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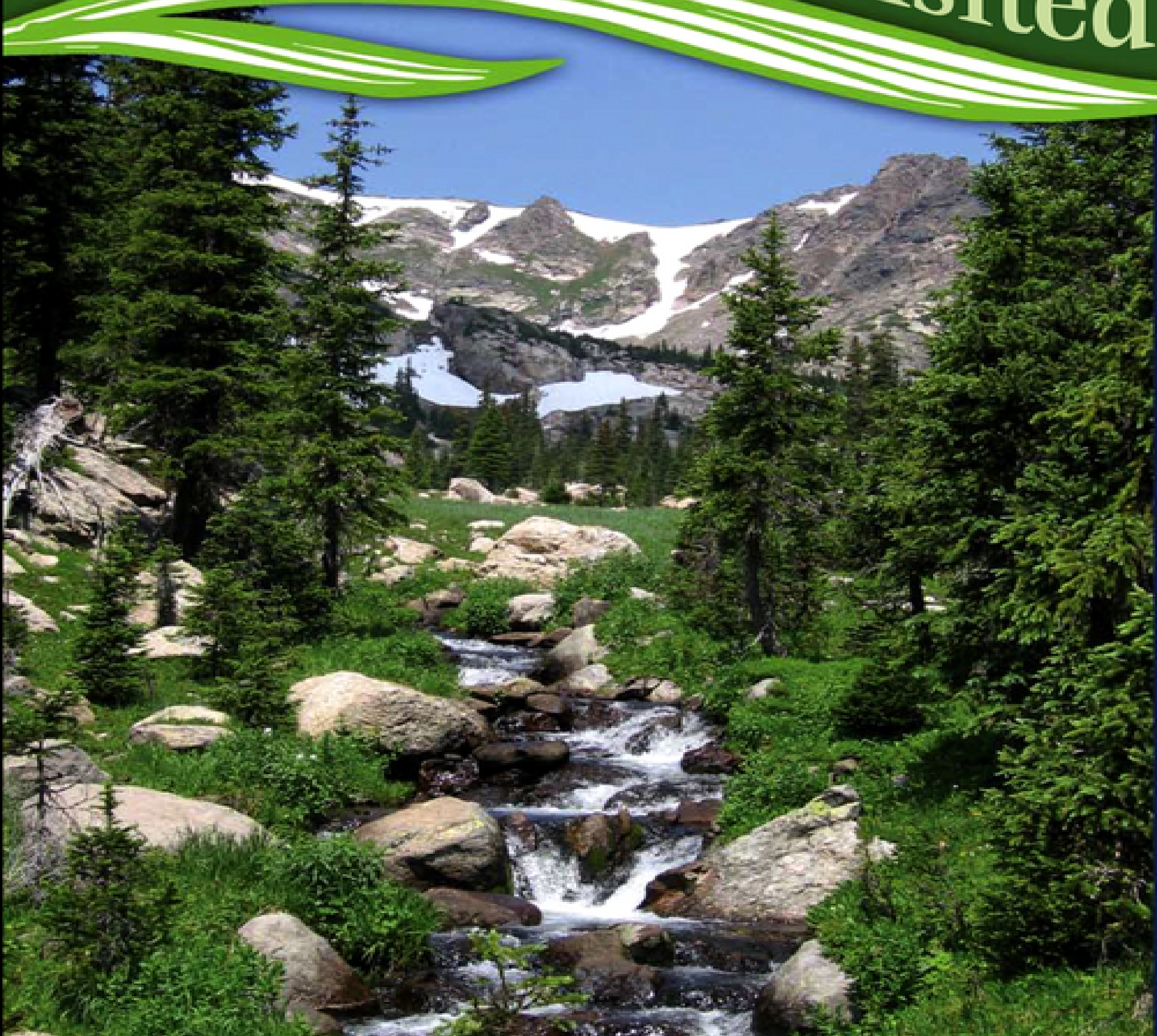
Mountain Rivers Revisited



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Ellen Wohl

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Ellen Wohl

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Cover photographs by Ellen Wohl. (front) Tributary of Tonahutu Creek, Rocky Mountain National Park, Colorado. (back) Rio Sardinal in Braulio Carillo National Park, Costa Rica.

PREFACE

I wrote the first edition of this book, published in 2000, in response to a need expressed by one of my Ph.D. students at the time, David Merritt, who walked into my office one afternoon for a summary reference on mountain rivers. When I realized that such a reference did not exist, I set out to create one. The inclusion of topics reflected my own belief that rivers need to be examined not solely as physical systems but also as river ecosystems with chemical and biological components that exist in the context of pervasive and long duration human alteration of the environment. As research on topics related to mountain rivers grew dramatically during the past decade, I decided that it was time to write a second edition, and I reorganized the book to reflect my understanding of evolving knowledge.

As with the first edition, this second edition is aimed primarily at an audience already familiar with the basics of river process and form, although the reader with little knowledge of related topics, such as river chemistry, hyporheic zones, or riparian and aquatic ecology, can also gain a quick introductory overview of those topics from this volume. Advanced undergraduates, graduate students, and professional scientists and engineers who possess some general knowledge of river systems will find this volume of use, both for its own sake and to help them build on their existing knowledge of mountain rivers to better understand the unique aspects of these rivers. You can read the book straight through, because each section builds upon the sections that precede it, or use the book as a spot reference to provide a synthesis of current knowledge on specific topics.

