 1963), and later hydrological characteristics (Arts and Nienhuis, 2003). Despite these changes, other problems with the model became evident, specifically: (i) the predicted sequence of zones differed from one river to the next; (ii) some zones were absent from rivers; and (iii) some zones repeated along the downstream gradient of rivers. With few exceptions (e.g., Aarts and Neinhuis, 2003), fixed/biocoenotic zones are now rarely seen in the literature.

River continuum concept

Biocoenotic zonation was replaced by the river continuum concept – RCC (Vannote *et al*., 1980). The RCC addressed limitations of biocoenotic zones by attempting to explain longitudinal changes in ecosystem form and function. It was designed to reflect gradual downstream transitions that had been observed in studies that found conflicts with the abrupt changes prescribed by fixed/biocoenotic zonation. The central premise of the RCC was that hydrological and geomorphological conditions change predictably from headwaters to terminus within a river network and with these come concomitant shifts in ecological processes and community structure. The RCC was simplified to describe ecological changes relative to stream order as the basis for defining the location of physical and ecological components longitudinally. One component that remained consistent between the RCC and biocoenotic zones was that both emphasised the longitudinal dimension and asserted there were predictable, fixed (in terms of location along the longitudinal gradient) zones with specific physical and ecological attributes, hence the RCC provided a model that was more broadly applicable than the taxon-specific methodology of biocoenotic zones. Moreover, relating expected ecological and physical conditions to stream order made it readily applicable to both researchers and managers.

Testing of the RCC began immediately after its publication and it still serves as a useful null hypothesis for river ecosystem studies. While some studies found support for the RCC (i.e., Culp and Davies, 1982; Cushing *et al.*, 1983; Minshall *et al.*, 1983), many questioned its general applicability. Townsend (1989), in a review of aquatic ecological concepts, stated in regard to the applicability of the RCC that it '… is remarkable primarily because it is not usually realized and cannot provide a world-wide generalization'. This shortcoming has been observed in studies of community structure (e.g., Winterbourn *et al.*, 1981; Perry and Schaeffer, 1987) as well as predictions on trophic dynamics in streams and rivers (e.g., Lewis *et al.*, 2001, Delong and Thorp, 2006; Lau *et al.*, 2009). The value of using production/respiration ratios as a measure of trophic status has also been called into question given that river networks are largely heterotrophic (P/R < 1) because of microbial production that is typically independent of metazoan production (Thorp and Delong, 2002; Marcarelli *et al.*, 2011). Thus its usefulness in underpinning a framework on how to approach the interdisciplinary study of riverine landscapes and their management is limited.

Studies contradicting the RCC typically tied their findings to differences in local lithology, geomorphology and hydrology. While based on the hypothesis of gradual changes in stream characteristics, the RCC suffered one of the same limitations as fixed/biocoenotic zones; specifically, it did not account for differences in geomorphology and the repeatability of 'zones' within and among river networks. A subsequent revision of the RCC by Minshall *et al.* (1985) acknowledged the need to account for climate, local lithology, and geomorphology in its predictions: 'Further reflection (on the classic view of rivers) indicates that the ideal rarely is so clearly achieved' (Minshall *et al.*, 1985). It was suggested in this revision that expected differences in ecological and physical conditions should be viewed on a sliding scale where, as an example, a braided fifth-order channel might be better explained by viewing it as five third-order channels (Minshall *et al.*, 1985). In essence, the modifications of the ecological predictions of the RCC were to consider deviations created by geomorphology, lithology, tributaries and climate on a sliding scale that was still based on stream order.

The frequent inability to get a fit between ecological structure and processes and the conceptual basis of the RCC can be linked to the hydrogeomorphic concepts on which it is based. The hydrogeomorphic basis of the RCC is drawn from a suite of studies described by Leopold *et al.* (1964) on the longitudinal morphology of river channels. While these studies did describe conditions where a continuum of fluvial processes and morphology could occur, they emphasised that these circumstances were not applicable to all rivers and in fact were rare (Leopold *et al.*, 1964). In addition, much of the underlying physical basis of the RCC relies on stream order, which does not provide a meaningful template for describing hydrogeomorphic processes within river systems (Gregory and Walling 1973). The lack of a hydrogeomorphic continuum was further emphasised by Statzner and Higler (1985), who examined hydrological data of the rivers used by Minshall *et al.* (1983) and demonstrated no uniform longitudinal pattern to measures of hydraulic stress. Large-scale hydraulic discontinuities do occur in rivers (Statzner and Higler, 1985) and the simplicity of the relationship between physical and biological gradients within river networks is overstated in the RCC. Also lacking from the physical component of the RCC is consideration of the stochastic nature of rainfall and runoff patterns that have a tendency to create hydrological discontinuities.

