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Sustaining River Ecosystems and Water Resources

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Preface

People have deliberately manipulated rivers for centuries in an attempt to enhance specific river functions, including navigation and water supplies, and to limit hazards such as flooding and bank erosion associated with rivers. A narrowly focused conceptualization of rivers as primarily channels that convey water downstream is one result of this history of river management. Although river channels do convey water, they also transport and store solutes, sediment, and organic matter; create aquatic habitat; interact with the adjacent floodplain and underlying hyporheic zone; and support abundant and diverse biotic communities. River management focused only on water conveyance and hazard mitigation has led to a plethora of problems and to loss of river ecosystem services, prompting scientists, managers, and the public to seek more holistic conceptualizations of rivers as ecosystems.

This book summarizes the state of river science with regard to river ecosystems and argues that management centered on a more holistic perspective of rivers will more effectively sustain river ecosystems and water resources. The book is designed to be accessible to students of river science and to river managers, as well as to scientists from diverse disciplines related to the study of rivers. Following the introductory chapter, succeeding chapters summarize river science, the ways in which human activities directly and indirectly alter river ecosystems, and new management approaches for rivers.

In writing this book, I have benefited from decades of stimulating discussions with research colleagues, graduate students, and natural resources managers in the United States and other countries. I feel fortunate to be able to study rivers and to work with people who are passionate about rivers. I would like to thank Sherestha Saini for the invitation to contribute to the SpringerBrief series, which led to the idea of writing about river ecosystems and river management, and Professor Jacqueline King, Dr. Katherine Skalak, and an anonymous reviewer for detailed and insightful comments that improved this book.

Fort Collins, CO — Ellen Wohl

Contents

Chapter 1
Introduction

The basic objectives of this book are twofold. First, the book provides an overview of rivers as ecosystems that exist within the greater landscape of a watershed or drainage basin. Second, the book explores the management implications of conceptualizing rivers as ecosystems rather than simply as channels to convey water downstream. If rivers are viewed solely as conduits for water, then management can be designed to maximize delivery of specified quantities of water at specified times via intensive engineering and flow regulation. If rivers are viewed as ecosystems, then management must be designed to include other outcomes such as maintenance of physical diversity, connectivity, and biodiversity within rivers. Since the final decade of the twentieth century, river management has increasingly emphasized aspects such as diversity and connectivity. This book reviews scientific understanding of rivers relevant to the shifting emphases in river management and suggests pathways to sustain this management shift.

My intent in writing the book is to summarize recent developments across multiple aspects of river science that are relevant to river management. The book provides an interdisciplinary perspective for students and professionals within individual subsets of river science and an overview accessible to those primarily concerned with river management. I believe that this book is needed because paradigms—theoretical frameworks that shape how we think and act—change slowly, in science, management, and society. A paradigm shift among river scientists has been underway for at least two decades. Ecologists and physical scientists increasingly emphasize the interconnectedness of channels with the floodplain and underlying hyporheic zone, the watershed, and the broader world (e.g., Fausch et al. 2002; Muehlbauer et al. 2014; Harvey and Gooseff 2015; Gurnell et al. 2016). Scientists also increasingly highlight the importance of changes through time—floods, droughts, fires—in maintaining a healthy river ecosystem (Nilsson and Berggren 2000; Tockner et al. 2003). This paradigm shift has been slower to reach those charged with managing rivers and other natural resources, as well as society at large.

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Following this introductory chapter, the second chapter covers basic aspects of physical and ecological science that underlie contemporary scientific understanding of rivers. This information supports and expands on a primary thesis of the book: rivers are most appropriately considered as ecosystems rather than as simple channels for downstream conveyance. The intent of the second chapter is to support this contention by reviewing how physical characteristics of rivers support biotic communities and river ecosystem functions. The third chapter reviews the diversity of human alterations of rivers throughout history in order to provide context for what has been changed and why river restoration is so widely undertaken. The final chapter discusses different forms of research and management that are being used to restore rivers.

