KIRSTIE A. FRYIRS and GARY J. BRIERLEY

Geomorphic Analysis of River Systems

An Approach to Reading the Landscape

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Geomorphic Analysis of River Systems: An Approach to Reading the Landscape

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WILEY-BLACKWELL
A John Wiley & Sons, Ltd., Publication

Blackwell Publishing was acquired by John Wiley & Sons in February 2007. Blackwell's publishing program has been merged with Wiley's global Scientific, Technical and Medical business to form Wiley-Blackwell.

Registered office: John Wiley & Sons, Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

Editorial offices: 9600 Garsington Road, Oxford, OX4 2DQ, UK
The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK
111 River Street, Hoboken, NJ 07030-5774, USA

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Library of Congress Cataloging-in-Publication Data

Fryirs, Kirstie A.
Geomorphic analysis of river systems : an approach to reading the landscape / Kirstie A. Fryirs, Gary J. Brierley.
p. cm.
Includes bibliographical references and index.
ISBN 978-1-4051-9275-0 (cloth) – ISBN 978-1-4051-9274-3 (pbk.) 1. Watersheds. 2. Fluvial geomorphology. I. Brierley, Gary J. II. Title.
GB561.F79 2013
551.48'3011–dc23
2012016112

A catalogue record for this book is available from the British Library.

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Set in 10/12.5 pt Minion by Toppan Best-set Premedia Limited

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'Playful Platypus', Les Elvin, NAIDOC Artist of the Year 2008. © Glenelg Art Gallery, South Australia. Reproduced with permission of the artist.

Back cover:
Huang He at Dari, China. © Brendon Blue.

Cover design by:
Design Deluxe

1 2013

To those who have guided and supported us on our river wanderings

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Preface

Purpose and aims of this book

> Geomorphology is the science concerned with understanding the form of the Earth's land surface and the processes by which it is shaped, both at the present day as well as in the past.
>
> British Society for Geomorphology; sourced at: http://www.geomorphology.org.uk/pages/geomorphology/

> The most engaging and interesting intellectual work on geomorphic forms such as river channels has not come from computer specialists and theoretical models but from field measurements and observations.
>
> Luna B. Leopold (2004: 10)

The scientific study of geomorphology has very divergent origins and approaches in different parts of the world. Perhaps inevitably, our perspectives and thinking are deeply rooted in our training, culture and the landscapes in which we live and work. In other words, scientific understandings have a genealogy, wherein cultural and experiential underpinnings fashion our way of thinking.

The approach to *reading the landscape* that is outlined in this book provides a way to interpret rivers across the range of environmental and climatic settings. It builds upon a solid understanding of the science of fluvial geomorphology. Field-based understandings are tied to theoretical and conceptual principles to generate catchment-specific analyses of river character, behaviour and evolution. This approach to landscape analysis views geomorphology as an interpretative and analytical science rather than a descriptive one.

Reading the landscape entails identification of river landforms and appraisal of their relationships to adjacent features. Primary controls upon contemporary dynamics are interpreted, framing analyses in relation to their landscape and catchment context, and the imprint from the past.

This book has been constructed as an introductory text on river landscapes, providing a bridge to more advanced principles outlined in Brierley and Fryirs (2005). Chapters 1–9 present foundational understandings that underpin the approach to reading the landscape that is documented in Chapters 10–14. The target audience is second- and third-year undergraduate students, as well as river practitioners who use geomorphic understandings in scientific and/or management applications.

Inevitably, no book can cover all geomorphic principles and practices, and much material has been 'left out' of the foundation chapters. For example, those interested in the details of bedload transport modelling, of hydraulic analyses of bank erosion processes and channel geometry models or of Quaternary science are encouraged to develop more advanced understanding from other geomorphology, engineering or earth science textbooks.

This book does not provide a fully grounded and comprehensive background to geomorphic analysis. Emphasis is placed upon documentation of the approach to reading the landscape. Selected readings outlined at the end of the book provide additional background information on material covered in the various chapters. The book does not deal with specific case-studies in the body of the text. Rather, many of the figures use case-studies or real examples drawn from the literature and our own sources to complement the use of principles and forms of analysis. These are accompanied by comprehensive captions that stand alone from the body of the text. These visual guides reflect the age-old saying: 'a picture is worth a thousand words'. We encourage the reader to 'ponder' each figure and consider what is embedded within it to gain a more complete understanding of the approach to river analysis. Similarly, there is minimal referencing in the text. This is an attempt to keep it clean and easy to read on one hand, and to not overemphasise some literature at the expense of other literature. Instead, an extensive reading list is provided at the back of the book.

The approach to reading the landscape that is outlined here is complementary to a plethora of other approaches available to the geomorphologist. Scientific enquiry is multifaceted. The material in this book complements, and can be used in parallel with, modelling applications, geographic information science and remote-sensing applications, quantitative process measurements, Quaternary research and sedimentology and case-study applications. Many of these fields incorporate significant technological advances. This book is based on the premise that applications of these techniques must be appropriately contextualised through field-based, landscape-scale analyses and interpretations. Such 'geographic' knowledge is integral to geomorphic applications. Technological applications cannot replace our ability to interpret a landscape. Generic information must be framed in its place-specific context. Hopefully, emphasis upon foundation principles in fluvial geomorphology provides an appropriate platform with which to ask the right questions and make interpretations of landscape forms, processes and evolution.

The approach to reading the landscape outlined in Chapter 1 has been carefully structured to scaffold the presentation of the book. However, this is not a 'how to' book, framed around prescriptive step-by-step instructions on how to interpret fluvial forms and processes. Given space limitations, we do not provide guidance on the specific tools and techniques that can be used to support such investigations (e.g. remote sensing, process-based field measurements, modelling applications, sedimentology). Instead, the book is about interpreting forms and processes and piecing them together at the landscape scale.

We hope that the contribution provided by this book is appraised in relation to these aspirations.

Kirstie A. Fryirs and Gary J. Brierley

Structure of the book

The structure of the book is shown in Figure 1. Chapters 2–9 scaffold information to provide the relevant foundations for reading the landscape. Chapter 1 sets the context for why fluvial geomorphology is important and useful in science and management. Chapter 2 documents key spatial and temporal concepts that underpin enquiry in fluvial geomorphology. Chapter 3 overviews catchment-scale relationships in river systems, describing downstream relationships along longitudinal profiles and catchment morphometrics. Chapter 4 focuses on hydrologic relationships in river systems. Chapter 5 documents impelling and resisting forces that drive river adjustment. Chapter 6 explores sediment transport in rivers in relation to entrainment, transport and deposition processes. Chapter 7 describes the range of bed and bank erosion and deposition processes that determine channel shape and size. Chapter 8 analyses process–form associations of instream geomorphic units, documenting the spectrum of features from sculpted bedrock forms to mid-channel and bank-attached bars and finally fine-grained sculpted features. Chapter 9 analyses process–form associations of floodplain geomorphic units, outlining the role of formative and reworking processes. The influence of valley confinement as a control upon floodplain forms is outlined.

The approach to reading the landscape is documented in Chapters 10–14. Tips for reading the landscape are presented at the ends of these chapters. Chapter 10 combines analyses of channels, sediment transport and geomorphic units with channel planform to assess the spectrum of river diversity from bedrock-confined, to partly-confined to alluvial river forms. This is framed around a contructivist approach to analysis of river form. Chapter 11 interprets river behaviour, outlining forms of adjustment for different types of river and the range of river behaviour at different flow stages. Chapter 12 examines river evolution and river change. The imprint of geologic and climatic controls on contemporary forms and processes is discussed. Chapter 13 explores direct and indirect human impacts on rivers. Chapter 14 brings together analyses of sediment budgets and connectivity to present a framework for examining catchment-scale sediment flux and how this can be used to predict likely future river adjustments. The final chapter draws together these threads, summarising the approach to reading the landscape under three banners: Respect diversity, Understand system dynamics and evolution, and Know your catchment.

