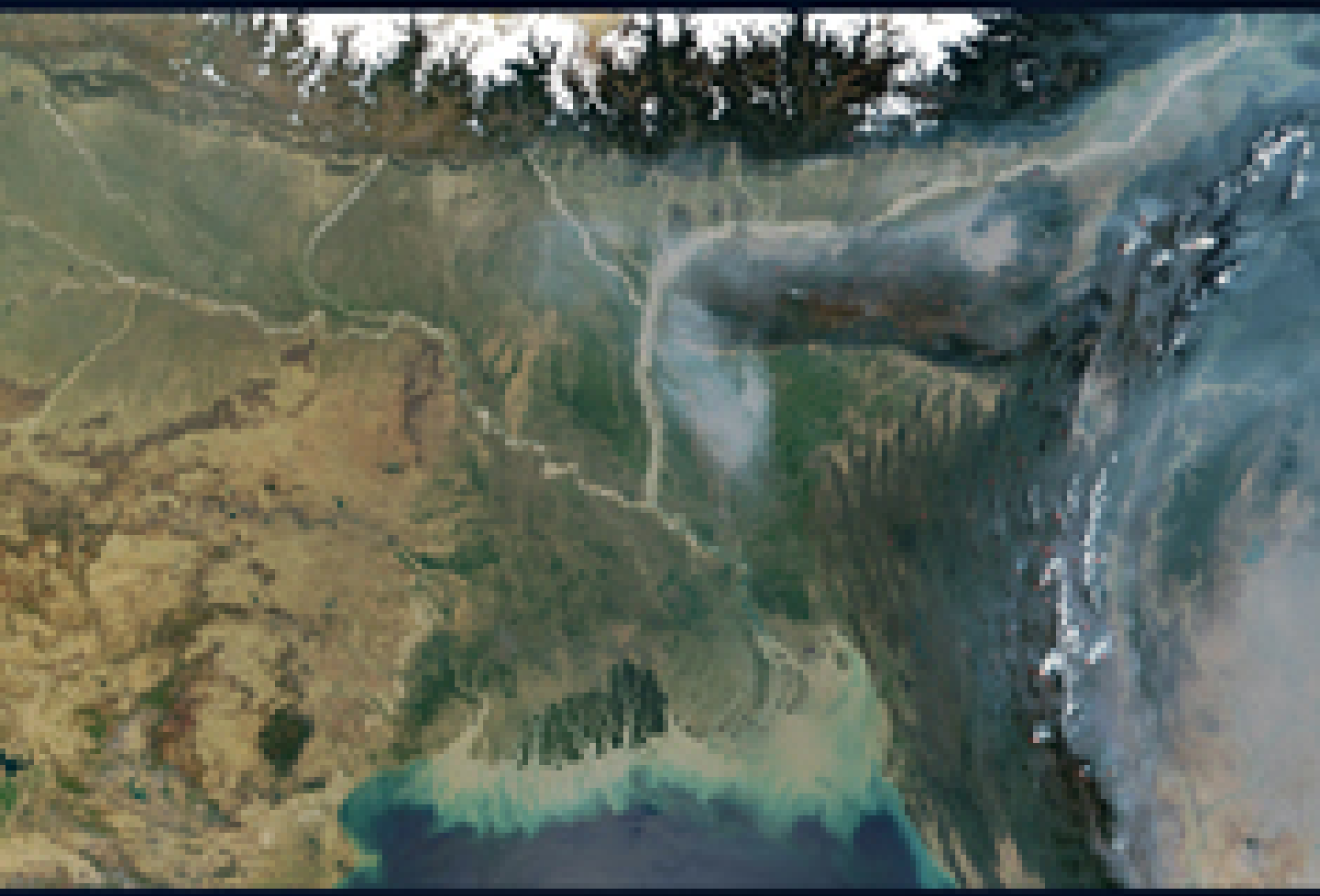
River Discharge to the Coastal Ocean

A GLOBAL SYNTHESIS



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River Discharge to the Coastal Ocean
A Global Synthesis

Rivers provide the primary link between land and sea, historically discharging annually about 36 000 km^3 of freshwater and more than 20 billion tons of solid and dissolved sediments to the global ocean. Together with tides, winds, waves, currents, and geology, rivers play a major role in determining the estuarine and coastal environment. The movement of freshwater and the distribution of river-derived sediments to the ocean have fundamental impacts on a wide variety of coastal environments, ranging from the Mississippi and Nile deltas, to coastal Siberia, to the Indonesian archipelago.

Utilizing the world's largest database – 1534 rivers that drain more than 85% of the landmass discharging into the global ocean – this book presents a detailed analysis and synthesis of the processes affecting the fluvial discharge of water, sediment, and dissolved solids. The ways in which climatic variation, episodic events, and anthropogenic activities – past, present, and future – affect the quantity and quality of river discharge are discussed in the final two chapters. The book contains more than 165 figures – many in full color – including global and regional maps. An extensive appendix presents the 1534-river database as a series of 44 tables that provide quantitative data regarding the discharge of water, sediment and dissolved solids. The appendix's 140 maps portray the morphologic, geologic, and climatic character of the watersheds. The complete database is also presented within a GIS-based package available online at www.cambridge.org/milliman.

River Discharge to the Coastal Ocean: A Global Synthesis provides an invaluable resource for researchers, professionals, and graduate students in hydrology, oceanography, geology, geomorphology, and environmental policy.

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River Discharge to the Coastal Ocean

A Global Synthesis

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Contents

Foreword

We began this book primarily to collate into a single database relevant environmental data for rivers that discharge directly into the global ocean. As the book evolved, however, it began to take on a life of its own, and now contains, following a brief introductory chapter, three rather long chapters that attempt to give an overview to the environmental controls on fluvial discharge, short-term and longer-term temporal variations, and the impact of human activities on global rivers and their watersheds.

As geological oceanographers, we tend to view rivers differently than most hydrologists, geochemists or geomorphologists. While our data, analyses and interpretations of these data touch upon fundamental processes that govern fluvial runoff, physical, and chemical weathering, transport, dispersal and sedimentation, we do not explain in detail how fluvial systems work. We do, however, include a rather extensive bibliography that can help direct the interested reader to relevant literature.

In presenting such a large database – more than 1500 rivers – some of the data almost invariably will prove to be erroneous. We may have transposed numbers, and almost surely we have missed some key data sources. Where errors or omissions occur, we request the reader notify us – kindly, if possible – so that we can correct our mistakes and set the record straight.

There are many people whose help made this book possible. Because of the long time – more than three decades for JDM – over which we acquired and analyzed these data, we almost certainly have inadvertently omitted several (we hope not many) people, to whom we apologize. The Global River Data Centre (GRDC) and the US Geological Survey National Water Information System (NWIS) provided a large number of data used throughout the book. Charlie Vörösmarty's RIVDIS and Arctic RIMS databases were also very helpful, particularly in creating their various user-friendly internet databases. We also made liberal use of Michel Meybeck's global river database (Meybeck and Ragu, 1996), without which our discussion of chemical weathering in Chapter 2 would have been impossible.

Maria Michailova deserves special mention for the way in which she substantially clarified the extensive database for Russian rivers, many of which we either did not know or got wrong in our earlier attempt at a collation of global data (Milliman *et al*., 1995). We also thank Yoshi Saito for help with data from Japan and China; Steve Smith for data from Mexico and southeast Asia; Yang Zuosheng, Wang Ying, Wang Houjie, S. L. Yang and Kevin Xu (China); Jim Wilson (Ireland); Kristinn Einarsson (Iceland); Lea Kauppi and Pirkko Kauppila (Finland); Des Walling (England); Wolfgang Ludwig, Maria Snoussi and Albert Kettner (Mediterranean and Black Sea rivers); Guadalupe de la Lanza Espino (Mexico); Bastiaan Knoppers (Brazil); Pedro Depetris (Argentina); Juan Restrepo (Colombia); John Largier (South Africa); Pham Van Ninh (Vietnam); Murray Hicks and Berry Lyons (New Zealand); Kao Shuh-ji (Taiwan); Harish Gupta (India); Peter Harris (Australia); and Professor da Silva (Sri Lanka). Jeff Mount and Jon Warrick opened our eyes regarding California rivers.