First, however, it is useful to consider how different people perceive rivers and what they mean in using the phrases *river health* and *river ecosystem*.

1.1 Perceptions of Rivers

Perceptions and language matter. Consider the jungle versus the rainforest. Perceptions of the jungle have traditionally been largely negative, emphasizing the darkness under the dense tree canopy and the danger hidden within that darkness. This is reflected in expressions such as 'it's a jungle out there' or 'the urban jungle'. The word rainforest, which is used for many of the same tropical forest environments as the word jungle, has come to have very positive connotations. Rainforest is commonly equated with biodiversity and a threatened, fragile environment. A jungle is something to be overcome and tamed. A rainforest is something to be cherished and protected. I start with this anecdote because human perceptions of natural environments are at the heart of how we attempt to manage those environments and whether we emphasize alteration and subjugation of an environment or protection and restoration. Consequently, the next two sections discuss perceptions of rivers and river health.

Rivers are one of the most important and endangered ecosystems on Earth. An ecosystem is a community of living organisms linked together and to the adjacent environment through fluxes of nutrients and energy. Rivers have sometimes been conceptualized as simple channels for the downstream conveyance of water and sediment, but this conceptualization misses the critical aspects of rivers that sustain life by providing ecosystem services. Ecosystem services include the general categories of provisioning, regulating, supporting, and cultural (MEA 2005), and rivers provide all of these services abundantly. Provisioning refers to products obtained from ecosystems. River provisioning comes from water, food such as subsistence and commercial fisheries, and fertile soil in the floodplain. Regulating describes benefits obtained from the regulation of ecosystem processes. Regulating in river ecosystems comes from reduced flood hazards associated with energy dissipation across floodplains. Supporting ecosystem services are those necessary for the production of all other ecosystem services (De Groot et al. 2002; MEA 2005). Examples of supporting ecosystem services from rivers include primary production by plants in the channel and floodplain and nutrient recycling by microbial organisms and macroinvertebrates inhabiting the channel and floodplain. Cultural ecosystem services describe the non-material benefits that people derive from ecosystems: who among us does not enjoy spending time along a river?

Diverse groups of people perceive rivers differently. This can be illustrated in an academic context by simple generalizations about traditional engineering, geomorphic, and ecologic perceptions of rivers (Fig. 1.1; Table 1.1). A traditional engineering disciplinary perspective is likely to focus on how water flowing down a river channel interacts with the channel boundaries to create a distribution of hydraulic force that can modify the channel in ways that may be undesirable for those seeking to use the channel for navigation or to limit bank erosion or overbank flooding. The ideal river from a traditional engineering perspective is one that remains stable, without substantially incising its banks, eroding its bed, accumulating sediment within the channel, or flooding out of the channel. Engineering emphasizes using mathematical relations to predict the channel form best suited to create this stability. Engineers also design channel modifications such as bank protection or instream structures to promote channel stability. Equations describing water flow in an open channel and the mechanics of sediment transport provide the foundation for engineering understanding of rivers.

A geomorphic disciplinary focus is more likely to start with how interactions across the drainage basin influence water and sediment entering the river network. Geomorphic investigations also emphasize how channel form and process result from interactions among water and sediment within the channel, the erosional resistance of the channel boundary, and the stability of relative base level. Geomorphic investigations of rivers include how these diverse interactions occur across differing scales of time and space. Qualitative and quantitative conceptual models of equilibrium and nonlinear dynamics that describe river process and form provide the foundation for geomorphic understanding of rivers.

An ecological perspective of rivers is most likely to focus on how interactions between abiotic factors and biota create fluxes of matter and energy, as well as structuring biotic communities. As with geomorphic investigations of rivers, ecological investigations examine processes and biotic communities across diverse scales of space and time, from entire ecoregions and drainage basins over hundreds to thousands of years, to channel units such as pools and rivers and nutrient uptake at minutes to hours. Conceptual models of longitudinal and lateral patterns of matter and energy fluxes and communities (Fig. 1.1) provide the foundation for ecological understanding of rivers.