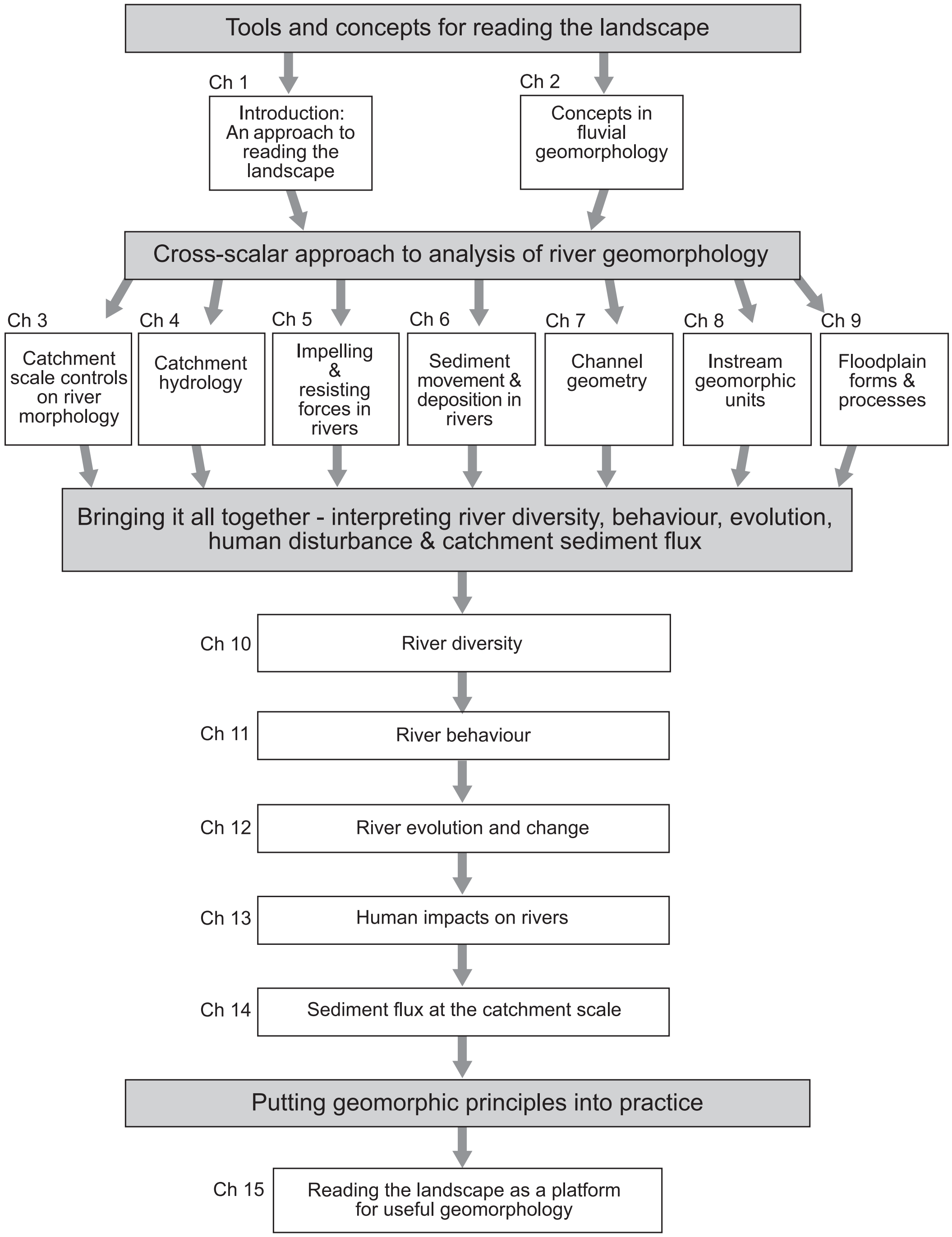


Figure 1 Structure of this book.

Acknowledgements

Writing a book is always challenging. At the outset, we thought our earlier efforts in writing our 2005 book would prepare us well to meet this challenge. Perhaps inevitably, this proved to be a little naive. With this book, our intent was to provide a background resource book that would 'fill a gap' in setting up the River Styles framework. Our return to first principles of geomorphic enquiry led us to question everything. In this light, it is amazing that this book is now complete (though such matters are never finished).

Teaching undergraduate and postgraduate courses over many years has helped us in our efforts to communicate complex ideas and develop interpretative skills in fluvial geomorphology. The test of these understandings comes through applications in different field situations. We thank those challenging and supportive undergraduate and postgraduate students who have assisted us in our respective teaching environments.

Field experiences and professional short courses have greatly enriched our careers, fashioning the way we see, analyse and interpret landscapes. We are indebted to our teachers, mentors and fellow practitioners who have helped to frame our way of thinking and communicating.

The approach to reading the landscape that is conveyed here reflects our way of synthesising collective understandings and experiences gained through our careers. We hope that our efforts effectively capture shared understandings in our endeavours to interpret river forms, processes and evolutionary trajectory. Ultimately, it was our shared desire for better use of geomorphology in river management practice that has encouraged us to write this book.

Most of the graphics in this book were designed by Kirstie Fryirs and drafted by Dean Oliver Graphics, Pty Ltd. We thank Dean for his commitment to this project. Alan Cheung also drafted several figures for the book. Comments by two anonymous reviewers substantially improved the book.

We also thank colleagues in the Department of Environment and Geography, Macquarie University, and the School of Environment, University of Auckland, for their support.

Kirstie acknowledges the support of a Macquarie University Outside Studies Program grant for finance towards her study leave in 2010. This allowed her to dedicate significant time to completing this book.

Gary also received significant support from the University of Auckland for study leave in 2009. During this period he worked in Beijing, western China and Singapore. Stimulating intellectual conversations accompanied his writing efforts at this time. He is indebted to Zhaoyin Wang (Tsinghua), He Qing Huang (Chinese Academy of Sciences), Xilai Li and Gang Chen (Qinghai University) and David Higgitt (National University of Singapore) for their support. The Director of the School of Environment at the University of Auckland, Glenn McGregor, also supported Gary's efforts to complete this book. Megan de Luca, Petra Chappell and Simon Aiken worked as research assistants to provide resources to assist in the writing of several chapters. Many of the ideas outlined here have benefited from stimulating conversations at the University of Auckland and elsewhere; particular thanks are given to Claire, Helen, Carola, Kes, Stephanie, Ashlee, Marc, Brendon and Cecilia . . . among many others, and with apologies to those overlooked.

The front cover of the book depicts a painting by an Australian indigenous artist, Les Elvin, who was NAIDOC Artist of the Year in 2008. Les is of the Wonnaruah community of the Upper Hunter region in eastern NSW. His painting 'Playful Platypus' depicts one of the local rivers with pools and Platypus, an indigenous species of freshwater ecosystems in Australia. We chose this painting for several reasons. Firstly, because of its connection to place and country which is a key message in the reading the landscape approach advocated in this book. Also, the Upper Hunter is a place where we have both spent considerable time undertaking fieldwork. This landscape, amongst many others, has shaped the reading the landscape approach.

As always, our families are our strength. Again, we thank them for their unwavering support.

CHAPTER ONE

Geomorphic analysis of river systems: an approach to reading the landscape

Introduction

Landscapes have been a source of fascination and inspiration for humans for thousands of years. Sensory responses to landscapes vary markedly from person to person. To many, spiritual associations evoke a sense of belonging, perhaps tinged with nostalgic sentiments. To others, a sense of awe may be accompanied by alienation or innate fear. Artists strive to capture the essence of landscapes through paintings, prose, poetry or other media. Our experiences in life are often fashioned by the landscapes in which we live and play. Relationships and associations vary from place to place and over time. New experiences may generate new understandings, wherein observations are compared with experiences elsewhere. These collective associations not only reflect the bewildering range of landscapes in the natural world, they also reflect the individual consciousness with which we relate to landscapes, and the influences/experience that fashion our way of thinking, whether taught or intuitive. No two landscapes are exactly the same. Each landscape is, in its own way, 'perfect'. Different sets of controls interact in different ways in different settings, bringing about unique outcomes in any particular landscape. Just as importantly, interactions change over time, such that you cannot step in the same river twice (Heraclitus, 535–c. 475 BCE). Sometimes it seems a shame to formalise our understandings of landscapes within the jargonistic language of scientific discourse, but that is what geomorphologists do!

In simple terms, geomorphology is the scientific study of the characteristics, origin and evolution of landscapes. Geomorphic enquiry entails the description and explanation of landscape forms, processes and genesis. Implicitly, therefore, it requires both a generic understanding of the physics and mechanics of process and an appreciation of the dynamic behaviour of landscapes as they evolve through time. The key to effective use of geomorphic knowledge is the capacity to place site-specific insights and relationships in their broader landscape context, framing contemporary process–form linkages in relation to historical imprints. Theoretical and modelling advances are pivotal in the development and testing of our understanding. However, the ultimate test of geomorphological knowledge lies in field interpretation of real-world examples.