The first edition benefited substantially from discussions with, and critical reviews by, Paul Carling (University of

Southampton, England), Dan Cenderelli (U.S. Forest Service), Alan Covich (University of Georgia), Janet Curran (U.S. Geological Survey), Jim Finley (Telesto Solutions, Inc.), David Merritt (U.S. Forest Service), and LeRoy Poff (Colorado State University) and AGU reviews by John Costa (U.S. Geological Survey), Avijit Gupta (University of Leeds, England), and Malcolm Newson (University of Newcastle upon Tyne, England). Much of that material is still in this edition, and I thank each of these individuals for their efforts. The second edition has also benefited from discussions with Gordon Grant (U.S. Forest Service), Bob Hilton (Durham University), Neils Hovius (Cambridge University), Mark Macklin (University of Aberystwyth), and Grant Meyer (University of New Mexico) and reviews by Jim O'Connor (U.S. Geological Survey) and an anonymous reviewer, as well as the enhanced energy and concentration provided by Whole Foods' organic French roast coffee.

As with the first edition, I would like to dedicate this second edition to my graduate students. They continue to challenge, engage, and surprise me and to provide much of the pleasure that comes from working in fluvial geomorphology.

Ellen Wohl
Colorado State University

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INTRODUCTION

Rivers shape many of the world's landscapes. In the process of transporting water, sediment, and dissolved chemicals from uplands, rivers redistribute mass across the Earth's surface. Rivers set the pace at which weathering and erosion lower landscapes, and control the gradient of adjacent hillslopes. Fundamentally, rivers organize terrestrial landscapes into drainage basins. As the rivers incise or aggrade in response to changes in baselevel, they create valleys that influence local climate; provide travel corridors for animals and humans; and support aquatic and riparian ecosystems that contain some of the Earth's highest levels of biodiversity.

Scientists have systematically studied rivers for more than two centuries. Among the questions asked have been: How do rivers interact with other variables such as climate, lithology and tectonics that influence landscapes? What governs the spatial distribution of river channels? What factors control the yield of water and sediment from hillslopes to rivers? How do interactions between water and sediment influence channel geometry through time and space?

This volume summarizes contemporary understanding of these and other aspects of rivers, in the context of rivers draining mountainous environments. Although the study of rivers is well-established, investigators typically focused on the lowland rivers along which most people live until the final decades of the 20th century. A substantial increase in the amount of research directed toward mountain rivers during the first decade of the 21st century supports the need for this second edition of *Mountain Rivers*, which was originally published in 2000. Increased attention to rivers in mountainous regions results from several trends within science and the greater society. Among these is the focus on numerically simulating landscape evolution over long timespans, which requires that modelers quantitatively parameterize rates of river incision and rates of crustal uplift in mountainous regions. Another factor driving increased investigation of mountain rivers is attempts to maintain or restore rivers as ecological refuges and as critical components of water supply in mountainous regions, which tend to be less densely populated than adjacent lowlands. Finally, mountain rivers with steep, coarse-grained, poorly-sorted beds, and limited sediment supply are typically poorly described by empirical equations for hydraulics and sediment dynamics developed for rivers with lower gradients, making the study of mountain rivers an intellectual and management challenge.

1.1. Characteristics of Mountain Rivers

In this volume I define a mountain river as being located within a mountainous region and a mountainous region as having a mean elevation above sea level ≥ 1000 m [*Viviroli et al*., 2003]. Each of the continents includes at least one major mountainous region (Figure 1.1). (Selected images appear in print. All images are available on the CD-ROM that accompanies the book.) Mountains cover 52% of Asia, 36% of North America, 25% of Europe, 22% of South America, 17% of Australia, and 3% of Africa, as well as substantial areas of islands including Japan, New Guinea, and New

Zealand [*Bridges*, 1990]. Mountain rivers are thus widespread. Because of the steep topography of mountainous regions, mountain rivers typically have a gradient ≥ 0.002 m/m along the majority of the channel length [*Jarrett*, 1992], although substantial longitudinal variability of channel geometry is common in mountainous regions as a result of longitudinal variations in rock resistance, glacial history, and hillslope stability. Lower gradient reaches of channel typically occur upstream of glacial end moraines, massive landslide deposits, or beaver dams, for example, but these reaches create relatively short interruptions between the steeper channel segments up- and downstream.

As with lowland rivers, mountain rivers exhibit great variability in hydrologic regime; channel planform; channel gradient, grain size, and bedforms; sediment dynamics; and aquatic and riparian biota, both within individual mountain ranges and among diverse mountainous regions. Mountain rivers, as defined here, include firstorder channels less than a meter wide fed by snowmelt draining an alpine meadow (Figure 1.2); wider rivers cutting steep-walled valleys that dense tropical rain forest vegetation cannot stabilize against periodic landslides (Figure 1.3); ephemeral channels incised into bedrock in arid mountains (Figure 1.4); boreal rivers with cutbanks exposing permafrost (Figure 1.5); and big, powerful rivers like the Indus that carry thousands of kilograms of sediment down to the adjacent lowlands each year (Figure 1.6). Perhaps the only consistent characteristic of mountain rivers is their typically steep gradients, although steep gradients tend to correlate with other characteristics, including

- erosionally resistant and hydraulically rough channel boundaries associated with bedrock and coarse clasts;
- highly turbulent flow with numerous longitudinal transitions between sub- and supercritical flow;