None of these disciplinary perceptions of rivers is more correct than the others. They differ in their relative emphases, but they also share many areas of common interest. Ecologists can argue that their perceptions of rivers are the most comprehensive, because they include and build on understanding derived from engineering hydrology and hydraulics and geosciences temporal and spatial scales, but also

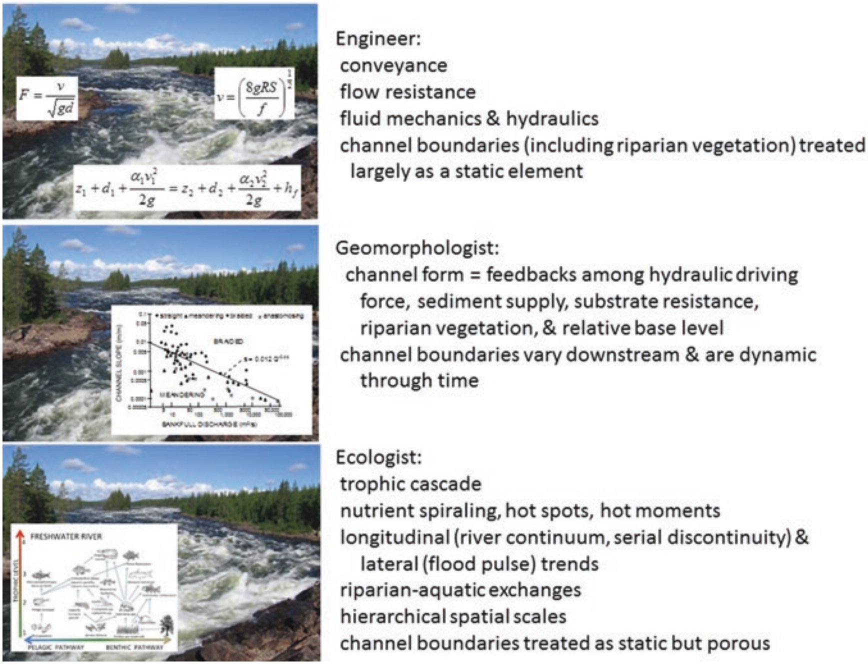

Fig. 1.1 Simplified representation of a river corridor as traditionally viewed from three different disciplinary perspectives: here, the Benbryteforsen (bone-breaker) rapid on the Pite River in Sweden

explicitly incorporate organisms. Engineers and physical scientists also increasingly acknowledge the importance of organisms in rivers, both as drivers of many aspects of river management (e.g., Stewart et al. 2005; Haase et al. 2013) and as ecosystem engineers that strongly influence river process and form (Corenblit et al. 2011; Merritt 2013; Riggsbee et al. 2013). Each disciplinary perspective adds an important piece to a holistic understanding of rivers.

Recognizing these traditional differences in disciplinary perspectives is useful when undertaking transdisciplinary river research or coordinated river management. No traditional disciplinary background effectively covers all aspects of river ecosystems, but each discipline has important insights to offer. Analogously, people living along rivers or using the rivers for their livelihood or for recreation can offer insights that are important to incorporate into river management, not least because these people are the stakeholders who support or do not support river management activities.

Table 1.1 Disparate disciplinary views of a river

Discipline	Structure	Stability	Energy	Form	River	Downstream flux
Ecology						
Aquatic	Organisms	10^0 y	Solar, flow	Hierarchical patches	Channel, hyporheic	Water, organic matter, nutrients, organisms
Riparian	Vegetation[a]	10^0–10^2 y	Solar, flow	Floodplain landforms	Channel, floodplain	Water, propagules, genetic information
Engineering	Dams, bridges	10^0–10^1 y	Flow	Cross sectional, gradient	Channel	Water, (sediment)
Geomorphology	Geologic underpinning	10^1–10^4 y	Flow, tectonics	Bedforms, planform, longitudinal profile	Channel, floodplain	Water, sediment