There are many other colleagues and friends without whom parts of this book would have been difficult, if not impossible, to write. Phil Jones (Climate Research Unit, University of East Anglia) provided us with a 100-year precipitation database from which Kehui (Kevin) Xu was able to synthesize several maps used in Chapter 2. Kevin also provided us with a number of other maps that we used throughout Chapters 3 and 4. Jon Warrick, James Syvitski, Kao Shuh-ji, Noel Trustrum and Bob Gammish were extremely helpful in supplying us with photographs used in Chapters 3 and 4, as was Juan Restrepo in sharing with us his land-use maps of the Magdalena watershed. Mike Page's and Noel Trustrum's photo of a dammed lake (Fig. 3.55) is also gratefully acknowledged. The time spent with Leal Mertes on the Santa Clara provided much insight and many memories, and she would have almost certainly provided us with a startling cover for this book; we mourn her passing.

Additional conversations with and insights from James Syvitski, Des Walling, Michel Meybeck, and Jean-Luc Probst over the past 15 years also were extremely helpful. We thank them all for their continued friendship.

Bob Meade has been an admirable mentor and longtime steadfast friend. Our many conversations and insights over the years have proved particularly useful in helping us understand better the whys and wherefores of, as Bob would term it, potamology. Bob's critical reading of the first draft of this book proved invaluable; any omissions or errors in this book almost certainly occurred after his careful editing.

A particular heart-felt thanks goes to Marilyn Lewis, at the SMS/VIMS library, who, through the wonders of Interlibrary Loan, obtained for us many of the books and reprints that facilitated our access to the river literature.

Harold Burrell's graphic skills, coupled with his patience as we continually reconsidered and re-thought figures for the book, are gratefully acknowledged.

Many of the data and insights in this book stem directly or indirectly from research grants awarded by the US National Science Foundation (NSF), the US Office of Naval Research (ONR), and the US Naval Oceanographic Office (NAVO). We thank in particular Peggy Schexnayder (NAVO) for her unfailing interest and encouragement over the 12 years that we spent working on this book.

Finally, JDM thanks Ann Milliman for enduring those many evenings when thoughts of rivers and this book took precedence over some of the more domestic and romantic aspects of our life. KLF thanks her family and friends for their patience and encouragement throughout the process.

1 Introduction

"Data! Data! Data!" (Holmes) cried impatiently.
"I cannot make bricks without clay."
Dr. J. Watson as transmitted to A. Conan Doyle

"Give me the facts, Ashley,
and I will twist them the way I want to suit my argument"
(statement attributed to W. Churchill)

Rivers and the coastal ocean

Rivers provide the primary link between land and sea, annually discharging about 36 thousand km^3 of freshwater and more than 20 billion tons (Bt) of solid and dissolved material to the world ocean. These fluxes, together with physiography and oceanographic setting, help determine the character of the estuarine and coastal environment. Although discharged water and sediments are generally confined to the coastal zone, if a flood is sufficiently large (e.g. Amazon River) or the shelf sufficiently narrow (e.g. southern California or eastern Taiwan) fluvial-driven plumes can extend to or beyond the shelf edge. In addition to their link to the coastal ocean, rivers historically have played key roles in human habitation and history, providing water, nutrients, transportation, and protection, among other things, for people living within their drainage basins.

Because of the wide range of physical and societal functions that a river can serve, one appealing – yet also daunting – aspect in the study of rivers and their watersheds is the diversity of perspectives and approaches used in their study. Geochemists and geologists often view a river in terms of landscape denudation or sediment transport, whereas geomorphologists may be more concerned with landscape character and its evolution. Engineers design and plan human adaptations to a watershed, while planners and policy makers may focus on the societal implications of these anthropogenic changes. Oceanographers tend to view rivers in terms of their discharge – and the fate of that discharge – to the coastal ocean. One outcome of this diversity of approaches is an ever-expanding database and an even wider range of published and unpublished literature. This is seen by the variety of journals and books referenced in this book. It may be unusual, for example, for an oceanographer to read *Catena*, a journal devoted to soil science, or a geomorphologist to read *Marine Geology*, but for someone interested in rivers, these journals – and a great many more like them – become almost required reading.

Superimposed on the interest in local, regional and global watersheds and their discharge to the marine environment has been a growing concern about the impacts of global climate change and human perturbations on present and future water resources (e.g. Shiklomanov and Rodda, 2003; Vörösmarty and Meybeck, 2004). An increasing number of international programs, such as those under the auspices of the International Geosphere–Biosphere Programme (IGBP), focus on the connective links between rivers, their watersheds, and the coastal ocean. The number of organizations (and, sadly, their acronyms) involved in water-related issues has literally exploded over the past 15–20 years into a veritable smorgasbord of alphabetical constructions. Gleick (2002), for example, used more than 10 pages to list water-related websites, and the number has increased substantially since then. Of particular relevance to this book are the programs within IGBP, most notably LOICZ (Land–Ocean Interactions at the Coastal Zone), PAGES (Past Global Changes), GAIM (Global Analysis, Integration and Modeling), ILEAPS (Integrated Land Ecosystem–Atmosphere Processes Study), WCRP (World Climate Research Programme), and GWSP (Global Water System Project). These IGBP efforts have led to a series of valuable and timely books dealing with global change. Of particular relevance to rivers are *Global Change and the Earth System* (Steffen *et al*., 2003), *Paleoclimate, Global Change and the Future* (Alverson *et al*., 2003), *Vegetation, Water, Humans and the Climate* (Kabat *et al*., 2003), and *Coastal Fluxes in the Anthropocene* (Crossland *et al*., 2005).

About this book

In this book we attempt to document and provide an overview and understanding of river fluxes to the coastal ocean. Our global database of more than 1500 rivers (see Fig. 1.1) includes only rivers that discharge directly to the ocean, not tributaries. The Mississippi and Amazon, for example, are included but not the Ohio or the Negro.

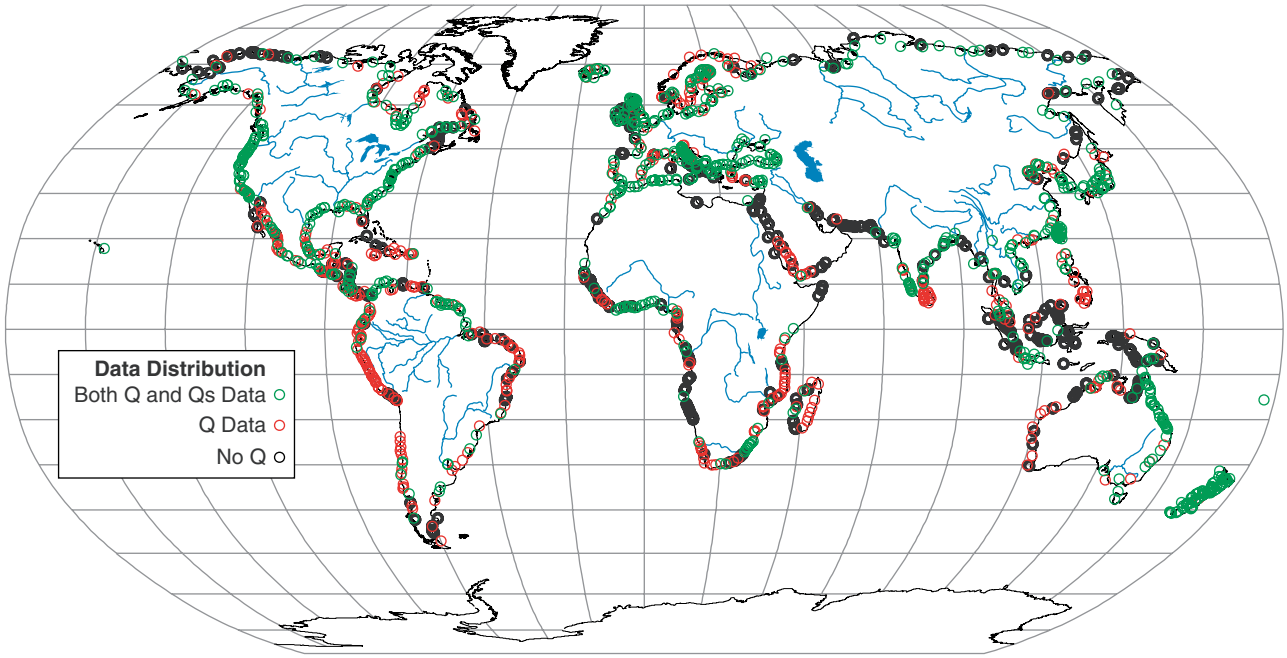

Figure 1.1. Locations of the 1534 rivers represented in our global database. Green circles represent rivers for which mean annual discharge and sediment and/or dissolved solid discharge are available; red circles represent those rivers for which only discharge is available; and black circles rivers for which no discharge values have been reported (or at least not which we could find in the literature).