- limited supply of sediment of fine gravel and smaller size;
- bedload movement that is highly variable in space and time, with higher thresholds for initiation of motion than many lowland rivers;
- strongly seasonal discharge regime associated with glacial melt, snowmelt, or seasonal rainfall;
- substantial spatial variability in discharge as a result of spatial variability in precipitation and runoff caused by differences in elevation, basin orientation, and land cover;
- large longitudinal variations in channel geometry associated with variations in tectonics, lithology, glacial history, and sediment supply;
- in some cases, lesser temporal variations in channel geometry than lowland rivers because only infrequent floods or debris flows can exceed boundary resistance sufficiently to cause substantial channel change;
- relatively narrow valley bottoms with limited development of floodplains and lateral movements by rivers;
- in the absence of wide valley bottoms and the associated buffering of stream channels from hillslope processes, mountain rivers have the potential for orders-of-magnitude increase in water and sediment yield over a period of a few years following watershed-scale disturbances such as wildfire or timber harvest; and
- longitudinal zonation of aquatic and riparian biota influenced by river characteristics and by elevation as it relates to temperature and precipitation.

Mountain rivers tend exhibit high degrees of connectivity. *Landscape connectivity* [*Brierley et al.*, 2006] is high because individual landforms such as hillslopes and stream channels are closely coupled within a drainage basin. *Hydrological connectivity* [*Bracken and Croke*, 2007] is high because water moves rapidly from one landform to another and through the entire drainage basin relative to lowland watersheds with extensive groundwater storage. *Sediment connectivity* [*Fryirs et al.*, 2007] is high because limited storage means that sediment moves relatively rapidly from production sites on hillslopes through the drainage basin. Increasing research emphasis on different forms of connectivity reflects a desire to move beyond small spatial and short temporal scales of investigation in order to focus on emergent properties that evolve from the selforganization inherent in river catchments [*Phillips*, 2003; *McDonnell et al.*, 2007; *Reid et al.*, 2007b; *Ali and Roy*, 2009].

1.2. Advances Since the First Edition

Writing the second edition proved to be a much more time-consuming and expansive process than I had initially expected, but this reflects the dynamic nature of contemporary studies of geomorphology and mountain rivers. Many areas of investigation have expanded dramatically since the late 1990s and the volume of associated literature has grown correspondingly. Dramatic increases in the amount of research in topics such as: the interactions of tectonics, topography, and climate [*Willett et al., 2006]*; hillslope hydrology and modeling [*Franks et al.*, 2005]; debris flows and associated hazards [*Jakob and Hungr*, 2005]; soil development and hillslope processes [*Heimsath et al.*, 2001; *Roering*, 2004]; hydraulics of steep channels [*Ferguson*, 2007]; braided river process and form [*Sambrook Smith et al.*, 2006]; diverse types of numerical models and associated predictions [*Wilcock and Iverson*, 2003; *Tucker and Hancock*, 2010]; geochronology [*Madsen* *and Murray*, 2009]; and instrumentation [*Jones et al*., 2007] have made it challenging to keep track of and synthesize the literature. As a result, I have introduced several new sections to the second edition, substantially expanded other areas, and altered the organization of the volume to reflect changing research emphases within the community.

One broadly applicable change is the increasing emphasis on quantification, numerical modeling, and prediction in studies of the Earth's surface. This is exemplified by *Dietrich et al.'s* [2003] call for increased development and application of *geomorphic transport laws*. "A geomorphic transport law is a mathematical statement derived from a physical principle or mechanism, which expresses the mass flux or erosion caused by one or more processes in a manner that: 1) can be parameterized from field measurements, 2) can be tested in physical models, and 3) can be applied over geomorphically significant spatial and temporal scales" [*Dietrich et al*., 2003, p. 103]. Geomorphic transport laws have been developed for some processes, including soil production from bedrock and river incision into bedrock, but do not yet exist for many geomorphic processes, including landslides, debris flows, and surface wash. Section 1.4 is designed to highlight the existing geomorphic transport laws relevant to mountain rivers and to provide an overarching conceptual framework for reading the succeeding, more detailed discussions of each of the processes and forms briefly mentioned in section 1.4.

1.3. Purpose and Organization of This Volume

This volume on mountain rivers is intended for the reader who already has a basic understanding of fluvial geomorphology, as developed in texts including *Leopold et al.* [1964], *Schumm* [1977], *Morisawa* [1985], *Richards* [1987], *Easterbrook* [1993], *Ritter et al*. [1995], *Bloom* [1998], *Knighton* [1998], *Bridge* [2003], or *Anderson and Anderson* [2010]. The emphasis of this volume is on channel processes and morphology, but the volume also includes brief reviews of other aspects of mountain rivers. The second chapter focuses on form and process at the scale of drainage basins (10^1-10^6 km^2), starting with interactions among tectonics, climate, and topography, and then reviewing hillslope processes, channel initiation and arrangement in a network, and valley geometry, including changes in process and form during the Quaternary. The third chapter covers process at the channel scale (10^{-2}-10^1 km^2), including hydrology, hydraulics, sediment dynamics, river chemistry, instream wood, and physical disturbances such as floods and debris flows. The fourth chapter examines types of channel morphology characteristic of mountain rivers and the fifth chapter discusses aquatic and riparian communities of mountain rivers. The sixth chapter explores human interactions with mountain rivers.