The apparent lack of congruence in the physical template of the RCC and associated ecological discrepancies *does not* provide a viable working model for scientists and managers except in its usefulness as a starting null hypothesis. The intent of the RCC was to provide a cohesive basis for the study of river networks through the integration of physical and biological gradients (Minshall *et al*., 1985). This is reflected by Cushing *et al*. (1983), who stated that 'streams are best viewed as gradients, or continua, and that classification systems which separate discrete reaches are of little ecological value'. Furthermore, the emphasis on longitudinal change in physical structure and associated ecological processes was done in the absence of scale. Minshall *et al*. (1985) does address spatial and temporal heterogeneity in the context of its influence on the habitat templet (sensu Southwood 1977) but the RCC does not account for how physical and biological structure at smaller spatial scales may shape structural organisation at larger spatial scales (e.g., Boys and Thoms, 2006) or the influence of physical and ecological change occurring at multiple spatial and temporal scales.

Riverine ecosystem synthesis

Neither biocoenotic zonation nor the RCC has the potential to provide a basis upon which river research or management can be placed. While many reasons have been provided (Poole, 2002; Thorp *et al*., 2008), chief among these is the failure to recognise that physical conditions are not always highly predictable on a longitudinal gradient and that a given set of hydrogeomorphic conditions can be repeated at multiple locations within a river network. Recognition of these attributes emerged in the late twentieth century as scientists came to appreciate river networks as a mosaic of patches existing at multiple spatial and temporal scales, with the type and arrangement of these physical patches influencing ecological form and function (e.g., Thoms, 2006; Townsend, 1989).

Physical patch structure of rivers was increasingly emphasised around the turn of the twenty-first century, and a series of concepts such as the process domain concept (Montgomery, 1999), river discontinuum (Poole, 2002) and hydrogeomorphic zones (Thoms, 2006) emerged. These various concepts put forward the view that rivers resemble a mosaic of physical patches operating at multiple spatiotemporal scales, where patches can be defined by their hydrological, sedimentological and morphological attributes independent of location within the stream network. The concepts of Poole (2002) and Thoms (2006) went further to note that patches can be found at multiple locations within a stream network where similar hydrological and geomorphological conditions exist. Development of the hydrogeomorphic mosaic is based on well-established principles of fluvial geomorphology and landscape ecology and complements the independent work of Townsend (1989) who suggested that a unifying stream framework based on the patchy nature of rivers would provide a more realistic and generalised means of examining ecological processes than continuum/clinal based concepts.

The riverine ecosystem synthesis (RES), integrates the hydrological and geomorphological constructs of the hydrogeomorphic mosaic perspective with expected ecological responses to the physical mosaic of river networks (Thorp *et al.*, 2008). This is where the RES departs from other concepts and models. While biocoenotic zonation and the RCC emphasised longitudinal patterns and were limited to what could best be considered fixed large-scale patches, the conceptual approach of the RES recognises that hydrogeomorphic–ecological linkages operate at multiple scales. Additionally, the RES does not have a preconceived bias of 'I am in "X" stream order, therefore I should expect "Y" physical conditions and "Z" ecological processes'. Instead, the RES calls for an analytical approach to allow for self-emergence of where you are and what should be expected. More importantly, this concept departs from the location-specific approaches that have constrained the advancement of river science and broader applications of what we learn (sensu Fisher 1997).

Patches are hierarchically organised in time and space within the RES, with each patch type possessing intrinsic hydrological, sedimentological and geomorphological attributes. Ecological traits, in turn, are also hierarchically organised, thus allowing for integration of hydrological, geomorphological and ecological character appropriate for the scale of interest in research and management. Patches vary in hydrological variability and physical complexity, including potential differences in number and permanency of lateral channels, spatial diversity of current velocities, temporal variability in flow/flood pulse rate and extent, substrate size and variability, chemical characteristics, riparian–channel interactions and riverscape–floodscape exchanges. Included at larger spatial scales are functional process zones (FPZs), which are repeatable along the longitudinal dimension and only partially predictable longitudinally, especially when comparing among ecoregions.