This book outlines general principles with which to interpret river character, behaviour and evolution in any given system. Emphasis is placed upon the development of field-based skills with which to read the landscape. Field-based detective-style investigations appraise the relative influence of a multitude of factors that affect landscape-forming processes, resulting patterns of features and evolutionary adjustments. Interactions among these factors change over time. Inevitably, such investigations are undertaken with incomplete information. Information at hand has variable and uncertain accuracy. Some facets of insight may be contradictory. Individual strands of enquiry must be brought together to convey a coherent story. Significant inference may be required, drawing parallels with records elsewhere. Unravelling the inherent complexities that fashion the diversity of the natural world, the assemblages of features that make up any given landscape and the set of historical events that have shaped that place is the essence of geomorphic enquiry. Just as importantly, it is great fun!

Although this book emphasises process–form relationships on valley floors, it is implicitly understood that rivers must be viewed in their landscape and catchment context. Rivers are largely products of their valleys, which, in turn, are created by a range of geologic and climatic controls. Hillslope and other processes exert a primary control upon what happens on valley floors. Sediment delivery from river systems, in turn, exerts a major influence upon coastal-zone processes. Source-to-sink relationships are a function of catchment-scale controls on sediment supply, transport and delivery. Efforts to read the landscape place site-specific observations, measurements and analyses in an appropriate spatial and temporal context. Understanding of this dynamic landscape template provides a coherent platform for a wide range of management applications.

Geomorphic Analysis of River Systems: An Approach to Reading the Landscape, First Edition. Kirstie A. Fryirs and Gary J. Brierley.

How is geomorphology useful?

Geomorphologists have a long tradition of applying their science in environmental management. Geomorphic insights provide a physical platform with which to develop cross-disciplinary practices and applications that build upon an understanding of how the natural world looks and behaves. Landscapes determine the template upon which a range of biophysical processes interacts (Figure 1.1). For example, insights from fluvial geomorphology provide an understanding of physical processes that create, maintain, enhance or destroy riverine habitat (i.e. the physical space that flora and fauna inhabit). Habitat availability in the channel and riparian zone (and floodplain) of a river is a function of the diversity of landforms on the valley floor. Marked differences are evident; for example, along perennial and ephemeral streams or in a gorge relative to a swamp. Distinct vegetation patterns are found on differing channel and floodplain surfaces, reflecting access to water (and inundation frequency), substrate conditions and morphodynamic interactions between flow and vegetation. Vegetation may have a negligible influence upon some rivers; elsewhere, it may be a primary determinant of process–form relationships. Concerns for ecohydraulics and ecohydrology have major implications for the management of flow, sediment and nutrient fluxes. Water chemistry and turbidity are largely a function of catchment lithology, and the nature/amount of sediment that can be readily entrained by a river.

Alterations to the geomorphic structure of rivers have enormous implications for the operation of biophysical fluxes that affect the movement of water, sediment, nutrients, etc. Hence, a geomorphic template provides a basis for 'whole of system' thinking, aiding the development of coherent plans and strategies for environmental management, guiding decision-making for concerns relating to global change, natural resource management, natural hazards or conservation and rehabilitation issues. End users of geomorphological research are typically land or resource managers who address societal concerns for issues such as erosion and sedimentation problems, channel instability, hazard mitigation, pollution and contamination of water and sediments, ecosystem management, water supply and quality, and so on.

Fluvial geomorphologists have long recognised the nested, hierarchical nature of physical processes that structure river systems across various scales (Chapter 2). Geomorphic relationships vary markedly in differing ecoregions, as climatic controls upon ground cover affect runoff and sediment movement through landscapes, among many considerations. Understanding of source-to-sink relationships at the catchment scale provides a critical platform with which to develop and apply management plans and actions. If geomorphologists are to explain complex landscape behaviour and provide appropriate tools for effective management practice, process knowledge must be related to the configuration of landscape components within any given catchment and the changing nature of process linkages over time. Such understandings are required to convey a coherent view of landscape forms, processes and their evolution. These are innately geographic considerations.

Landscapes are linked and dynamic systems. Disturbance responses or management activities at one place and time may have off-site consequences over various timeframes. Although these are typically scale-dependent relationships (small impacts have minimal consequences that are restricted to closer (proximal) areas), this is not always the case (e.g. local disturbance may induce off-site responses that breach threshold conditions). Often, these relationships are predictable. Gravitationally induced flow and sediment flux is the key driver of upstream–downstream linkages in river systems. Sometimes, however, surprising outcomes may occur. For example, headcut activity and bed incision may cut back through valley floor deposits, impacting upon the river upstream. The effectiveness and efficiency of linkages vary markedly from catchment to catchment. Understanding of imprints from past disturbance events, and associated lagged and off-site responses, is critical in the development of proactive planning appli-

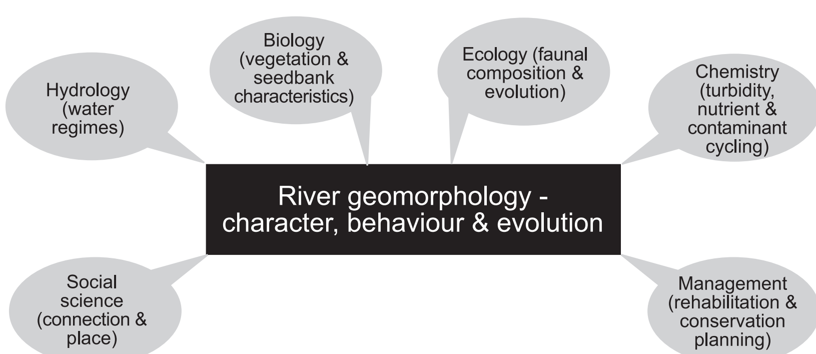


Figure 1.1 Geomorphology as a physical template atop which other interactions occur.

cations. These various considerations underpin visioning exercises that determine 'what is biophysically achievable' in the management of any given catchment.

Geomorphic analysis of river systems: our approach to reading the landscape

Analysis of geomorphic systems cannot be meaningfully formalised using a prescriptive check-list, tick-box set of procedures. Such rigidity belies the inherent diversity of landscapes, and the overwhelming range of factors, process-relationships and controls that combine to generate the pattern of features formed (and reworked) at any given place. This is not to say that all landscapes are necessarily complex; indeed, some may be extremely simple or even near featureless! An open-minded approach to enquiry recognises implicitly the potential for unique outcomes (manifest as assemblages of features and their interactions) in any given setting.

The pattern/configuration of a landscape is derived from its composition (the kinds of elements it contains), its structure (how they are arranged in space) and its behaviour (how it adjusts over time to various impulses for change). Analysis of relationships between landforms can be used to provide insight into the history of formative and reworking events, and the evolutionary history of that system. Ultimately, these space–time interactions can only be unravelled through appraisal of source-to-sink relationships at the catchment scale.

Reading the landscape is an approach by which practitioners use their knowledge and experience to *identify* the assemblage of landforms or features that make up rivers, *develop hypotheses* to *interpret* the processes responsible for those landforms, *determine* how those features have/will adjust and change over time and, finally, place this understanding in its *spatial* and *temporal context*. Successful interpretations draw on existing theory, questioning and testing its relevance to the system under investigation.

All observations and interpretations in geomorphology must be appropriately framed in their spatial and temporal context. This requires appraisal of geologic, climatic and anthropogenic controls upon landscapes at any given locality. Topographic and geologic maps, aerial photographs and satellite images, and Google Earth® provide a simple basis with which to frame analyses in their landscape context, enabling meaningful comparisons with other places. Stark contrasts can be drawn between uplifting terrains at the margins of tectonic plates and relatively stable plate-centre locations, glaciated and non-glaciated landscapes, desert and rainforest areas, or rural and urban streams. Flow–sediment relationships which fashion process–form interactions along valley floors vary markedly in these different settings. It is also important to consider position within a catchment, and the scale of the system under consideration. These insights provide the contextual information within which the approach to reading the landscape is applied.