The diversity of topics addressed in this volume is designed to promote the realization that a mountain river is an integrated physical, chemical and biological system influenced by controls acting across various scales of time and space. The need to move beyond traditional disciplinary boundaries is reflected in the discussion of *Earth system science* starting in the late 20th century. A system is a collection of interdependent parts enclosed within a defined boundary; in this case, the interdependent parts within the boundary of the Earth are the lithosphere, hydrosphere, biosphere, and atmosphere. Emphasis on a systems approach reflects an increasing realization that we cannot effectively respond to global warming, contaminant dispersal, and other contemporary challenges unless we think about natural processes in ways that transcend disciplinary boundaries. The establishment of critical zone observatories in the United States (the *critical zone* is defined as the Earth’s outer layer, from the lower atmosphere and vegetation canopy to the soil and groundwater, which sustains living organisms) is also designed to promote integrative study of surface processes and landforms. Rivers provide an obvious mechanism for integrative thinking because a seemingly simple, discrete channelized flow of water in fact reflects influences from high in the atmosphere to deep in the crust and across hemispheres.

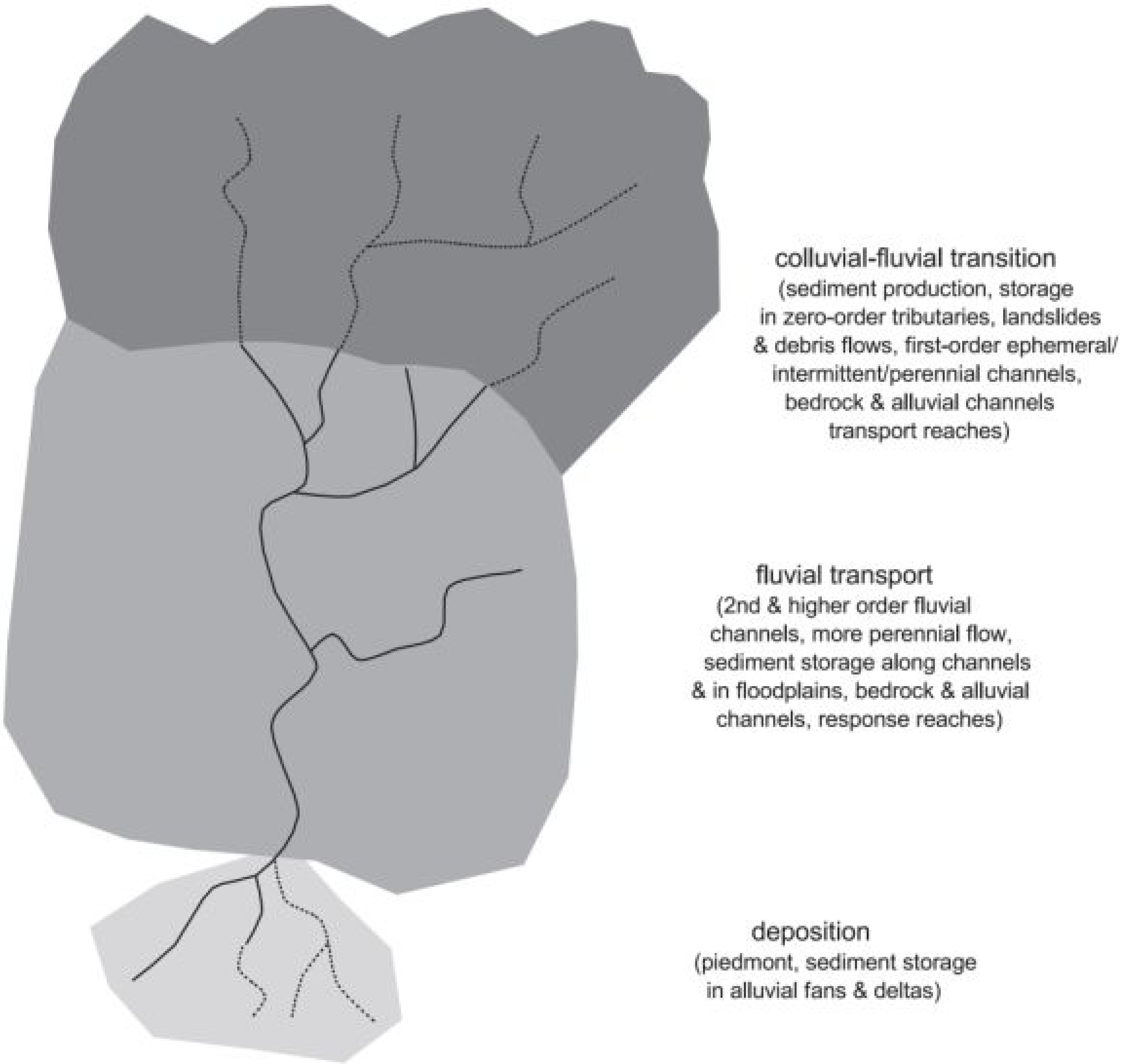
This volume is primarily an integration and synthesis of existing knowledge of mountain rivers. Although it is not feasible to cite every published study on all aspects of mountain rivers, the list of references at the end of the volume is unusually long because I wanted to be as inclusive as possible. I have avoided citing abstracts or unpublished theses or dissertations unless these are the only published material relevant to a particular topic and I have mostly avoided citing references that are not in English. Because this volume focuses primarily on physical processes, the discussions and reference lists for river chemistry and for aquatic and riparian ecology are not as complete as those for other topics treated in this volume. Topics of which we have particularly limited knowledge are highlighted throughout this synthesis and the concluding summary emphasizes aspects on which further research is particularly needed.