Early attempts to collate a global database suffered from the lack of data, particularly for rivers that drain developing countries and for smaller rivers, even though they play critical roles in the global delivery of fluvial sediment to the coastal ocean (Milliman and Syvitski, 1992). A 1994 LOICZ-sponsored GLORI (Global River Index) meeting in Strassbourg (France), hosted by Jean-Luc Probst, provided the initiative to expand the global river database, and a subsequent LOICZ–GLORI compilation of more than 600 rivers (Milliman *et al*., 1995) provided a template on which future additions or corrections could be added. This was followed by an expanded GLORI database collated by Meybeck and Ragu (1996). Based in large part on the international response to the LOICZ report, the database has grown to the 1500+ rivers presented in the appendix of this book.

We define a river as a linear depression that drains to progressively lower elevations – in this book, ultimately to the ocean. By this definition, frequency and quantity of discharge are not factors in delineating a river, although they certainly help define the character of a river. Thus a wadi in Sudan or an ephemeral stream in Mexico is geomorphically, if not hydrologically, as much a river as the Amazon, even though its flow may be infrequent or, in the case of Libyan rivers, presently non-existent.

Our database contains entries from more than 100 countries, the most entries (128) being from the USA. But other countries have a surprising number of entries; for example, 60 from Mexico, 30 from South Africa, and even 11 from Yemen. The rivers included in the database in part depends on the size of the country. For larger countries, such as USA, Russia or China, we generally list only rivers larger than 3000 km^2 in area, except where annual suspended-sediment or dissolved-solid data are available. For smaller countries, such as Italy or Cuba, we include some rivers with basin areas smaller than 1000 km^2.

The 1534 rivers in our database collectively drain 86 600 000 km^2 of watershed. The cumulative area of the 34 rivers with watersheds larger than 500 000 km^2 (Fig. 1.2) accounts for 52 900 000 km^2, half of the ~105 000 000 km^2 that drains into the global ocean (Fig. 1.3b). Assuming that the number of global rivers is inversely proportional to their basin areas (Fig. 1.3a) and that our database includes essentially all rivers with drainage basins larger than 30 000 km^2 (292 rivers), we derived an algorithm (# rivers = 16.92*(basin area in millions of km^2)$^{-0.7903}$; r^2 = 0.997) that allows us to calculate the number of global rivers relative to their basin areas. Our algorithm, for example, predicts that there are 644 global rivers with basin areas greater than 10 000 km^2. Our database, in fact, shows 643 rivers (Fig. 1.3a) in this size range, suggesting that that our database contains all or nearly all rivers with drainage basins larger than 10 000 km^2. Cumulative basin area for these 643 rivers is 83 200 000 km^2.

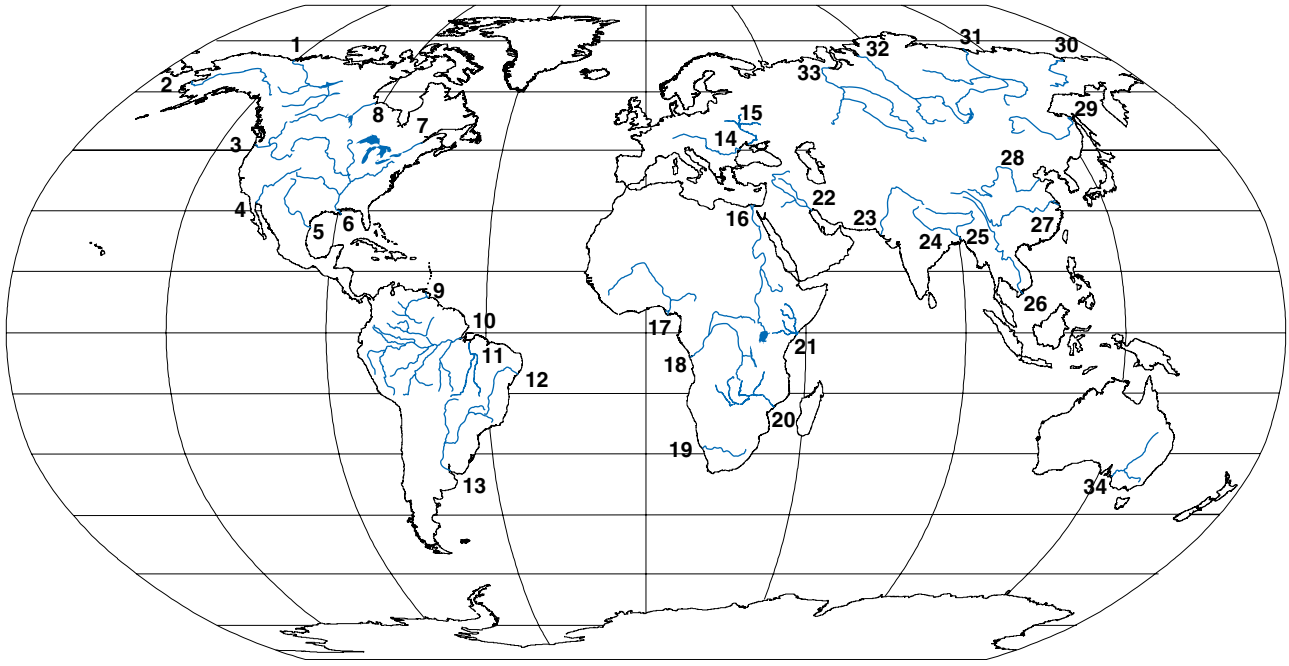

Figure 1.2. Locations of the 34 rivers with basin areas greater than 500 000 km^2; collectively these drainage basins account for half of the land area draining to the global ocean. 1, MacKenzie; 2, Yukon; 3, Columbia; 4, Colorado; 5, Rio Grande; 6, Mississippi; 7, St. Lawrence; 8, Nelson; 9, Orinoco; 10, Amazon; 11, Tocantins; 12, Sao Francisco; 13, Parana; 14, Danube; 15, Dnieprr; 16, Nile; 17, Niger; 18, Congo; 19, Orange; 20, Limpopo; 21, Shebelle-Juba; 22, Shatt al Arab; 23, Indus; 24, Ganges; 25, Brahmaputra; 26, Mekong; 27, Changjiang; 28, Huanghe; 29, Amur; 30, Kolyma; 31, Lena; 32, Yenisei; 33, Ob; 34, Murray.

Because our database is oriented towards rivers larger than 3000 km^2, it is less inclusive for smaller rivers. Of the approximately 24 500 global rivers with basin areas larger than 100 km^2, we calculate that there are ~23 000 rivers having watersheds between 100 km^2 and 3000 km^2 in area; collectively they drain about 10 000 000 km^2. Our database includes only 450 of these rivers, draining a cumulative area of 700 000 km^2 (Fig. 1.3b). In spite of their relative paucity, these 450 rivers nonetheless represent perhaps the most extensive small-river database yet published.

At the end of the book we present our GIS-based database – in both printed form and as a online at www.cambridge.org/milliman – which provides an environmental characterization of the 1534 rivers. For ease of presentation, we divide the world into 44 regions, for each of which we present three maps that identify river location and drainage basin morphology, average runoff (both annual and monthly), and drainage basin geology. The database lists the body of water into which the river discharges and important climatic and geomorphic characteristics, such as basin area, maximum elevation, geology, and discharge volumes of water, sediment and dissolved sediments; see pages 165–169 for a more complete discussion of the database and maps.