The constructivist (building block) approach to reading the landscape that is developed in this book assesses how each part of a system relates to its whole in both spatial and temporal terms (Figure 1.2). This 'bottom-up' approach synthesises the behaviour and evolution of landscapes through systematic analysis of fluvial landforms (termed geomorphic units). These features are generated by certain process–form interactions at particular positions in landscapes, and are comprised of differing material properties. Reaches are comprised of differing assemblages of landforms that are formed and reworked under a particular behavioural regime. Catchments are comprised of downstream patterns of reaches that are (dis)connected and through which fluxes of water, sediment and vegetation drive river behaviour, evolution and responses to human disturbance.

Although remotely sensed or modelled data provide critical guidance in our efforts to interpret landscapes, it is contended here that genuine understanding is derived from field-based analyses.

Reading the landscape entails four steps, for which different generic skills are required (Figures 1.3 and 1.4).

1. *Identify individual landforms (geomorphic units) and the process–form relationships that determine their process regime.*
   Landforms (or geomorphic units) are the component parts of a landscape. In general terms, they form under a given set of energy conditions at particular locations in a landscape. They are produced by a particular set of processes that fashion and rework the size and shape of the characteristic form. Geomorphologists have a good understanding of these process–form (morphodynamic) relationships, whereby the process affects the form and vice versa. Individual landforms have certain material and sedimentologic properties with a characteristic geometry and bounding surfaces (i.e. erosional or depositional contacts). Geomorphic units commonly have characteristic vegetation associations reflecting hydrologic and substrate conditions (among many considerations). Combinations of erosive and depositional processes that sculpt, create and rework the feature define the range of behaviour of each particular unit. From this, magnitude–frequency relations of formation and reworking can be inferred. This allows interpretation of the sensitivity/resilience of that feature when it is subjected to disturbance events (i.e. whether the feature will simply have additional

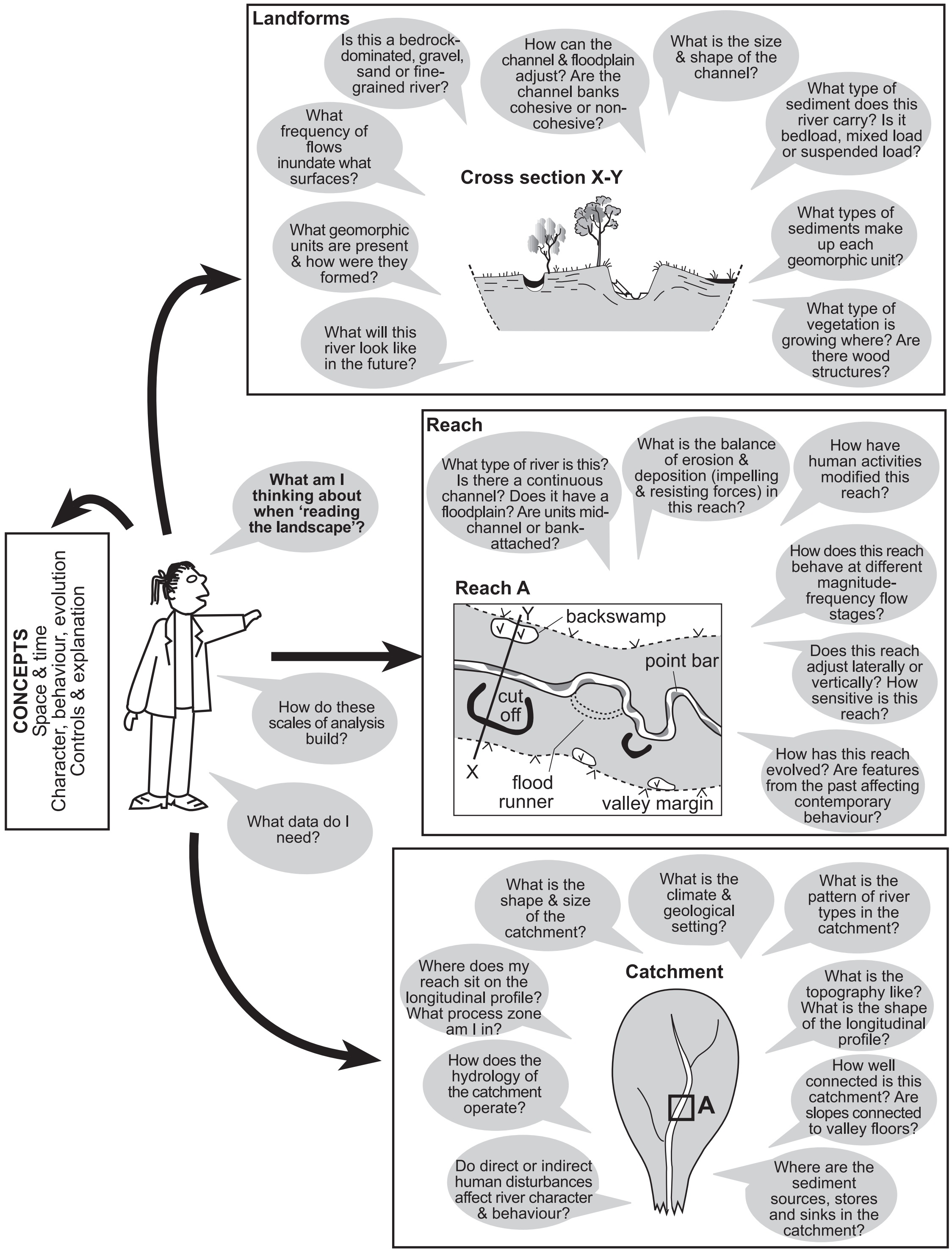


Figure 1.2 Questions you should ask when reading the landscape at the landform, reach and catchment scales.

deposits added to it, whether it will be partially reworked or whether it will be destroyed (eroded and removed)).

2. *Analyse and interpret the package and assemblage of landforms at the reach scale and how they adjust over time.*

Sections of river with a distinct assemblage of geomorphic units that reflect particular combinations of erosional and depositional processes are referred to as a reach. By definition, reaches upstream and downstream are characterised by different packages of landforms. Reading the landscape at the reach scale entails

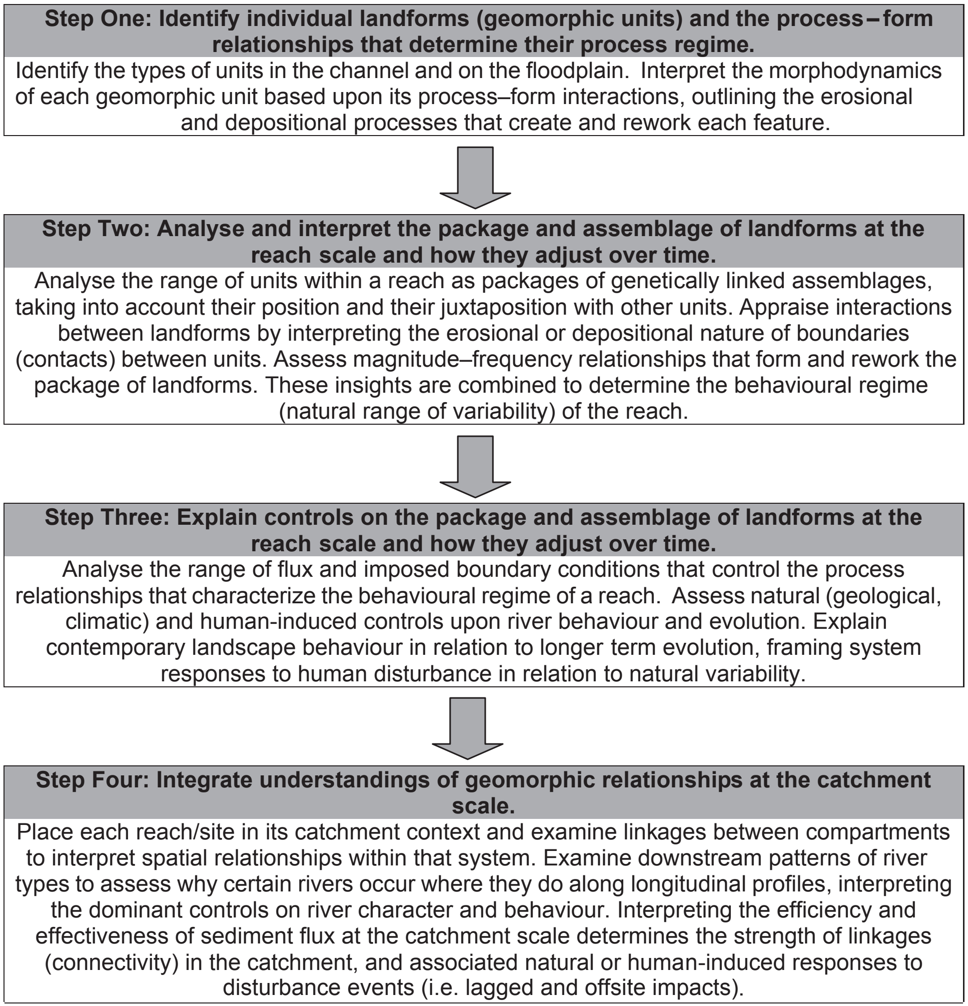


Figure 1.3 An approach to reading the landscape.