1.4. A Mountain River Described and Enumerated

Headwater regions encompass substantial spatial and temporal variations in geomorphic processes. The upstream extent of the channel network represents the transition from hillslope to channel processes, and downstream portions of channel networks in steep terrain include the transition from debris flows to fluvial processes, as well as substrate transitions such as bedrock to gravel and gravel to sand [*Sklar and Dietrich*, 1998; *Montgomery*, 1999; *May*, 2007; *Stock and Dietrich*, 2003]. Figure 1.7 presents a schematic overview of the components of mountain rivers discussed in this volume and, where possible, examples of equations developed to quantify these components. These equations are discussed in detail in succeeding portions of the text. Some of the equations are developed from a theoretical basis such as a balance of forces; others are empirical equations that may be of limited usefulness when extrapolated beyond the data from which they were developed. Whether theoretically or empirically based, quantitative statements of geomorphic process and form help to guide and focus continuing research by identifying processes or forms that we cannot yet adequately parameterize or that deviate from existing observations.

Building on *Schumm's* [1977] zonation of a fluvial system into three basic zones of production, transfer and deposition, Figure 1.7 organizes mountain rivers into three primarily spatial zones, each of which is dominated by a distinct suite of geomorphic processes and landforms. The *colluvial-fluvial transition* area occupies the uppermost portion of the drainage basin, where sediment produced from bedrock weathering is moved downslope into channels by mass movements such as debris flows and landslides, and where fluvial channels begin. Channels in the *fluvial transport zone* in the middle section of the basin typically have progressively less direct hillslope influences as wider valley bottoms and floodplains buffer materials coming from hillslopes by creating at least temporary storage zones. Lower gradients, less lateral confinement, and/or lower velocity and discharge facilitate deposition along channels in the *depositional zone*, which is typically beyond the mountain front but may also occur in locally wider valleys.

Figure 1.7 Highly stylized illustration of the three primary zones of a mountain drainage basin, followed by some of the equations used to describe process and form in each of those three zones. Variables used in each equation are defined in subsequent portions of the text.

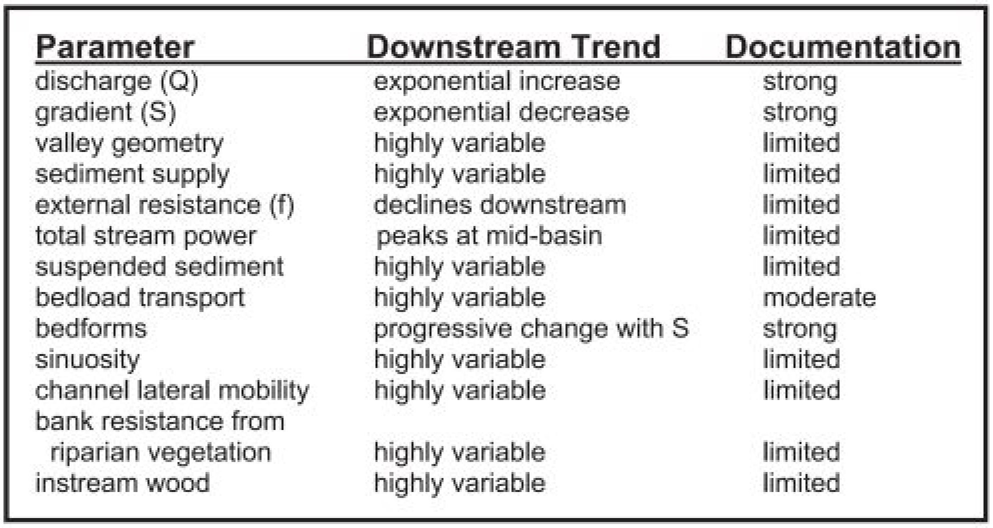


This downstream zonation of mountain drainage basins reflects progressive downstream trends in discharge, gradient, grain size and other stream characteristics that numerous investigators have documented across a range of mountain drainage basins. Other variables that do not show progressive downstream trends also characterize mountain drainage basins; hydraulic resistance and magnitude of bedload transport, for example, do not necessarily change progressively downstream. Most variables show both progressive downstream trends and dominantly local (10^1-10^3 m) variation, depending on the spatial scale under consideration: Gradient and grain size both decrease downstream at the scale of a larger mountain watershed, but can exhibit local reversals as a result of spatial and temporal variation in driving factors such as lithology, tectonic uplift or hillslope stability and associated sediment inputs (Figure 1.8).

The local, and potentially longitudinally discontinuous, values of some parameters support the concept of *geomorphic process domains*. Spatial variability in geomorphic processes governs temporal patterns of disturbances that influence ecosystem structure and dynamics [*Montgomery*, 1999]. Mass transfer in the uppermost portions of hillslopes might be dominated by avalanches and rockfall, for example, whereas debris flows exert a greater influence in the middle portions of the catchment, and fluvial processes dominate the lower portions.