The hydrogeomorphic patch approach contrasts sharply from the longitudinal perspective by recognising that rivers are more than a single thread passing through a terrestrial landscape (c.f., Ward and Tockner 2001). This view has been emphasised by others through observation of the heterogeneous and discontinuous nature of river systems (Fausch *et al.*, 2002; Ward *et al.*, 2002; Thorp *et al.*, 2008; Carbonneau *et al.*, 2012). It is for this reason that a foundational property of the RES is recognition that river networks must be viewed as mosaics consisting of patches of differing size, quality and character as a function of their hydrological and geomorphological condition (Wiens, 2002; Thorp *et al.*, 2008). Additionally, the hydrological and geomorphological attributes of these patches will shape ecological structure and processes within these patches. The character of patches, therefore, establishes the basis on which the structure and function of river systems should be considered in research and management.

The scalar nature of patches leads to an additional key point on which the RES is based; specifically, the acknowledgement that river networks are comprised of hierarchically arranged patches that are formed by hydrological and geomorphological processes. Patches are not isolated entities functioning wholly independently of their surroundings. Ecological and hydrogeomorphic characteristics of patches are also shaped by their association with adjacent patches. The type and arrangement of smaller patches within any portion of the river network gives rise to distinctive, larger-scale patches with their own inherent qualities. The location of a patch, regardless of its scale, will be based on its hydrological and geomorphological character, giving their location low predictability along the longitudinal gradient of the network (Poole, 2002). A further advantage of the hierarchical nature of patches is that it provides a mechanism for clearly defining boundaries. Clearly defined spatial and temporal boundaries allow for clearer definition of the processes, both physical and ecological, operating within a patch and to delineate flow pathways across patch boundaries (Cadenasso *et al.*, 2003; Strayer *et al.*, 2003).

Underlying concepts for the use of frameworks in River Science

The complexity of riverine landscapes challenges many traditional scientific approaches and methods (Dollar *et al.*, 2007). A river's multi-causal, multiple-scale character constrains the usefulness of conventional reductionist-falsification approaches, except when applied at very small scales and within limited domains (Thoms and Parsons, 2002). The complex character of rivers instead requires a more iterative process that is scale aware, akin to what Pickett *et al.* (2007) labelled the new philosophy of science. Frameworks for the successful interdisciplinary study have been proposed; most notably that by Thoms (2002) and Dollar *et al.* (2007). Here we review the underlying concepts of these, the majority of which are based upon hierarchy.

A hierarchy is a graded organisational structure. A hierarchical level (or holon) is a discrete unit within a system and the features of a level reflect both the level above it and those of the level below it within the hierarchy (Figure 2.1). Higher levels within a hierarchy exert some constraint on lower levels, especially the level immediately below (i.e., L-3 influences L-4 more than it does L-5; Figure 2.1). Conversely, lower levels influence the structure and functioning of those at higher levels, particularly the level immediately above. Therefore, downward constraints and upward influences explain the character most strongly at the adjacent levels, and this gives rise to emergent properties of the level of interest. It is also important to note that a level within a hierarchy is not a scale but may be characterised by a scale (O'Neill *et al.*, 1989).

Scale defines the physical dimension of an entity and Quinn and Keogh (2002) characterise scale in terms of grain and extent. Grain refers to the smallest spatial or temporal interval in an observation set and it has also been referred as the smallest scale of pattern to which an organism may respond (O'Neill *et al.*, 1989) or the smallest scale of influence of an ecosystem disturbance or process driver (Rogers, 2003). Extent is the total area or duration over which observations are made, the largest pattern to which an organism responds (i.e., the habitats used by a fish or the time over which a given habitat is used), or the largest scale at which a disturbance or process driver exerts influence on the system. Therefore, grain and extent define the upper and lower limits of resolution in the description of a level of organisation or an ecosystem. Assigning a scale to a hierarchical level of organisation provides contextual meaning and more importantly it determines the variables and units of measure that can be associated with each level of a particular hierarchy.

Hierarchical concepts are common in the sub-disciplines of river science – ecology, geomorphology and hydrology – with each sub-discipline having distinct levels of organisation. The familiar hierarchical levels of ecological organisation (organism, species, community, ecosystem) are also fundamental to ecological understanding