assessment of which types of geomorphic units are present (or absent), what types of sediments they are made of, and whether the units are formed and reworked by genetically linked contemporary processes or they reflect former conditions (Figures 1.2 and 1.4). Interpretation of the array of process–form relationships for the range of geomorphic units along a reach, and associated channel–floodplain interactions (if present), is used to determine the character and behaviour of a river. Adjustments around a characteristic state over geomorphic timeframes determine the *range of behaviour* of a river, as systems respond to disturbance events (Chapter 2). Inevitably, the magnitude–frequency domains with which these features are generated and interact may vary from system to system.

Significant insights into landscape history can be gained through analysis of whether adjacent features in a landscape are genetically linked or not (i.e. whether they formed contemporaneously, or whether they formed over differing periods of time). This provides guidance into the evolutionary history of a landscape, highlighting erosional events that rework landscape features (i.e. a temporal discontinuity). For example, terraces are older than adjacent floodplain and channel features, and they were often formed by quite different processes under differing environmental conditions.

3. *Explain controls on the package and assemblage of landforms at the reach scale and how they adjust over time.*
All landscapes adjust and evolve. Among the many inherent complexities of analysis of landscape systems is determination of the timeframe over which differing features are created and/or reworked and appraisal of the ways in which adjustments to one part of a system affect responses elsewhere in that system. The true value of geomorphic understanding lies in being

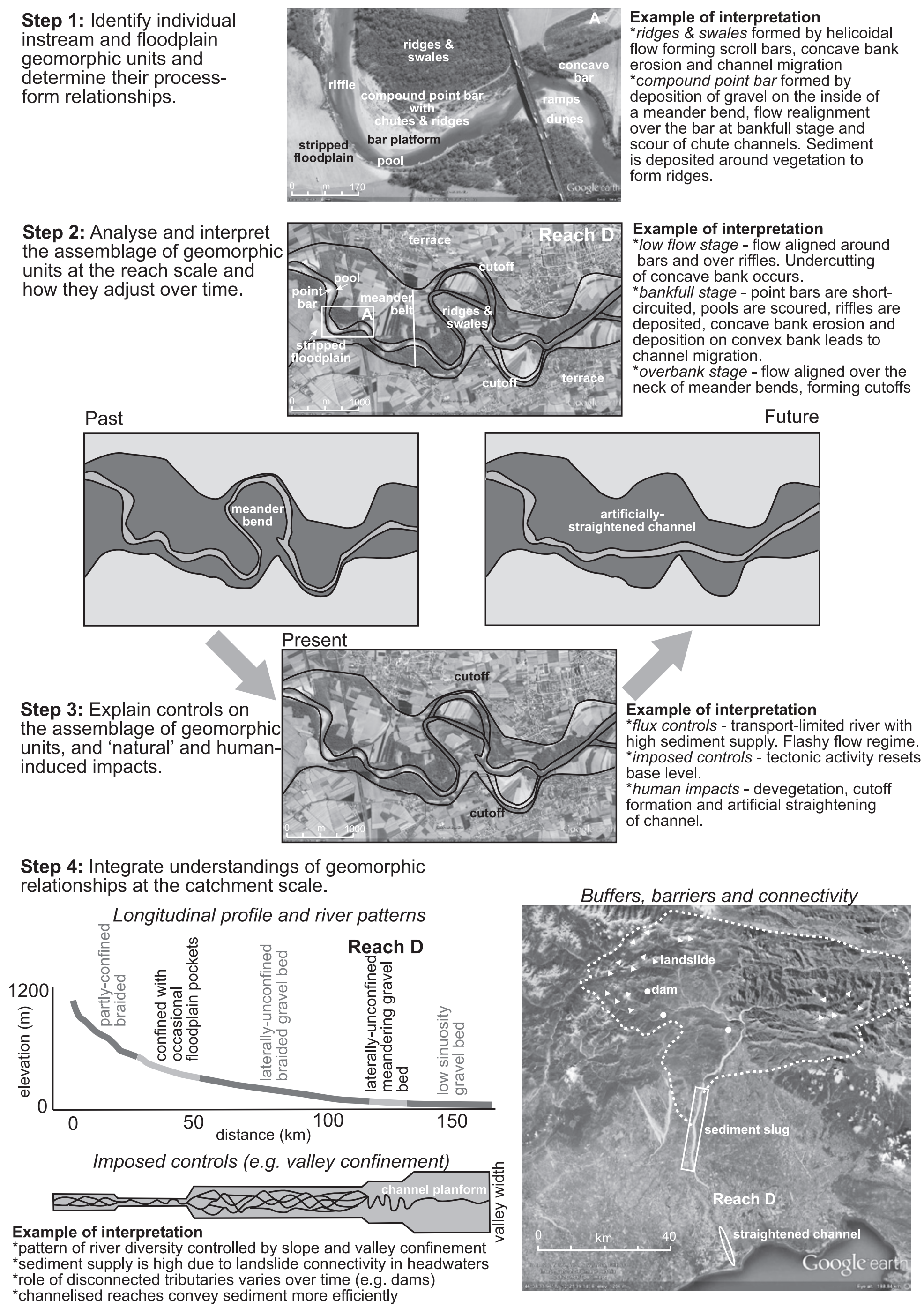


Figure 1.4 An example of how to apply the reading the landscape approach to a real river system (See Colour Plate 1). The example used here is the Tagliamento River in Italy. The approach begins by interpreting process-form relationships for individual, then assemblages of geomorphic units along different reaches of river type. River behaviour is interpreted for a range of flow stages. The role of natural and human induced disturbance on river adjustments over time is considered when analysing river evolution. Finally, each reach is placed in its catchment context, analysing flux and imposed controls on river diversity along longitudinal profiles and how reaches to fit together in a catchment. Interpreting the efficiency of sediment flux at the catchment scale determines the (dis)connectivity of the catchment and associated off-site responses to disturbance. Maps constructed using Google Earth © 2012 images. Based on information in Bertoldi et al. 2009, Gurnell et al. 2000, Surian et al. 2009 and Tockner et al. 2003. The interpretation of river types, river evolution and connectivity are our own.

able to explain the controls that drive process interactions and how they have changed/adjusted over time and interpreting what has triggered these changes/adjustments.

Differing controls upon landscape behaviour operate over variable spatial and temporal scales. By definition, the package of geomorphic units at the reach scale is fashioned by a consistent set of controlling factors. Valley setting (slope and width) is the primary determinant of *imposed boundary conditions* that are set over timeframes of thousands of years or longer (Chapter 2). In contrast, flow and sediment transfer relationships that recurrently adjust over much shorter timeframes set the *flux boundary conditions*. Primary differences in geomorphic setting (and associated behavioural regime) can be attributed to patterns of geologic (imposed) and climatic (flux) controls. Geologic factors such as tectonic setting, lithology and resulting topography affect the erodibility and erosivity of a landscape. Climatic factors influence the nature and rate of process activity (e.g. geomorphic effectiveness of flood events).

Effective integration of process-based insights through appraisals of the ways in which landscape compartments interact and evolve over time provides the basis to explain why certain behavioural adjustments have occurred. Analysis of landscape evolution enables determination of whether the contemporary system adjusts around a characteristic state, adjusts among differing states or has a different evolutionary pathway. These interpretations can be used to relate landscape responses to human disturbance to the *natural range of variability* of a system.