[a]Canopy height and stem density; ages of plants within a population

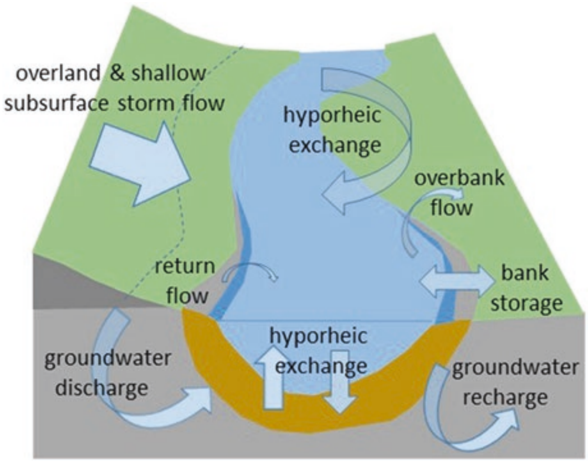

Fig. 1.2 Schematic illustration of the river corridor, including a main channel, floodplain (left boundary outlined by *dashed line*), and hyporheic zone (*orange* fill beneath channel), and highlighting hydrologic exchanges within the river corridor. These hydrologic exchanges represent forms of connectivity in the longitudinal dimension (downstream movement of water), lateral dimension (surface and subsurface movements of water from uplands into the river corridor and between different components of the river corridor), and in the vertical dimension (hyporheic and groundwater exchanges). (Modified from Harvey and Gooseff 2015, Fig. 1)

1.2 Healthy Rivers

Because rivers are ecosystems, throughout this book I refer to the physical environment of a river as the river corridor, rather than just the channel. A river corridor includes the main channel and secondary channels, where these are present; the floodplain; and the hyporheic zone underlying the channel and floodplain (Fig. 1.2). The floodplain is that portion of the valley bottom inundated by water overflowing the channel banks during peak flows that occur every year or every few years. The hyporheic zone underlies the river corridor and is delineated by flow paths originating from and terminating in the channel (Harvey and Gooseff 2015). A river corridor is thus an integrated physical system, which can be distinguished from a river ecosystem that includes the biotic communities within the river corridor. The distinction between river corridor and ecosystem is to some extent arbitrary because physical process and form in rivers are tightly coupled with biota, as discussed throughout this book.

A focus on river corridors emphasizes diverse forms of connectivity within a river ecosystem. Connectivity refers to the transfer of materials (e.g., water, sediment), energy, and organisms between components of an ecosystem. Components in a river ecosystem include the channel, floodplain, and hyporheic zone, as well as different segments of the river network, such as headwaters versus downstream portions. Longitudinal, lateral, and vertical dimensions of connectivity exist among the components of the river ecosystem.

In addition to the obvious downstream movements of water and sediment, longitudinal connectivity includes upstream movements by organisms. Lateral connectivity is present within the river corridor—between the main channel and secondary channels and floodplains, and between the river corridor and adjacent uplands. Vertical connectivity is present within the river corridor over relatively short distances between the channel or floodplain and the hyporheic zone. Vertical connectivity exists over longer distances between the atmosphere and the river corridor and between ground water and the river corridor. Each of these forms of connectivity is explored in greater detail in Chap. 2.

The history of economic development and industrialization in most countries is a history of altering rivers to convert them from ecosystems and spatially heterogeneous corridors to simpler, more spatially uniform channels. People have built levees and drained floodplains, in the process severing connections between the channel and floodplain. Communities and industries have dumped waste products into river corridors, changing water quality, nutrient loads, and the ability of individual organisms and biotic communities to survive within the river. People have regulated flows to reduce flooding and store water for dry periods or to generate hydropower, in the process altering natural river flow regimes. People have channelized rivers to reduce their lateral mobility and used rivers to transport goods ranging from masses of cut logs to immense barges. And, people have relied on rivers for water supplies and fisheries.