Chapter 2 discusses the discharges of water, suspended and dissolved solids to the global ocean, as well as the environmental factors that control these fluxes. Chapter 3 addresses temporal variations and changes, ranging from climatic cycles to the impact of episodic events (e.g. floods, or volcanic eruptions). Few rivers and their watersheds, however, are immune from human activities and their environmental impacts, and in Chapter 4 we discuss some of the impacts of human-induced change on rivers, culminating in a short discussion of probable impact(s) of present and future use and climate change. Said in another way, Chapter 2 describes how rivers work and the final two chapters throw up numerous caveats and cautions to any synthetic interpretations based on long-term means. The discussion and our data presented herein should not be considered complete, but rather as a moving target that will evolve as new data become available and as future shifts in climate and watershed character, both natural and anthropogenic, make themselves felt.

Other global databases

It was only in the early nineteenth century that river discharge was systematically monitored, first in northern Europe, most notably the Gøta (Sweden), Nemanus (Lithuania), and Rhine (Germany) rivers, and 50 years later in North America (St. Lawrence). Few non-European discharge measurements pre-date the twentieth century. As

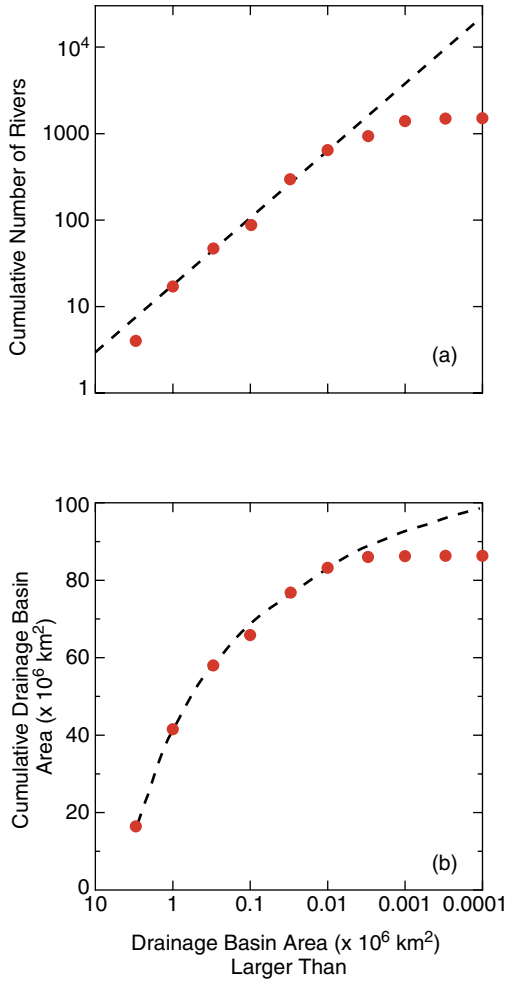

Figure 1.3. (a) Calculated number of global rivers (dashed line) and number of rivers in our database (red dots) vs. drainage basin size. The algorithm (# rivers = 16.92*(basin area in millions of km^2)$^{-0.7903}$) on which the calculation is based was derived from rivers in our database larger than 1 000 000 km^2, 300 000 km^2, 100 000 km^2 and 30 000 km^2. This plot suggests that our database effectively captures all or nearly all rivers larger than 10 000 km^2 that discharge into the global ocean. (b) Calculated cumulative basin area vs. basin size (dashed line) closely follows cumulative basin areas from our database (red dots) for rivers larger than 10 000 km^2. Given our emphasis on rivers larger than 3000 km^2, our database includes relatively few smaller rivers. The calculated global drainage basin areas for rivers larger than 10 km^2 in area – 103 000 000 km^2 – closely approximates the total land area draining into the global ocean, 105 000 000 km^2, lending confidence to our calculations.

such, the global database – or least that which is accessible – is rather thin both spatially and temporally.

In terms of both coverage and time-series, the UNESCO compilation of river discharge data remains a singularly valuable contribution. Beginning with *Discharge of Selected Rivers of the World* (1969), UNESCO ultimately published monthly and annual discharge records of 1000 rivers, a number of records extending back into the nineteenth century. Publication of an African river database (UNESCO, 1995) was particularly useful, since discharges for many of these rivers would otherwise have been difficult if not impossible to access. UNESCO World River reports ceased publication in 1992 (data entries extending only to 1984), but fortunately Charles Vörösmarty and his colleagues at the University of New Hampshire (www.watsys.unh.edu) maintained the UNESCO database on a GIS-based web page (www.rivdis.sr.unh.edu). The New Hampshire group also compiled valuable data sets for the Arctic and Latin American rivers. The ArcticRIMS (http://rims.unh.edu/data.shtml) webpage, another contribution from the Vörösmarty group, has proved particularly useful in accessing up-to-date discharge records for most pan-Arctic rivers.

The Global Runoff Data Centre (GRDC; http://www.grdc.bafg.de) in Koblenz, Germany, has the largest and most active global database. As of July 2008, it had captured water discharge data from more than 7300 stations, many records presented as daily, monthly, and yearly discharges. As many of the data are from tributaries or rivers that drain to inland basins (e.g. central Asia), we find that only 611 of the GRDC rivers discharge directly to the sea, and only 21 have records longer than 100 years; the Gøta's discharge record extending back to 1807 being the longest. Cumulative basin area upstream of the 611 river-gauging stations is ~61 000 000 km^2 (Table 1.1), about 60% of the total land area draining to the global ocean, and collectively these 611 rivers discharge ~65% of the global fluvial water. Only ~30% of the GRDC rivers, however, have discharge records longer than 50 years (Table 1.1; Fig. 1.4a), which is barely long enough to encompass short-term climatic cycles such as El Niño–Southern Oscillation or North Atlantic Oscillation. To capture longer cycles, such as the Pacific Decadal Oscillation or the Atlantic Multidecadal Oscillation (see Chapter 3), more than 50 years of data are needed. Moreover, as of 2008, the records for less than half of the 611 GRDC ocean-discharging rivers extended beyond 2000 (Fig. 1.3b); of these, only 124 rivers had records longer than 50 years (Fig. 1.4a). Cumulative basin area upstream of gauging stations for these 124 rivers is only 16 000 000 km^2, and collectively they account for only ~12% (4400km^3/yr) of the average global discharge.

It is not surprising that European and North American rivers rank high in terms of number of rivers in the GRDC database, as well as their lengths of record (Fig. 1.4b). In contrast, African rivers are woefully underrepresented: the GRDC lists only four African rivers with >50 years of data (Nile, Congo, Senegal, Orange), and data entries for most African rivers end by the mid 1980s.

Of the world's 12 highest-discharge rivers (see Table 2.3), one (Irrawaddy) is not found in the GRDC database, two

Table 1.1. *Summary of Global River Data Center (GRDC) database as of July 2008. Of the 611 rivers in the GRDC database that discharge directly to the ocean, 179 (<30%) are represented by more than 50 years of discharge data, about 2/3 of them (135) from Europe or North America. Collectively, South American and Asian rivers account for nearly 2/3 of the cumulative global discharge, but only 29 of these rivers are represented by more than 50 years of data.*

	# Rivers	Avg. yrs data	> 50 yrs data	ΣArea (× 10^6 km^3)	Σ*Q* (km^3/yr)
Europe	144	50	65	5.7	1550
N. America	173	47	70	13.6	3150
S. America	69	24	10	11.2	8450
Africa	71	25	4	8.3	2100
Asia	86	33	20	20	5600
Oceania	68	37	11	2.2	570
Totals:	**610**	**40**	**179**	**61**	**21 400**