4. *Integrate understandings of geomorphic relationships at the catchment scale.*
Drainage basins are comprised of relatively self-contained, gravitationally induced sets of biophysical relationships. The balance of erosional and depositional processes varies markedly in source, transfer and accumulation zones of a catchment. Erosion is dominant in source zones, deposition is dominant in accumulation zones and an approximate balance of erosional and depositional processes is maintained in transfer zones (Chapter 3). Analysis of source-to-sink relationships at the catchment scale provides the most logical basis to consider the linked nature of spatial and temporal adjustments in landscapes, enabling meaningful interpretation of lagged and off-site responses to disturbance events. The unique configuration and temporal sequence of drivers, disturbances and responses of each landscape, along with the historical imprint, result in system-specific behavioural and evolutionary traits.

Catchment-scale investigations frame analyses of river character, behaviour and evolution in relation to the size and shape of the catchment, the drainage network pattern and density, and topographic relationships (especially relief, longitudinal profile shape and valley morphology) (Figures 1.2 and 1.4). Each site/reach must be viewed in its catchment context, assessing relationships to upstream and downstream considerations. Flow–sediment linkages between reaches and tributary–trunk stream relationships in differing landscape compartments (or process domains) are captured by the term *landscape connectivity* (Chapter 2). In some landscapes, hillslope and valley-floor processes are inherently coupled or connected; elsewhere they are not. Valley floors may be disconnected from adjacent hillslopes, but directly linked to sediment supply from upstream. Analysis of downstream patterns of rivers, and associated implications for flow and sediment flux, determines how adjustments to one feature (or reach) affect adjacent or other forms. The way in which disturbance responses in one part of a catchment affect river adjustments elsewhere within that system is termed a response gradient. Understanding of these catchment-scale considerations provides critical guidance in interpreting the behavioural regime and evolutionary trajectory of a river.

In summary, reading the landscape is an open-ended, interpretative, field-based approach to geomorphic analysis of river systems. Efforts to read the landscape can be summarised as follows: identify features and assess their formative processes, appraise how these features fit together in a landscape (reaches and catchments) and assess how these features adjust and evolve over time. Meaningful *identification* and *description* underpins effective *explanation*, providing a platform with which to make realistic *predictions* about likely future states. Landscape relationships are analysed through appreciation of system dynamics, recognising the variable imprint/memory of influences from the past. Behavioural regimes are differentiated from river changes as landscapes evolve. Human impacts upon rivers are differentiated from natural variability. Chapters 2–9 of this book outline contextual principles and theories with which to ground these analyses, which are explained more fully in Chapters 10–14.

Key messages from this chapter

- Geomorphology is the science concerned with understanding the form of the Earth's surface and the processes by which it is shaped, both at the present day and in the past.

- Rivers are a product of their landscape. As rivers are spatially linked systems, they are best studied at the catchment scale. Catchments synthesise process–form relationships over a range of spatial and temporal scales.
- No two landscapes (and associated river systems) are exactly the same. Reading the landscape presents a grounded basis to examine the character, behaviour and evolution of any given river system.
- Reading the landscape is a thinking and interpretative exercise. Detective-style investigations are required to differentiate among the myriad of factors that affect river character, behaviour and evolution. The approach to reading the landscape outlined in this book has four steps:

1. Identify and interpret landforms and their process–form relationships.
2. Analyse assemblages of landforms at the reach scale to interpret behaviour.
3. Explain controls on process–form interactions at the reach scale and how they adjust over time.
4. Integrate spatial and temporal considerations through catchment-specific investigations to explain patterns of river types and their evolutionary adjustment, framing system responses to human disturbance in relation to the natural variability of the system.

CHAPTER TWO
Key concepts in river geomorphology

Introduction

This chapter outlines a range of concepts and theories about how a river landscape looks, adjusts and evolves. These spatial and temporal concepts build upon each other helping us to frame catchment-scale, system-specific applications that assess geomorphic responses to human disturbance in relation to natural variability. These concepts aid our efforts to read the landscape.

This chapter is structured as follows. First, spatial considerations are reviewed. This starts with an overview of nested hierarchical approaches to analysis of river systems. Imposed and flux boundary conditions that control the range of river character and behaviour are defined and differentiated. Then the complexity of river structure is differentiated in terms of landscape heterogeneity and homogeneity. The final spatial concept outlined here is a summary of landscape (dis)connectivity.

Second, temporal concepts that are used to characterise river systems are appraised. This starts with a synthesis of geologic (cyclic), geomorphic (graded) and engineering (steady-state) timescales. Equilibrium notions developed via negative feedback mechanisms are used to describe geomorphic adjustments around a mean (*characteristic*) state. River behaviour is differentiated from river change; the latter records a shift to a different type of river with a different behavioural regime. These transitions may be brought about by positive feedback mechanisms that breach threshold conditions. Press, pulse and ramp disturbance events are differentiated. Responses to disturbance are assessed in terms of their reaction and relaxation times. These notions are used to discuss prospects for river recovery. Magnitude–frequency relations highlight how geomorphic work and geomorphic effectiveness vary for disturbance events of differing size and recurrence. Variability in landscape sensitivity, among many factors, results in complex responses to disturbance, as landscapes preserve a variable record of past events (termed memory or persistence). Lagged and off-site responses emphasise the need to explain patterns and rates of geomorphic adjustment at the catchment scale. The principle of equifinality highlights how similar-looking forms may result from different sets of processes.

These various spatial and temporal concepts are pulled together in the final section of this chapter. The system-specific configuration of any given catchment, along with its unique history of responses to disturbance, is characterised in relation to non-linear dynamics. Principles of emergence, contingency and path dependency are outlined. System responses to human disturbance are appraised relative to natural variability. Collectively, these considerations frame the evolutionary trajectory of any given system.

Spatial considerations in reading the landscape

Catchments as nested hierarchies: the spatial configuration of landscapes

Nested hierarchical models of catchment organisation frame small-scale (and short-term) river features and processes in relation to larger scale (and longer term) factors (Figure 2.1, Table 2.1). Smaller spatial scales are nested within higher level scales. Each nested level within a hierarchical view of catchments is controlled by the conditions set by higher level scales. This allows interpretation of higher level controls on physical processes that operate at smaller scales.

Different scalar units in the nested hierarchy are commonly not discrete physical entities. Rather, they are part of a complex continuum in which the dimensions of units at each scale may overlap significantly. Interaction between units, at each scale and between scales, determines the character and behaviour of the system under investigation. When used effectively, nested hierarchical frameworks provide an elegant tool with which to organise

Geomorphic Analysis of River Systems: An Approach to Reading the Landscape, First Edition. Kirstie A. Fryirs and Gary J. Brierley.