The unintended cumulative effects of the long history of river manipulation are increasingly apparent (Williams et al. 2014). Irrigated agriculture has expanded 174% globally since the 1950s and now accounts for ~90% of global freshwater consumption (Scanlon et al. 2007). Widespread nutrient pollution of river corridors that reflects use of agricultural fertilizers reduces river ecosystem processes (Woodward et al. 2012). Indeed, disruption of global nitrogen and phosphorus dynamics has likely exceeded planetary boundaries of a safe operating space for humanity with respect to global environments (Rockström et al. 2009; Steffen et al. 2015). Other widespread contaminants in river corridors include metals, synthetic chemicals such as pesticides and PCBs, untreated human and animal wastes, and pathogens (Meybeck 2003; Wohl 2014). Nearly 80% of the world's population is exposed to high levels of water insecurity resulting from lack of potable water (Vörösmarty et al. 2010).

Decades of intensive river engineering have facilitated greater construction and settlement within river corridors, resulting in substantial increases in flood damages and exposure to flood hazards (Jongman et al. 2012). Reservoirs trap an estimated 26% of global sediment flux to the oceans (Syvitski et al. 2005), so that sediment flux has declined despite accelerated erosion in uplands, causing widespread erosion of river deltas (Syvitski and Kettner 2011). Dams and diversions homogenize river discharge (Poff et al. 2007) and river engineering homogenizes the configuration of river corridors (Peipoch et al. 2015). Both of these forms of homogenization reduce the ability of river corridors to support diverse and abundant biota and to provide ecosystem services (Moyle and Mount 2007). Projected mean future extinction rates of freshwater fauna in North America exceed those of terrestrial fauna by a factor of five (Ricciardi and Rasmussen 1999). Freshwater faunas have become increasingly homogeneous as a result of extirpation of native species, introduction of nonnative species, and habitat alterations that facilitate these two processes (Rahel 2002). Although freshwater fisheries are not as well tracked as marine fisheries, both commercial and recreational fisheries are causing collapse of fish species in many rivers (Pauly et al. 2002; Post et al. 2002; Carpenter et al. 2011).

I have visited river corridors around the world and I repeatedly hear people—river scientists, natural resources managers, concerned citizens—asking what they can do to restore river ecosystems and the services that they provide. Although they may not use these scientific terms, the concerns are universal: how can we make the water clean again, or bring back the fish, or make the river stop eroding its banks without covering the banks in concrete? How can we make the river healthy again?

River health is a nebulous concept. River scientists do not necessarily embrace the phrase and they differ in how to define and assess it (Boulton 1999; Karr 1999; Norris and Thoms 1999). River health continues to be used because it is intuitively appealing and provides a ready analogy for human health. River health can be defined as the degree to which river corridor energy sources, water quality, flow regime, habitat, and biota match the natural conditions (Wohl 2012). This can be very difficult to assess in regions with many centuries of river manipulation by humans, but comparison to natural or reference conditions remains the most widely used standard for any form of ecosystem health (Palmer and Febria 2012). In this context, natural or reference conditions typically refer to the characteristics of the river ecosystem present prior to intensive human manipulation of the environment within the watershed and the river corridor (Wohl and Merritts 2007; Wohl 2011).

The historical timeline of intensive human manipulation varies widely among diverse locations. In many regions of the world, alteration of upland vegetation for agriculture or timber harvest was one of the earliest human activities to alter water and sediment yields entering river corridors. This occurred as early as 8000 years ago in parts of China (Zhuang and Kidder 2014), and is now occurring in countries such as Uganda (Kasangaki et al. 2008). Direct engineering of channels and regulation of river flows typically occurred more recently, but again over varying timespans. At least some of the rivers in Eurasia have been channelized for more than a century (Pišút 2002), whereas river channelization in the United States occurred primarily during the mid to late twentieth century (Goodwin et al. 1997).

Understanding the perceptions that underlie the use of the phrase 'river health' and the processes that create and maintain healthy rivers is critical to management designed to improve the functioning of rivers as ecosystems. The next chapter focuses on the processes that support healthy rivers.

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