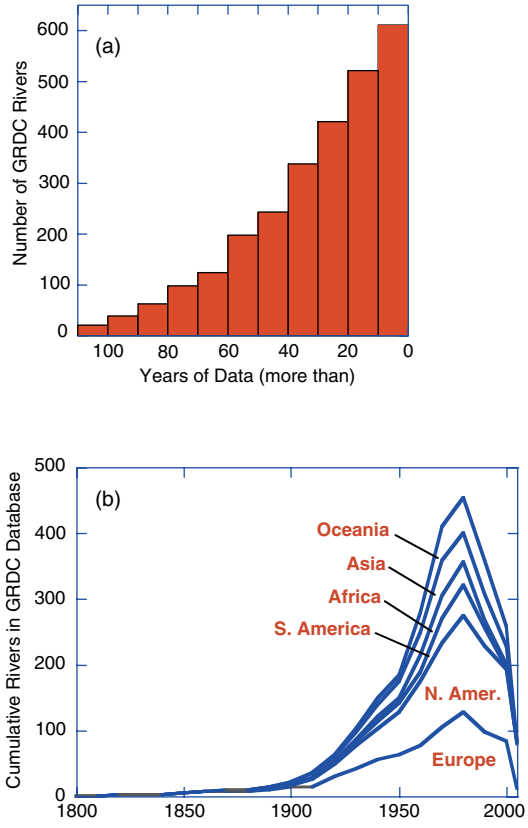

Figure 1.4. (a) Number of years of data for the 611 rivers in the GRDC database that discharge directly into the global ocean. Relatively few rivers are represented by more than 50 years of data. (b) GRDC discharge data, 1800–2005. Much of the steep decline of between 1980 and 2000 reflects a decrease in the reporting of discharge data, particularly from Africa and South America, and in part reflects a decline in global river monitoring (Vörösmarty *et al.*, 2001). The decrease in post-2000 data is partly the result of the lag time needed for some countries to forward their data to GRDC.

(Brahmaputra, Mekong) are represented by fewer than 15 years of post-1950 data, the Ganges has no post-1973 data, the Amazon's data begin at 1968, and the Congo's (at Kinshasa), Orinoco's and Parana's GRDC data end in 1983, 1989, and 1994, respectively. In fact, of the 12 rivers, the 2008 GRDC database lists post-1995 discharge for only the Changjiang, Lena, Ob, Yenisei, and Mississippi. Viewed another way, of the world's 50 largest rivers in terms of discharge (accounting for ~55% of the total global discharge), 14 are either not listed (e.g. Salween, Meghna, Fly, San Juan) in the GRDC's meta-database or only upstream data are listed (e.g. Niger, Zambezi, Khatanga). For the 50-yr period between 1951 and 2000, more than half of the collective ~20 000 km^3/yr discharge in the GRDC rivers is represented by less than 30 years of data (Fig. 1.5). If one were to rely solely on GRDC data, meaningful trends over this 50-yr period would be difficult to detect.

Despite the GRDC's laudable effort to collate a global discharge database, the above paragraphs suggest that some of GRDC's accomplishments have fallen short of their goals. The problem lies not with GRDC but rather with those counties who either have not measured river discharge or have been reluctant to share their data with the global community. India, Indonesia, Iran, Iraq, Italy, and Ivory Coast, to mention only the "I" countries, apparently have ceased (or have severely limited) submitting river data to GRDC. This has only increased the data disparity between countries (Table 1.2). Compounding the problem, in recent years many gauging stations have been closed (Vörösmarty *et al.*, 2001). This problem is particularly acute for rivers draining the higher latitudes, where longer records are needed to help delineate short- and longer-term effects of global climate change (see Chapter 4).

We have made particular use of a database compiled by Meybeck and Ragu (1996), which, unfortunately, may prove difficult for some readers to obtain. The 545 rivers listed by Meybeck and Ragu are principally confined to those rivers

Table 1.2. *GRDC database (2008) for selected countries whose rivers discharge into the global ocean.*

Country	# River in our database	# Rivers with GRDC data	# Rivers with post-1997 GRDC data
USA	124	71	62
Canada	85	56	33
Australia	82	35	31
Japan	25	22	22
Russia	67	31	15
New Zealand	69	15	14
Mexico	62	25	18
India	43	14	0
Italy	45	4	1
Indonesia	88	2	0

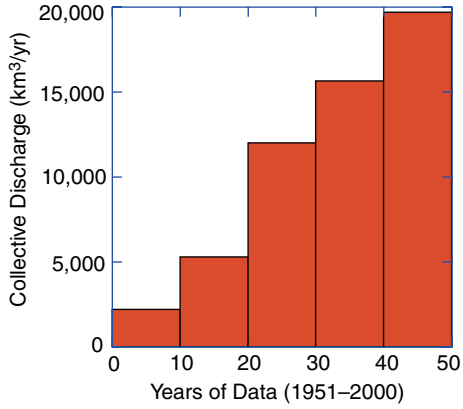

Figure 1.5. Length of record, 1951–2000, for the world's 50 largest rivers in terms of annual discharge; the collective 19 700 km^3/yr represent ~55% of the global total. Of this total, ~60% (12 000 km^3/yr) is represented by <30 years of GRDC-accessible data.

with drainage basins >10 000 km^2, annual water discharges > 10 km^3/yr, or annual suspended loads > 5 million tons (Mt)/yr. Some smaller rivers that drain polluted watersheds are also included. Of particular importance is Meybeck's and Ragu's documentation of reported concentrations, loads and yields of dissolved solids and nutrients discharged from many of these rivers.

Fierro and Nyer (2007) recently published their third edition of *The Water Encyclopedia*, which contains more than 1100 tables and 500 figures. For US rivers, Fierro and Nyer provide a reasonable access to primary data although, regrettably, many of the fluvial data are presented in English, not metric, units. While the subtitle of the book promises a guide to internet resources, as the authors state in their Preface, the internet historically has been unable to provide adequate data. The internet landscape, however, is rapidly changing and improving. Some countries, USA, Australia, Taiwan, and China, to mention a few, have initiated accessible internet web pages. The extensive US Geological Survey (USGS) dataset (www.nwis/usgs.gov) allows one to access discharge, sedimentological, and geochemical data, all of which were extremely useful in the preparation of this book. In early 2008, GWSP produced an on-line water atlas (http://atlas.gwsp.org) that provides maps (and their databases) for a number of environmental and socio-economic aspects of the Global Water System. But for many global rivers one is forced to rely on available published literature or personal assistance from international colleagues.

In the 1990s, the International Hydrological Programme (IHP), under UNESCO, began FRIEND ("Flow Regimes from International Experimental and Network Data" – we wonder how long it took to create *that* acronym?), which has developed a number of regional working groups. The southern Asia group, under the leadership of K. Takeuchi, released several comprehensive reports on various rivers in the region (Takeuchi *et al*., 1995; Jayawardena *et al*., 1997).

The United Nations Global Environment Monitoring System (GEMS) river database, distributed by the Canada Centre for Inland Waters in Burlington, Canada (http://www.cciw.ca/gems/intro.html), has centered its attention on major fluvial watersheds as a measure of regional and global water quality. Sixty-six countries have submitted data to GEMS; the total number of stations in the GEMS data archives exceeds 700. The GEMS menu offers a wide range of parameters including inorganic and organic constituents as well as pH and Biological Oxygen Demand (BOD). Meybeck *et al*. (1989) and Fraser *et al*. (1995) presented overviews of the GEMS program as well as listing data for 124 rivers. In recent years, however, the GEMS effort appears to have flagged. For instance, on-line data for the Rhone River ends in 1994, the Acheloos (Greece) in 1995, and the Guayas/Duale (Ecuador) in 1983, whereas Godavari (India) data begins in 1996. Moreover, the types of data submitted by each country vary, some countries submitting many measurements for each river, others only a few. Creating a regional or global time series based on GEMS data alone seems unlikely.

In recent years a number of working groups have attempted to collate available river discharge data. One of the more comprehensive collections is by the Woods Hole World Rivers Group (http://www.whoi.edu/page.do?pid=19735). As of the writing of this book, there were more than 1500 rivers in their on-line *Land2Sea* database, many of the rivers with watersheds smaller than 1000 km^2. The oft-cited FAO/AGL database (http://www.fao.org/landwater/aglw/sediment/default.asp), last updated in 2005, contains sediment yields for 872 rivers. These entries, however, include yields from upstream stations, tributaries of larger rivers (the Mekong River within Thailand, for instance, has 49 entries), and rivers draining inland

countries (Ethiopia and Lesotho, for example); sediment yields for rivers relative to our discussion probably number less than 100. On a much smaller scale, Eurosion (http://eurosion.org/database/index.html/) has collated water and sediment discharges for a number of larger European rivers. Similar types of projects have increased in recent years.