One way to conceptualize mountain river form and process is within the framework of driving forces versus substrate resistance. Channel configuration at any point along the drainage network fundamentally reflects the ratio of hydraulic driving forces to substrate resistance. *Hydraulic driving forces* reflect the movement of a volume of water from higher to lower elevation and thus incorporate discharge and channel gradient. The potential energy converted to kinetic energy via the downstream flow of water can be expended on overcoming external frictional resistance, internal frictional resistance, and sediment transport; the expenditure of energy thus incorporates channel configuration, sediment supply, and the erodibility of the channel boundaries. The ratio of driving forces and *substrate resistance* varies temporally as tectonic uplift alters landscape relief or storms passing over the watershed or land use alter water and sediment yield to the channel. The ratio also varies spatially as progressively greater contributing area increases discharge in the channel or as the channel flows from glaciated to unglaciated portions of the catchment. Some forms of spatial variation, such as downstream increase in discharge, are well documented from a range of field settings and are best described as linear or exponential functions. Some forms of spatial variation, such as the magnitude of external frictional resistance, may show analogous downstream trends, but lack extensive field documentation. Other forms of spatial variation, such as bank resistance created by riparian vegetation, are not adequately described by linear or exponential functions and appear to predominantly reflect local controls that do not vary progressively downstream. Figure 1.9 lists channel forms and processes and what is known about their downstream trends in mountain rivers. Although limited work to date suggests that hydraulic driving force as reflected in stream power peaks in the upper third to middle part of the basin [*Knighton*, 1999], substrate resistance is so spatially variable in mountain drainage basins that it precludes generalizations. It may thus be more useful to apply the ratio of driving force to substrate resistance at the local scale rather than at the basin scale.

Figure 1.9 Downstream trends in selected parameters for mountain rivers and relative documentation (with progressively less documentation from strong through moderate to limited) of these trends based on field data from diverse settings.



Parameter	Downstream Trend	Documentation
discharge (Q)	exponential increase	strong
gradient (S)	exponential decrease	strong
valley geometry	highly variable	limited
sediment supply	highly variable	limited
external resistance (f)	declines downstream	limited
total stream power	peaks at mid-basin	limited
suspended sediment	highly variable	limited
bedload transport	highly variable	moderate
bedforms	progressive change with S	strong
sinuosity	highly variable	limited
channel lateral mobility	highly variable	limited
bank resistance from riparian vegetation	highly variable	limited
instream wood	highly variable	limited

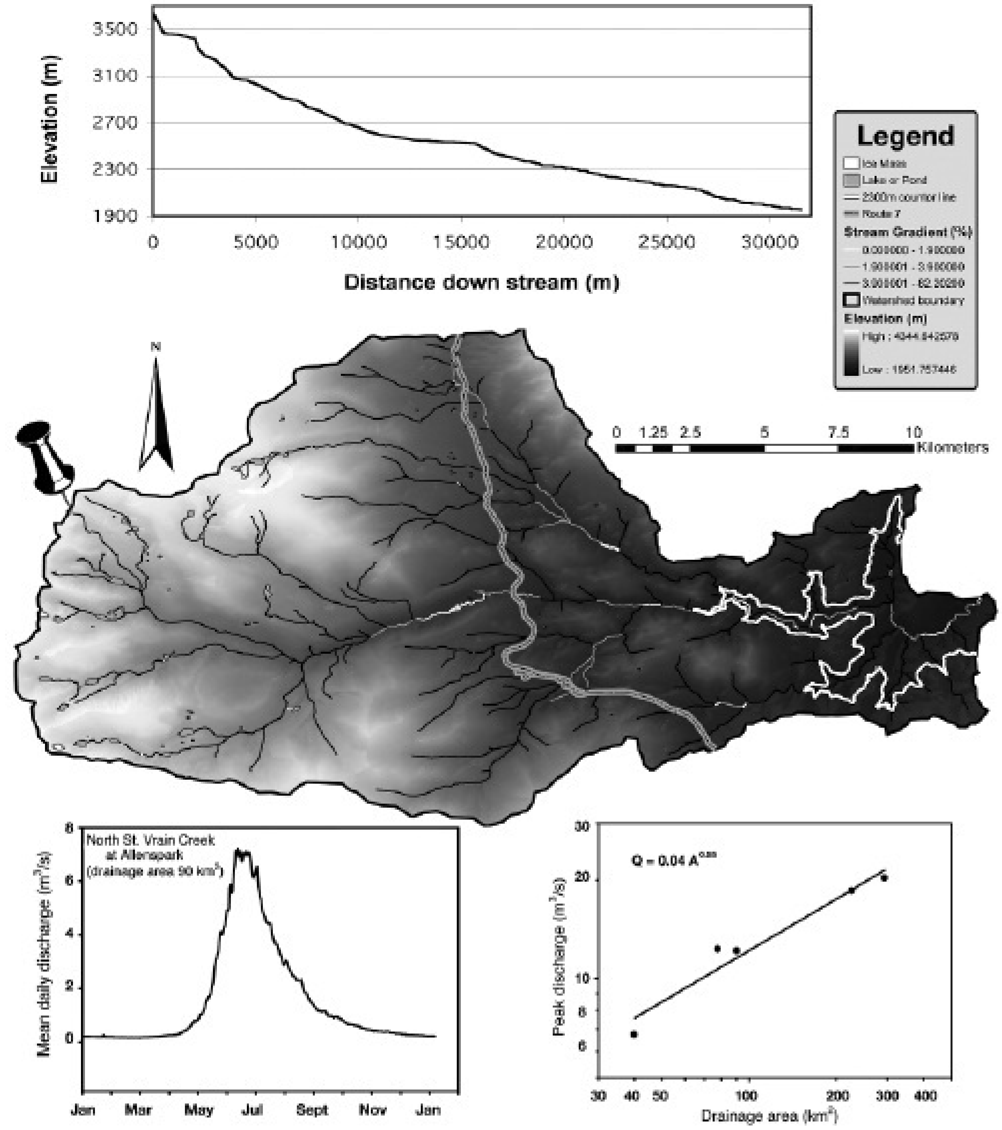
Each of the very broad parameter categories outlined in Figure 1.9 is explored in greater detail in subsequent sections of this book, but Figure 1.9 provides a quick overview of our relative understanding of diverse patterns in mountain drainage basins. This figure also indicates how much work remains to be done.