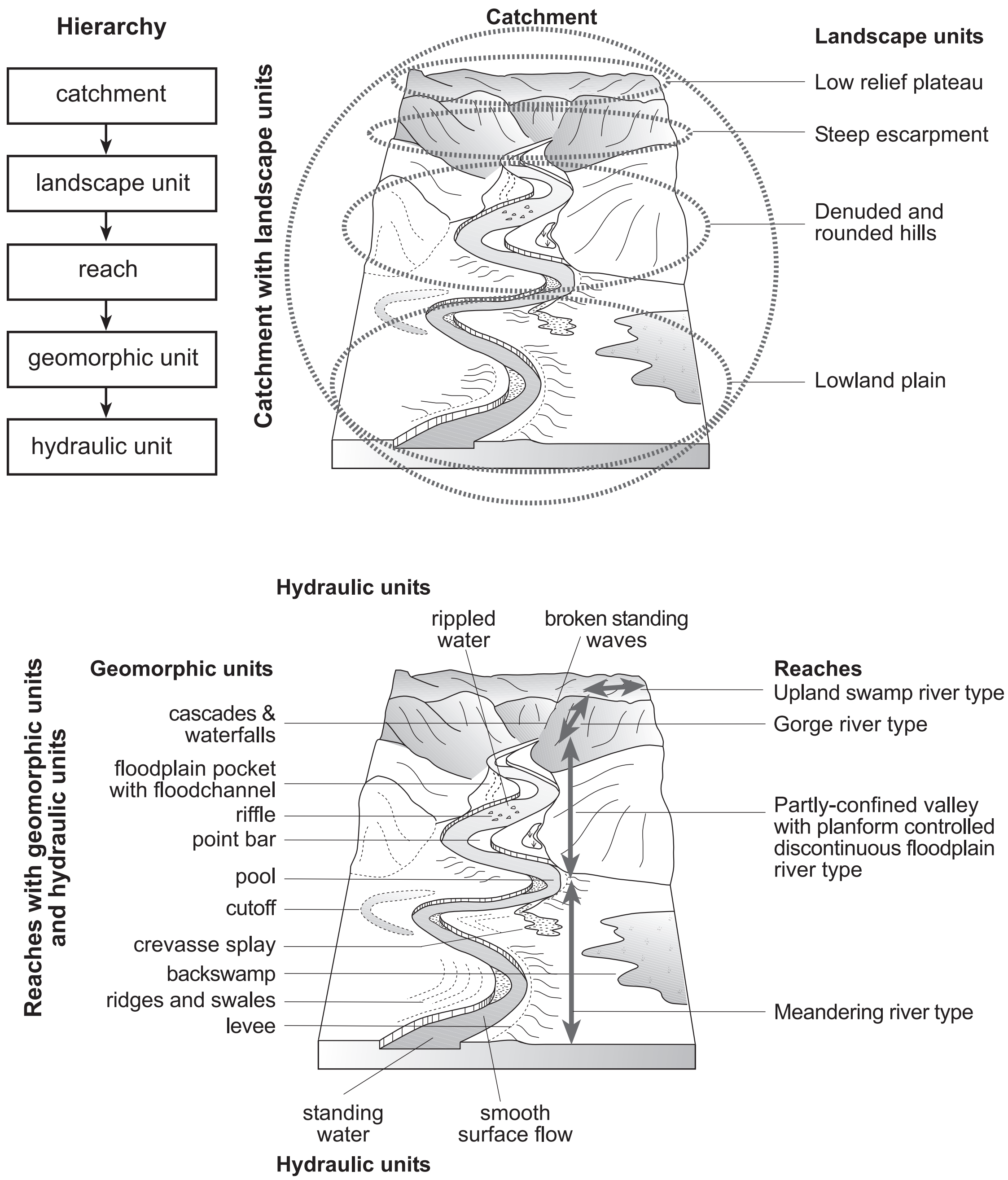


Figure 2.1 Scales of river structure. A hierarchical approach to landscape analysis frames catchments as assemblages of landscape units, reaches, geomorphic units and hydraulic units. Adjustments in bed material size operate at the hydraulic and geomorphic unit scales, channels and river planform adjust at the reach scale and slope adjustments along longitudinal profiles occur at the landscape unit and catchment scales.

information, thereby presenting a coherent platform for management applications.

Catchment (also called watershed or drainage basin)

A catchment is a single fluvial system that is linked internally by a network of channels. Regional geology and climate, among other factors, determine topography, valley width, sediment transport regime and the discharge regime. Catchment-scale factors are relatively insensitive to change, but if disturbed will take considerable time to recover. Within any catchment, individual subcatchments may have quite different physical attributes, with differing types and proportions of landscape units and associated variability

Table 2.1 A nested hierarchy of geomorphic scales

Scale	Evolutionary adjustment timeframe (yr)	Disturbance event frequency (months)	Geomorphic influence
Catchment	10^5–10^6	10^3	Tectonic influences on relief, slope and valley width combined with lithologic and climatic controls on substrate, flow and vegetation cover (among other factors) determine the imposed boundary conditions within which rivers operate. The drainage pattern and stream network influence the nature, rate and pattern of biophysical fluxes (these relationships are also fashioned by catchment geology, shape, drainage density, tributary–trunk stream interactions, etc). Vegetation cover and land use indirectly influence river character and behaviour through impacts upon flow and sediment delivery.
Landscape unit	10^3–10^4	10^2	Landscape units are readily identifiable topographic features with a characteristic pattern of landforms. The nature, rate and pattern of biophysical fluxes are influenced by landscape configuration (i.e. the pattern of landscape units and how they fit together in any given catchment) and the connectivity of reaches. At this scale, the channel, riparian zone, floodplain and alluvial aquifer represent an integrated fluvial corridor that is distinct from, but interacts with, the remaining catchment.
Reach	10^1–10^2	10^1	Geomorphic river structure and function are relatively uniform at the reach scale. Morphological attributes such as channel planform and geometry are fashioned primarily by flow regime, sediment transport regime, floodplain character and vegetation and groundwater–surface-water exchange. Distinct assemblages of channel and/or floodplain landforms characterise reaches.
Geomorphic unit	10^0–10^1	10^0	These landform-scale features reflect formative erosional and depositional processes that determine river structure and function. Distinct features are evident in channel and floodplain compartments. Morphodynamic relationships fashion these landforms, where process influences form and vice versa.
Hydraulic unit	10^{-1}–10^0	10^{-1}	This scale of feature is determined by (and shapes) flow–sediment interactions that reflect the energy distribution along a river course. Relationships vary markedly with flow stage. Pronounced local-scale variability in surface roughness, flow hydraulics or sediment availability and movement may be evident around basal materials, logs and organic debris. Surface–subsurface flow linkages fashion hyporheic zone processes.

in geomorphic process zones. As such, interpretation of controls on river character and behaviour is best framed in terms of subcatchment-specific attributes such as the shape of the longitudinal profile, lithology, etc. (see Chapter 3).

Landscape units (also called land systems)

Just as drainage basins comprise a series of subcatchments, so each subcatchment can be differentiated into topographic compartments based on relief variability and landscape position. Landscape units are areas of similar topography that have a characteristic pattern of landforms. Key factors used to identify landscape units include measures of relief, slope, elevation, topography, geology and position (e.g. upland versus lowland settings). As landscape units are a function of slope, valley confinement and lithology, they not only determine the calibre and volume of sediment made available to a reach, they also impose major constraints on the distribution of flow energy that mobilises sediments and shapes river morphology. Catchment-to-catchment variability in river character and behaviour, and the operation of biophysical fluxes, are largely determined by the type and configuration of landscape units. Different landscape units tend to be associated with differing land uses.

River reaches

Topographic constraints on river forms and processes result in differing ranges of river character and behaviour in differing valley settings along a longitudinal profile (see Chapter 3). Reaches are differentiated within each landscape unit. They are defined as sections of river along which controlling conditions are sufficiently uniform (i.e. there is no change in the imposed flow or sediment load) such that the river maintains a near-consistent structure. Alternating reaches made up of different river types are referred to as *segments*. Reaches are made up of distinct assemblages of geomorphic units.

Geomorphic units (landform-scale features)

The availability of material and the potential for it to be reworked in any given reach determine the distribution of geomorphic units, and hence river structure (see Chapters 8 and 9). Some rivers comprise erosional forms that are sculpted into bedrock (e.g. cascades, falls, pools), while others comprise depositional forms in channel and floodplain compartments that reflect sediment accumulation in short- or long-term depositional environments (e.g. mid-channel bars versus a backswamp). Geomorphic units are discrete morphodynamic entities. Certain processes produce the form and the form, in turn, affects the nature and effectiveness of the process. Adjacent geomorphic units may be genetically linked. For example, pools are functionally connected to adjacent riffles.

Hydraulic units (also called habitats or patches)

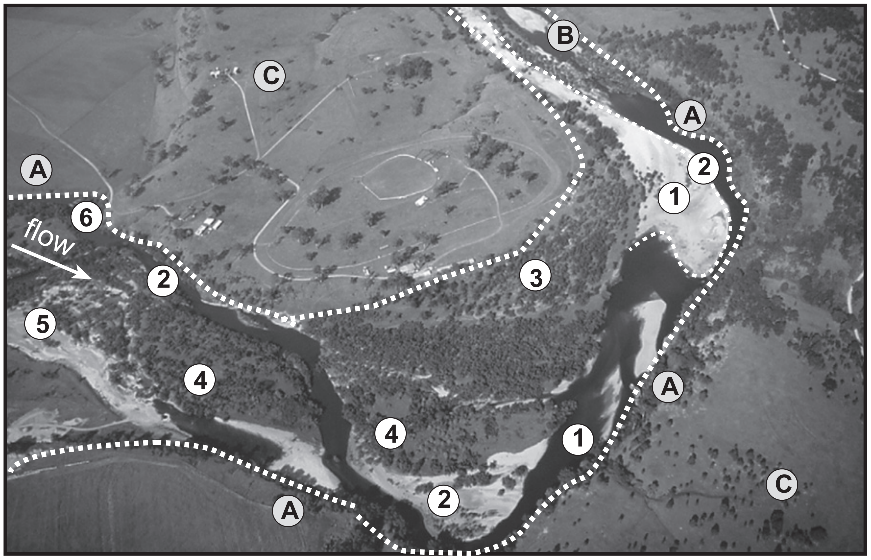
Hydraulic units are spatially distinct patches of relatively homogeneous surface flow and substrate character. These range from fast-flowing variants over a range of coarse substrates to standing-water environments on fine-grained substrates. Flow–substrate interactions vary at differing flow stages. Several hydraulic units may comprise a single geomorphic unit. For example, distinct zones or patches may be evident within individual riffles, characterised by differing substrate, the height and spacing of roughness elements, flow depth, flow velocity and hydraulic parameters such as Froude and Reynolds numbers (see Chapter 5). Some hydraulic units tend to be very sensitive to change, adjusting on an event-by-event basis, but they generally have considerable capacity to recover following disturbance.