Dams, a topic discussed in Chapter 4, have been documented intensively by the International Commission on Large Dams (ICOLD), as witnessed by their comprehensive register published in 1988. Since then, however, ICOLD's data have been restricted to ICOLD members. The World Commission on Dams (WCD; http://www.dams.org) was formed in 1998 to review and assess the design, construction and decommissioning of dams, often, it seems, at odds with ICOLD. Their first definitive report, mentioned further in Chapter 4, was issued in 2000.

Problems with existing data

Given the wide variety of sources for the data listed in our tables and discussed in the following chapters, one must acknowledge the many potential problems and pitfalls that can – and often do – affect the veracity of the data: bad measurements, unreliable rating curves, inadequate monitoring, watershed modification, erroneous transcription of the data, etc. Of the 77 rivers in our database that have reported or assumed pre-dam sediment loads greater than 20 Mt/yr, only 19 are considered to have adequate up-to-date data (Table 1.3), 11 of which are in China and Taiwan. The calculated annual sediment load for the Changjiang at the Datong gauging station, for example, is based on 30–60 daily to bi-weekly (depending on river stage) surface, subsurface and near-bottom suspended sediment samples taken at 10 to 12 cross-river stations, altogether thousands of samples annually.

The reported or assumed sediment loads of 41 rivers in (Table 1.3), by contrast, are based either on uncertain or out-of-date data (23 rivers) or are rivers for which we can find no reported measurements (18 rivers) (Table 1.3). The reported sediment load for the Susitna River (Alaska), for instance, is derived from measurements taken in the 1950s; because of ensuing human changes to the landscape (e.g. logging, mining) as well as climate change over the past 50 years, we judge these data to be marginal in terms of representing the present-day Susitna. Sadly, the Mississippi may be the only sediment-rich US river that is adequately monitored (by the US Army Corps of Engineers).

To compound the problem further, many of the rivers in our database have been dammed or irrigated such that reported water and sediment discharge may over-estimate (sometimes greatly) the actual present-day discharges to the coastal ocean. Some examples of erroneous sediment data are given in Table 1.4; other examples are discussed in greater detail in subsequent chapters.

Uneven geographic distribution

Although our river database attempts to represent a uniform geographical distribution of river data, the global distribution of the data unfortunately remains uneven. At first glance at Table 1.5, the distribution in our database looks reasonably well balanced – 199 rivers for Africa, 244 for Europe, etc. But on closer inspection we see that there are only 22 African rivers for which we have found dissolved-solid data, compared with 65 European rivers. Moreover, we can find no reported data for more than 20% of the African, Central American/Caribbean, Eurasian, and Oceania rivers listed in our appendices. Of the 70+ rivers draining western South America, for instance, only four have reported sediment data and we can find no dissolved-solid data. Any estimates of suspended or dissolved deliveries from western South America are therefore clearly precarious. Likewise, there are few sediment or dissolved data for the rivers draining southern Africa or Australia, and essentially none for Central America or Caribbean rivers (see Fig. 1.1). The lack of monitored data for Philippine and (particularly) Indonesian rivers is particularly frustrating, since the few available data suggest that collectively these numerous small rivers represent major sources for both suspended-sediment and dissolved-solid discharges to the global ocean (see Chapter 2).

Uneven data quality

In our tables and in the ensuing discussion we have compiled data reported by many scientists and engineers who used a variety of measuring techniques over different periods of time. Suspended-sediment samples, for instance, may have been collected from a bucket lowered into the side of a river, by depth-integrating samplers lowered from a bridge, or water samples taken from a moving boat. Some reported data may represent a single measurement, others long-term averages.

The problem of data reliability becomes clearer if we compare reported basin areas, the one fluvial parameter that should be relatively easy to quantify and easy to replicate. Of eight published estimates of the areas of the world's 10 largest rivers listed in Table 1.6, only four rivers (the Congo, Mississippi, Yenisei, and Lena) have listed areas that are reasonably consistent. The Niger's reported basin area, in contrast, ranges from 1.2 to 2.2 $\times$ 10^6 km^2, and the Nile's from 1.8 to 3.8 $\times$ 10^6 km^2. Some of these discrepancies can be explained by the different methods used to estimate basin area. Using digital elevation models with a 30′ resolution, for example, Vörösmarty *et al.* (2000) equated potential flow pathways as a measure of basin area. Their estimate of the Nile basin area (3 800 000 km^2) is 30% higher than other published estimates, but it does include dry drainage basins that may well have discharged into the Nile in the recent geological past (Chapter 3). The problem with using digital elevation databases can be seen in comparing some

Table 1.3. *Subjective appraisal of the quality of suspended sediment data for rivers whose estimated pre-dam sediment loads are reported to or assumed to have exceeded 20 Mt/yr. Data quality is based on the rigor with which measurements were made, length of record, and date of last reported measurements. The Copper River's (Alaska) load, for example, is based on measurements taken in the 1950s, hence it is considered to be out of date. Until recently, the Irrawaddy's sediment discharge and sediment load were based on measurements taken in the nineteenth century (Gordon, 1885), re-evaluated in 2007 by Robinson* et al.*, and judged to be questionable in quality and present-day relevance. Publication of recent discharge data (Furuichi* et al.*, 2009), however, changed our appraisal of the Irrawaddy's database from "poor" to "fair".*

Good		Fair		Poor	
		ALB	Semani	AUS	Ord
CAN	Fraser	ALB	Vijose	BAN	Ganges
CHI	Daling	ARG	Parana	BRA	Amazon
CHI	Hanjiang	BUR	Irrawaddy	BRA	Tocantins
CHI	Huanghe	CAN	MacKenzie	BUR	Kaladen
CHI	Liaohe	CAN	Skeena	BUR	Salween
CHI	Luanhe	COL	Magdalena	CGO	Congo
CHI	Pearl	IDA	Godavari	COL	Patia
CHI	Yangtze	IDA	Krishna	EC	Guayas
FRA	Rhone	JAP	Tenryu	EGT	Nile
MEX	Colorado	NZ	Waiapu	IDA	Damodar
MOR	Sebou	PNG	Fly	IDA	Mahandi
PAK	Indus	PNG	Purari	IDA	Narmada
ROM	Danube	RUS	Amur	INO	Barito
RUS	Lena	SA	Orange	INO	Barum
TW	Beinan	TH	Chao Phrya	INO	Brantas
TW	Choshui	VN	Song Hong	INO	Cimanuk
TW	Hualien			INO	Digul
TW	Kaoping			INO	Hari
USA	Mississippi			INO	Kajan
				INO	Kampar
				INO	Kapuas
				INO	Mahakam
				INO	Membarano
				INO	Musi
				INO	Pulau
				IRQ	Shatt Arab
				KEN	Tana
				MEX	Grijalva
				MOZ	Limpopo
				NIG	Niger
				PNG	Kikori
				PNG	Sepik
				SOM	Juba
				TAN	Rufiji
				USA	Alsek
				USA	Copper
				USA	Susitna
				USA	Yukon
				VEN	Orinoco
				VN	Mekong

Table 1.4. *Previous and current estimates of sediment loads transported by several of the rivers listed in our database. (1) Gibbs (1967); (2) Dunne* et al. *(1998); (3) Inman* et al. *(1998); (4) this book; (5) NEDECO (1973); (6) Restrepo and Kjerve (2000 a,b); (7) Qian and Dai (1980); (8) Wang* et al. *(2006); (9) Milliman and Meade (1983); (10) Wasson* et al. *(1996); (11) Xu* et al. *(2007).*

River	Previous estimate (Mt/yr)		Current estimate (Mt/yr)		Reason for "error"
Amazon	500	(1)	1200	(2)	Bad sampling
S. Clara (1968–85)	9.3	(3)	3	(4)	Bad rating curve
Magdalena	240	(5)	140	(6)	Inadequate data
Huanghe	1100	(7)	<100	(8)	Water consumption + drought
Murray	30	(9)	1	(10)	Error in transcription?
Changjiang	500	(9)	120	(11)	50 000 dams

Table 1.5. *Regional distribution of rivers that appear in the appendices from which many of the plots and much of the synthesis in Chapter 2 are based. Oceania (primarily Australia, New Zealand, and Indonesia) and Africa account for more than half the rivers (161) for which we can find no data. (NB. Central America includes the Caribbean islands.)*