1.4.1. North St. Vrain Creek, Colorado, USA

I use the specific example of North St. Vrain Creek in the Colorado Front Range, USA to further illustrate how individual parameters vary downstream or locally. I chose this watershed because it is one of the least altered by land uses in the region and because I have done much of my own research there. North St. Vrain Creek represents neither an exceptionally well-studied watershed nor a little known one; it falls somewhere between these extremes and in this respect represents many other mountainous drainages.

North St. Vrain Creek drains eastward from the Continental Divide (4050 m elevation) onto the Great Plains (1945 m elevation at the base of the mountains) and eventually joins the South Platte River (Figure 1.10A). The portion of the catchment within the mountains includes 250 km^2 of steep terrain underlain by Precambrian-age granites, gneiss, and schist [*Tweto*, 1979]. The Front Range has been relatively tectonically quiescent since the early Tertiary [*Crowley et al*., 2002; *Anderson et al.*, 2006b]. Pleistocene valley glaciers extended down to approximately 2500 m elevation [*Madole et al*., 1998]. Narrow, glaciated spines form the range crests at 4000 m elevation, below which lie widespread surfaces of low relief at 2300-3000 m elevation. Fluvial canyons are deeply incised into these low-relief surfaces [*Anderson et al*., 2006b]. Most bedrock outcrops in the region are densely jointed, and joint spacing and valley geometry correlate with the location of shear zones of Precambrian and Laramide age [*Abbott*, 1976]; wider, lower gradient portions of fluvial valleys typically correspond to more closely spaced joints and the location of shear zones [*Ehlen and Wohl*, 2002]. Variations in joint density, glacial history, and other large-scale controls create pronounced downstream variations in valley and channel geometry.

Figure 1.10 NSV map.



Parameter	Downstream Trend and Notes
discharge (Q)	exponential increase; as illustrated in Figure 1.10(A), peak annual discharge varies with drainage area with an exponent of 0.55, based on stream gage records covering multiple years at five sites with unregulated flow in and near the North St. Vrain catchment
gradient (S)	exponential decrease; as illustrated in Figure 1.10(A), longitudinal variation in stream gradient is readily obtained from 10-m DEM coverage of the catchment; spatial variation reflects primarily Pleistocene glacial history
valley geometry	highly variable; valley geometry can be directly estimated from 10-m DEMs via metrics such as connectedness (lateral distance between channel and base of valley wall) and entrenchment (ratio of channel width to valley width) or indirectly estimated from stream gradient on 10-m DEMs; Figure 1.10(A) illustrates spatial variation in stream gradient within the catchment, and the steepest gradient segments correspond to relatively deep, narrow valleys(< 50 m wide valley bottom), the moderate gradient segments to valleys of intermediate width and depth, and the lowest gradient segments to glacial troughs and broad valleys (> 50 m wide valley bottom) with meadows and wetlands
sediment supply	highly variable; little documentation in the North St. Vrain

	catchment, but volume and frequency likely vary with valley geometry, with coarser grained sediment episodically entering channels in mass movements along steep, narrow valley segments
external resistance (f)	declines downstream; limited documentation indicates that, as *S* decreases downstream, *f* also decreases (Wohl et al., 2004)
total stream power	peaks at mid-basin, as predicted by Knighton (1999), although values of stream power display a substantial amount of scatter rather than following smoothly ascending or descending trends (Wohl et al., 2004)
suspended sediment	highly variable; limited documentation indicates that suspended sediment increases during the annual snowmelt peak flow and following disturbances such as wildfire or debris flows
bedload transport	highly variable; limited documentation indicates increasing bedload transport in slightly finer grained channel segments downstream
bedforms	progressive change with *S*; spatial distribution of cascade, step-pool, plane-bed, and pool-riffle segments correlates well with *S* and can thus be predicted using 10-m DEM data (Wohl et al., 2004, 2007)
sinuosity	highly variable; like valley geometry, this correlates with *S* and can thus be indirectly estimated from 10-m DEM data, with high gradient corresponding to straight channels and lower stream gradients corresponding to greater sinuosity
channel lateral mobility	highly variable; as with sinuosity, this correlates with stream gradient and can be indirectly estimated from 10-m DEM data; steeper channels have lower lateral mobility than channels of lower gradient
bank resistance from riparian vegetation	highly variable; type of riparian vegetation varies with elevation and with valley geometry and can thus be indirectly estimated from 10-m DEM data; lower gradient channel segments flowing through relatively wide valleys are more likely to have dense herbaceous vegetation and willow (*Salix*) communities in relatively wide bands along the channel, whereas steep channel segments have limited riparian communities dominated by coniferous trees (Polvi, 2009)
instream wood	highly variable; limited documentation (e.g., Wohl and Jaeger, 2009; Wohl and Cadol, in press) indicates that higher wood loads and more frequent channel-spanning jams correspond to lower gradient stream segments