Imposed and flux boundary conditions

Catchment boundary conditions determine the range of processes and resulting assemblages of landscape forms in any given system. *Imposed boundary conditions* do not change over geomorphic timeframes (centuries to thousands of years). These controls reflect the landscape and/or environmental setting in which rivers operate. They determine the relief, slope and valley morphology (width and shape) within which rivers adjust (Figure 2.2). For example, geologic controls such as tectonic setting and lithology influence landscape elevation and relief (i.e. slope), and the type and amount of sediment made available to be moved by the river. Long-term landscape evolution fashions the drainage pattern and stream network, along with the width and alignment of valleys within which rivers are set. Although these geologic controls are not static in their own right, they are considered here as consistent controls upon the river (i.e. factors that do not change over geomorphic timeframes). These considerations determine how much potential energy is available to be used by the river. At the same time, they impose some constraints upon the way in which energy can be used (e.g. use of kinetic energy is influenced markedly by slope and valley width, and any factors that concentrate or dissipate flow energy). Imposed boundary conditions effectively dictate the pattern of landscape units, thereby determining the valley setting within which a river behaves and/or changes.

Flux boundary conditions are essentially inset within the imposed boundary conditions (Figure 2.2). Dynamic interactions that fashion the flow and sediment regime, and vegetation associations along a reach, exert a key influence

Imposed boundary conditions set by:
Ⓐ valley confinement and slope
Ⓑ base level at bedrock riffles and downstream gorges
Ⓒ low relief topography



Flux boundary conditions set by interactions between water, sediment, and vegetation:
① flow and sediment interaction dictate zones of sediment transfer and deposition
② flow and sediment interaction forming different types of instream geomorphic units (e.g. bars, riffles, pools)
③ flow and sediment interaction forming and reworking floodplains
④ sediment and vegetation interaction forming different geomorphic units (e.g. ridges)
⑤ flow and vegetation interactions dictating variability in roughness
⑥ flow inundates different surfaces during discharge events of varying magnitude and frequency

Figure 2.2 Imposed and flux boundary conditions. A mix of controls affects the morphology and behaviour of any river (see Chapter 11). Imposed boundary conditions or controls remain consistent over short timeframes. Valley confinement, base level set by bedrock (i.e. slope), topography and geology influence the type of river that can form in a given setting. Flux boundary conditions fashion the flow, sediment and vegetation interactions along a river, thereby determining its character and behaviour. This figure shows how imposed and flux boundary conditions have created a partly confined valley with bedrock-controlled discontinuous floodplain river in the Clarence catchment, NSW, Australia. From Brierley and Fryirs (2008). © Island Press, Washington, DC. Reproduced with permission.

on river character and behaviour. Catchment-scale controls on the flow regime are determined largely by the climate setting. Rivers are forever adjusting to variability in flow and sediment, over timescales ranging from short pulsed events (individual floods) through to sequences of floods, through to seasonal/interannual variability and longer term trends. Stark contrasts in discharge regime are evident in arid, humid–temperate, tropical, Mediterranean, monsoonal and other climate settings, marking the differentiation of perennial and ephemeral systems, among many things. Climate also imposes critical constraints on the amount and variability of runoff, the magnitude–frequency relationships of flood events and the effectiveness of extreme events. Secondary controls exerted by climatic influences at the catchment scale are manifest through effects on vegetation cover and associated rates of runoff and sediment yield.

Flux boundary conditions determine the energy conditions under which rivers behave. The balance of erosional and depositional processes on valley floors reflects the flow–sediment balance. Any given reach develops a characteristic behavioural regime over timeframes in which flux boundary conditions remain relatively consistent. However, flux boundary conditions may change over management timeframes. For example, alterations to ground cover may change surface erodibility and rainfall–runoff relationships. Alternatively, flow regulation disrupts flow and sediment transfer within river systems. Alterations to flux boundary conditions may induce river change whereby the river adopts a new behavioural regime that adjusts to the new flux boundary conditions.

Evolutionary adjustments in river systems are brought about by alterations to the imposed and flux boundary conditions, whether as a result of 'natural' trends or human induced impacts. Typically, these events suppress or expand the manner and/or rate of adjustment of the system.

Heterogeneity and homogeneity of landscapes

Some rivers are characterised by a wide range of morphological features, while others have a remarkably simple structure. The natural diversity in geomorphic and hydraulic units is an important determinant of the range of habitat availability along a river. The more complex and diverse the array of landforms is along a reach, the broader the range of available physical habitat. For example, there is significant diversity along a meandering sand-bed river, with riffles, runs and pools in the channel zone, differing bank forms, point bars on the inside of bends (possibly dissected by chute channels), while the floodplain may comprise features such as a levee, cut-off channels (oxbow lakes or billabongs), backswamps and floodplain ponds (Figure 2.3a). In stark contrast, the physical structure of a discontinuous watercourse may be remarkably homogeneous, essentially comprising a valley fill wetland and a discontinuous channel (Figure 2.3b).

Catchment linkages and (dis)connectivity

Landscape connectivity is a primary control upon catchment-scale fluxes of water and sediment. The nature and continuity of longitudinal, lateral and vertical linkages are controlled by different sets of processes at different positions in a catchment. Fluxes may be connected (coupled) or disconnected (decoupled). Patterns and/or phases of discontinuity in these linkages vary both spatially and temporally. These are catchment-specific relationships.

Longitudinal linkages refer to upstream–downstream and tributary–trunk stream relationships in the channel network. The strength of longitudinal linkages reflects the character and distribution of landscape units in a catchment. The cascading nature of these interactions is influenced by the pattern and extent of coupling in each subcatchment. Appraisal of these linkages is required to assess how off-site impacts such as sediment release and/or decreased water supply affect reaches elsewhere in a catchment, and associated lag times. The distribution of river types in each subcatchment, and how these subcatchments fit together in the catchment as a whole, provides a physical basis to interpret these linkages.

Lateral linkages include hillslope–channel and channel–floodplain relationships. Hillslope–channel connectivity records the frequency with which channel processes rework materials derived from hillslopes. In coupled systems, water and sediment are transferred directly from hillslopes to the channel network. Conversely, in decoupled systems, materials are stored for differing intervals of time in various features between the hillslope and the channel. Floodplains are the most common sediment storage feature in this location, preventing sediment transfer directly to the channel. In many landscapes, alluvial fans are also common in this location. Channel–floodplain connectivity reflects the two-way transfer of water and sediment between channel and floodplain compartments. The magnitude, frequency and duration of overbank events are primary determinants of the periodicity of inundation that drive channel–floodplain linkages.

Vertical linkages entail surface–subsurface interactions of water and sediment. Examples include inundation levels of differing geomorphic units and the connectivity of surface and subsurface flow pathways. Within-channel linkages are controlled by the texture of the bed material and the transport regime of the channel. In a broader sense, these relationships are affected by soil/regolith characteristics that control slope hydrology and relationships between surface flow, subsurface flow and groundwater. Hyporheic and parafluvial zones are areas of subsurface flow that occur through the substrate of channel beds, bars and floodplains. Hydrologic exchange and nutrient transformation between surface waters and alluvial groundwaters may extend a considerable distance beyond the channel margin beneath the floodplain.

Various forms of physical linkage inferred for an idealised catchment are shown in Figure 2.4. In confined headwater reaches, hillslopes and channels are coupled, such