Region	# Rivers	Discharge data	Sediment load data	Dissolved load data	No data
N. America	272	247	137	102	25
C. America	66	50	10	7	16
S. America	170	155	46	24	15
Europe	249	225	192	64	24
Africa	195	142	66	22	53
Eurasia	72	55	27	15	17
Asia	263	219	162	105	44
Oceania	244	136	91	26	108
Totals	1531	1229	731	365	302

Table 1.6. *Reported areas (× 10^3 km^2) of 10 largest river drainage basins as cited in the literature. GEMS data come from Fraser* et al. *(1995) and are also utilized by Meybeck and Ragu (1996). L & P = Ludwig and Probst (1998); Times = The* Times World Atlas *(1999); V* et al. *= Vörösmarty* et al. *(2000); Oki (1999), R & K = Renssen and Knoop (2000); D & T = Dai and Trenberth (2002).*

River	L & P	GEMS	Times	V *et al.*	Oki	R & K	D & T	This book
Amazon	5903	6112	7050	5854	6140	6400	6356	6300
Congo	3704	3690	3700	3699	3730	3820	3699	3800
Mississippi	3246	3270	3250	3203	3250	3240	3203	3300
Ob	3109	2550	2990	2570	3000	2750	2570	3000
Nile	1874	2960	3349	3826	2960	2830	3826	2900
Parana	2868	2600	3100	2661	2970	2760	2661	2800
Yenisei	2567	2550	2580	2582	2610	2600	2582	2600
Lena	2465	2440	2490	2418	2350	2460	2418	2500
Niger	1540	1240	1890	2240	2110	1640	2240	2200
Amur	1926	1920	1855	2903	1870	1880	2903	1900

of the basin areas calculated using the USGS Hydro1k; the Huanghe, for example, is listed as 990 000 km^2, compared with the generally accepted value of 780 000 km^2, the Orinoco as 950 000 km^2 vs. 1 100 000 km^2, and the Pyasina (Russia) as 64 000 km^2 vs. 180 000 km^2. Another source of discrepancy is that some reported basin areas are based on the area upstream of the seaward-most gauging station. For example the Niger's basin area reported by GEMS (Fraser

et al., 1995) apparently does not include the Benue River, which drains about 1 000 000 km^2. Other discrepancies may result from typographical errors that subsequently have been passed on in the published record (see below).

If it is so difficult to achieve consistency for a relatively straight-forward parameter such as basin area, what hope do we have in finding accuracy and consistency for more difficult parameters such as suspended and dissolved concentrations and transport? This quandary is discussed at greater length in Chapter 2.

Analytical and reporting errors

Poor analytical techniques can lead to errors that are perpetuated in the literature. The oft-cited nutrient fluxes from Russian Arctic rivers (Gordeev *et al.*, 1996), for instance, appear extremely high for pristine rivers. Reported NH_4–N values, for example, may be 2–3 orders of magnitude inflated due to inaccurate analyses (Holmes *et al.*, 2000; 2001).

Unfortunately, it is often difficult to vouch for the accuracy of many of the reported data, which in some cases may simply represent errors in data transcription. Once reported, these transcription errors may be recycled in other papers, thus perpetuating the error. A transcription error may explain the 2 900 000 km^2 basin area for the Amur River (generally agreed-upon area is 1 900 000 km^2) reported by Vörösmarty *et al.* (2000) and then cited by Dai and Trenberth (2002). Milliman and Meade (1983) listed the annual sediment load of the Murray–Darling River (in southern Australia) as 30 Mt/yr, whereas the proper number is probably 1 Mt/yr (Wasson *et al.*, 1996) (Table 1.4). Owing to a typographical error, Milliman and Syvitski (1992) listed the sediment load of the Mackenzie River as 42 Mt/yr rather than 142 Mt/yr, an error noted by Macdonald *et al.* (1998), but which continued to be cited in subsequent papers (e.g. Holmes *et al.*, 2002).

Duration of measurements and temporal change

Given the temporal fluctuations in river discharge, how long a record is needed to provide a reasonable estimate of mean discharge? Can we assume, for example, that annual sediment load for the Rio Terraba (Costa Rica; basin area 4800 km^2) is 1.9 Mt/yr (Krishnaswamy *et al.*, 2001) when this number is based on a single year (an El Niño year, at that) of gauging? Ironically, although annual and interannual variability are inversely related to basin size (see Chapter 3), large rivers generally are more thoroughly monitored. Capturing the impact of a storm or flood is therefore more likely to be missed on a small river than on a large one (Walling and Webb, 1988; Walling *et al.*, 1992). How, for example, does one factor in a three-day 1969 flood of the Santa Clara River (which luckily was monitored; see Chapter 3), one that discharged more sediment than the previous 20 years combined (Inman and Jenkins, 1999; Warrick and Milliman, 2003) (Fig. 1.6)? The timing of the sampling also can be important. Holmes *et al.* (2002), for example, suggest that the differences in reported sediment loads for rivers draining the Russian Arctic (e.g. 12–26 Mt/yr for the Lena, 4.7–16 Mt/yr for the Kolyma) may largely reflect different monitoring schedules.

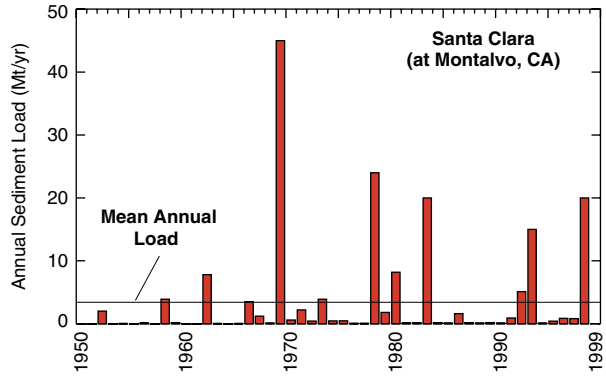

Figure 1.6. Annual sediment discharge from the Santa Clara River, as measured at the Montalvo gauging station, southern California. Note that the calculated mean load (3 Mt/yr) stems largely from flood-derived discharges in 1969, 78, 83, 93 and 98. Ignoring these one- to three-day events, collectively representing only about 20 days in a total of 50 years, the mean sediment load of the Santa Clara would be only ~0.5 Mt/yr.

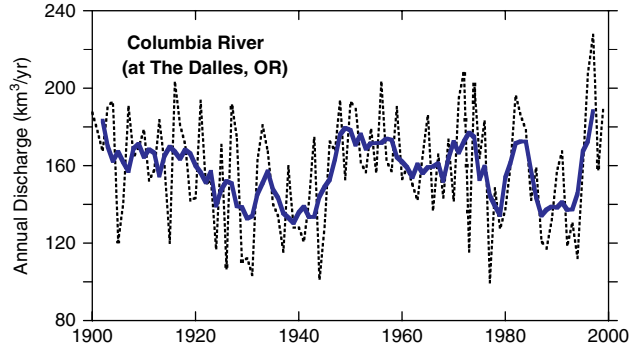

Figure 1.7. Annual discharge of the Columbia River (at The Dalles, Oregon), 1900–2000. The red dashed line shows annual discharge, the blue solid line shows the five-year running mean. Although long-term record shows no significant trend in annual discharge, interannually it deviated by more than 50% (100–227 km^3/yr) from the long-term mean of 158 km^3/yr.

The mean discharge of the Columbia River (670 000 km^2 basin area) in the Pacific Northwest is 5200 m^3/s, but during the 1930s and again in the late 1980s and early 1990s average annual discharge was ~4000 m^3/s, whereas in the 1950s it was ~6000 m^3/s (Fig. 1.7). Factoring in cyclic discharge, discussed further in Chapter 3, is particularly problematic in rivers that have been inadequately monitored.

Of even greater concern is the changing discharge of rivers whose flow has been affected by climate change and/or human impact. Over the past 60 years, for instance, discharges from the many large rivers (e.g. Indus, Yellow, Krishna, Don, Murray–Darling, etc.) have changed dramatically in response to both climatic variability and (more importantly) to increased water use and consumption. See Chapter 4 for a more thorough discussion of this problem.