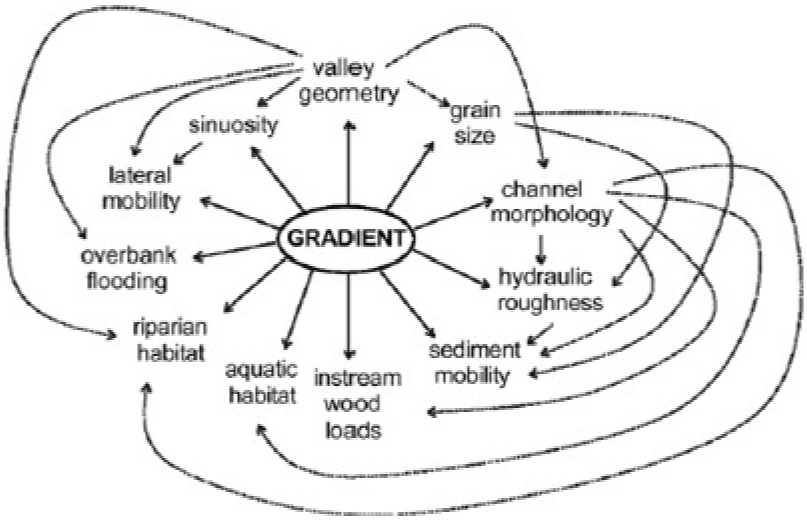
Snowmelt runoff dominates the annual hydrograph at all elevations within the catchment, producing a sustained May-June peak. On average, 85% of the annual flow occurs between May and September. Elevations below 2300 m also experience flash floods caused by summer convective storms. Rivers above this elevation have unit discharges of ~ 1 $m^3/s/km^2$, whereas rivers below 2300 m can have unit discharges of 40 $m^3/s/km^2$ [*Jarrett*, 1989]. Climate in the Front Range varies with elevation. Mean annual temperature varies from 1°C at the highest elevations to 11°C at the base of the range. Mean annual precipitation decreases from approximately 100 cm at the highest elevations to 36 cm at the mountain front, and the percentage of precipitation falling as snow also decreases with elevation.

Vegetation communities also vary with elevation, from alpine tundra above 3400 m, through subalpine spruce-fir forest, and montane pine forest below 2700 m [*Veblen and Donnegan*, 2005]. Wildfire and insect outbreaks are the most important forest disturbances in terms of extent, severity, and frequency. Three general types of historic fire regimes present in the catchment are: (i) infrequent, high-severity fires that kill all canopy trees over areas of hundreds to thousands of hectares and recur at intervals greater than 100 years in the subalpine zone; (ii) a complex pattern of low- and highseverity fires that burn areas of approximately 100 ha and recur at intervals of 40 to 100 years in the middle and upper montane zone; and (iii) frequent, low-severity firest that burn mainly the ground surface over areas of approximately 100 ha at intervals of 5-30 years in the lower montane zone [*Veblen and Donnegan*, 2005].

Beaver were trapped along the channels of the watershed starting in the early 19th century; the creek is named for French fur trapper Ceran St. Vrain. Although beaver have gradually recolonized the watershed, their populations are smaller than prior to trapping [*Wohl*, 2001]. The watershed is bisected by a two-lane highway; portions of the catchment upstream are largely in Rocky Mountain National Park and the mountainous portion downstream is largely in the Roosevelt National Forest. Flow in the creek is regulated starting at the base of the mountains. The information summarized in Figure 1.10 is drawn primarily from *Thompson et al*. [1996, 1999], *Wohl et al*. [2004], *Flores et al*. [2006], *Polvi* [2009], *David et al*. [2010], and *Wohl and Cadol* [in press]; with the exception of *David et al*. [2010], which is based on data collected in nearby drainages, these studies were conducted within the North St. Vrain catchment. Figure 1.10B reiterates Figure 1.9 with respect to the North St. Vrain catchment.

My research on North St. Vrain Creek and other mountainous catchments around the world has led me to conceptualize form and process in mountain rivers as illustrated in Figure 1.11. In this figure reach-scale gradient assumes primary importance. Gradient at channel lengths of 10^1-10^3 m can be a quasi-independent variable when the river does not have sufficient energy to create a smoothly concave longitudinal profile as a result of longitudinal variations in uplift rate, rock resistance, glacial history, sediment supply, or other parameters that influence gradient. Many other parameters correlate directly with reach-scale gradient (the solid arrows in Figure 1.11) and indirectly via intermediary parameters (the dashed arrows in Figure 1.11). Channel reaches of lower gradient, for example, correlate with wider valley bottoms or lower levels of connectedness (average distance from the channel edge to the valley edge) and higher values of entrenchment (ratio of valley width to channel width) [*Polvi*, 2009]. Wider valley bottoms in turn correlate with greater sinuosity, lateral channel mobility and overbank flooding, riparian habitat associated with greater inundation and higher water tables, finer grain sizes in the streambed, and channel morphology such as pool-riffle or dune-ripple [*Montgomery and Buffington*, 1997; *Wohl et al.*, 2007; *Polvi*, 2009]. These channel morphologies associated with lower gradient have lower levels of hydraulic resistance [Darcy-Weisbach f or Manning's n coefficients; *Wohl et al.*, 2004; *David et al.*, 2010], greater sediment mobility, larger instream wood loads [*Morris et al.*, 2010; *Wohl and Cadol*, 2010], and greater pool volume than high-gradient channels.

Figure 1.11 Schematic illustration of the correlations among variables along a mountain river. Reach-scale gradient assumes primary importance in this diagram because so many other variables directly or indirectly correlate with gradient, and because gradient is readily obtained from topographic data such as digital elevation models.



Most mountainous catchments around the world now have some level of topographic data available, allowing reach-scale gradient to be quantified at varying degrees of spatial resolution. The correlations between reach-scale gradient and a wide variety of other parameters thus provides an entry point for understanding at least relative spatial variations in multiple parameters within a catchment. Field calibration of these relations can of course improve the ability to specify the degree of variation within variables such as grain size or instream wood load with respect to gradient.