Considering all these potential problems, it is no wonder that data for many rivers only can be considered approximations, which helps explain why we report values only to their second digit (see appendix).

A shrinking database

Increased demographic pressures and predicted climate change (see Chapter 4) require increased river monitoring – water discharge but also suspended sediments and dissolved solids. In fact, in recent years the exact opposite has occurred, particularly in such climatically important areas as the Arctic (Vörösmarty *et al*., 2001) and southern Asia. Despite our best efforts to compile a functional global database, discharges reported in this book may be based on measurements made 20–40 (or more) years ago (especially in India and much of Africa) or they may come from second- or third-hand sources (e.g. data reported for Indonesian rivers). In the years since suspended- or dissolved-solid sampling ended, the watershed may have been altered (e.g. deforestation, reforestation, mining, etc.), climate may have shifted, the river may have been diverted, or the gauging station relocated.

More importantly, many river gauging stations have been decommissioned. Vörösmarty *et al*. (2001) cited a 25% reduction in the number of Canadian gauging stations since 1990, and in recent years more than 100 long-term gauging stations have been closed annually in the United States alone (cf. Lanfear and Hirsch, 1999). The Santa Clara River gauging station at Montalvo, a station at which a number of major floods were monitored (see Fig. 3.50), for instance, was decommissioned in 2004. Of greater concern is the decommissioning of pan-Arctic gauging stations, where future climate change may first be noted. The number of pan-Arctic rivers presently monitored approximates the number occupied in the early 1960s, but is only about 60% the number monitored in the early 1980s; the most severely affected have been gauging stations that had been occupied for 15 years or less (Shiklomanov *et al*., 2002). Pilot Station on the Yukon River, one of the largest (830 000 km^2) relatively unspoiled rivers in North America, for instance, was deactivated in 1996, leaving the Stevens Village station (with an upstream drainage area ~60% that of Pilot Station) the most downstream station (Brabets *et al*., 2000). Pilot Station was reactivated in 2001, but the five-year data-gap remains.

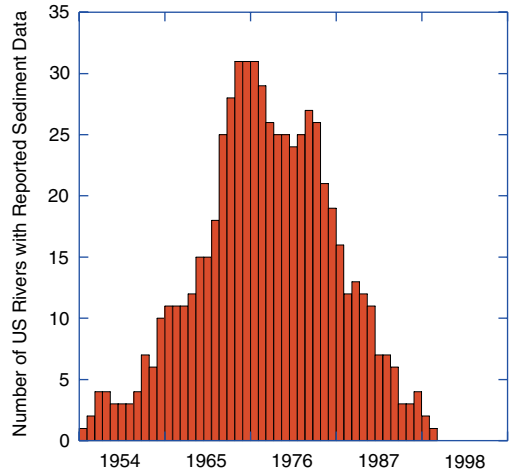

Figure 1.8. Daily suspended-sediment measurements taken in USA rivers discharging directly into the coastal ocean, as listed in the USGS NWIS (National Water Information System) database (http://co.water.usgs.gov/sediment/seddatabase.cfm). The number of rivers monitored daily for suspended sediments peaked in the late 1960s and began declining in the early 1980s. The last entries in the USGS NWIS database are for 1995. Suspended sediment is still being monitored in some rivers, but the data are not being included in the online database.

The problem of decreasing dissolved- and suspended-sediment monitoring is even more acute. The USGS web page (http://co.water.usgs.gov/sediment/) lists suspended-sediment data for 59 US rivers that appear in our database, most of which were measured between 1965 and 1980, peaking in the early 1970s (Fig. 1.8). By the mid 1990s the only rivers effectively monitored were those linked to the NAWQA (National Water Quality Assessment) program, and at present only the Missouri–Mississippi is thoroughly monitored, although by the US Corps of Army Engineers, not by USGS. To calculate sediment discharge for US rivers, one must therefore increasingly rely on sediment-rating curves based on data that are 30–40 years old that, considering landuse change, become less relevant with the passage of time. Now compare the poor USA database with those in Taiwan, which has probably the best monitored rivers in the world. A sufficient number of suspended sediment samples are taken from most Taiwan rivers each year, for instance, to create annual stratified rating curves (Kao *et al*., 2005; Kao and Milliman, 2008).

The reason for the shrinking global database is not difficult to understand: establishing a sediment-sampling station is expensive, and its long-term maintenance is sufficiently costly that, given a choice, many governments would rather use those moneys to address other priorities. Unfortunately the declining database increasingly limits our ability to quantify and predict the discharge of fluvial

water and its constituents to the ocean, particularly in response to present and future changes in landuse and climate (see Milly *et al*., 2008).

Some final cautions

We cannot emphasize too strongly that the values (particularly for suspended sediment) cited in tables throughout this book mostly represent measurements taken at a gauging station upstream from the river mouth. In some rivers, the station is located a considerable distance upstream to avoid any tidal influence. The Obidos gauging station, for example, 900 km upstream from the mouth of the Amazon River, represents *only* 4 600 000 km^2 of upstream basin area, compared with a total drainage basin area of 6 300 000 km^2. As much of the downstream area has an annual runoff greater than 1 m/yr (or more), more water is clearly discharged at the mouth than is reported at Obidos. Sediment discharge at the river mouth, however, may be less than that calculated at Obidos, depending on the amount of downstream floodplain deposition. The Eel River gauging station at Scotia in northern California (upstream basin area of 8640 km^2), in contrast, is located only 25 km from the head of the river's small estuary. The Eel's flood plain is small (<150 km^2) and the river discharge is event-driven (see Chapter 3), so that sediment discharge measured at Scotia probably approximates what actually escapes to the ocean (Sommerfield and Nittrouer, 1999).

Finally, one must always take into account the uniqueness of each river. A book about the Deschutes River, a tributary to the lower Columbia in western Oregon, edited and largely written by O'Connor and Grant (2003), is entitled *A Peculiar River.* While the Deschutes may be "peculiar," so are most other rivers. A change in one or two watershed parameters, even slightly, can alter the character of the river, sometimes dramatically. Creating algorithms from one or a group of rivers to predict present or future values for neighboring rivers – as we do here and many others have done before us – may be only slightly less masochistic than tilting at windmills. `

With these various caveats and cautions in mind, we trust that the reader will bear with us through the ensuing chapters.

2 Runoff, erosion, and delivery to the coastal ocean

Ev'ry valley shall be exalted,
And ev'ry mountain and hill made low
G. F. Handel (after Book of Isaiah 40:4)

Introduction

Much of the scientific interest in rivers revolves around attempting to quantify the flux and fate of fluvial discharge and to understand the processes that dictate these fluxes. No matter the motivation, a comprehensive understanding of fluvial processes and fluxes requires a synthetic approach, one that covers a wide range of spatial and temporal scales – local to global, hours to millennia – over which these processes occur and vary. In this chapter we discuss fluvial runoff and erosion and the transfer of their products to the coastal zone. We attempt to delineate the environmental factors that control these fluxes by utilizing both published literature and the database that we have collated in the book's appendix and GIS-based materials on the accompanying website, www.cambridge.org/milliman. This exercise, however, must be viewed within the context of numerous previous efforts that collectively have laid the foundation for much of what is said here. To mention just a few previous studies that have dealt with suspended and dissolved solid transfer: Fournier (1949), Livingstone (1963), Holeman (1968), Lisitzin (1972), Baumgartner and Reichel (1975), Meybeck (1979, 1988, 1994), Milliman and Meade (1983), Walling and Webb (1983, 1996), Berner and Berner (1987), Meade *et al*. (1990), Milliman and Syvitski (1992), Summerfield and Hulton (1994), Stallard (1995a, b), Meade (1996), Edmond and Huh (1997), Ludwig and Probst (1998), Syvitski and Milliman (2007), and de Vente *et al*. (2007). The total number of relevant studies stretches well into the hundreds.

The following discussion primarily concerns long-term means of the weathering processes and transfer of water and solids, ignoring for the moment temporal variations (discussed in Chapter 3) and impact(s) of anthropogenic activities (Chapter 4).

The hydrologic cycle and water discharge

River discharge (Q), often reported as m^3/s or km^3/yr, primarily reflects the climate and size of the drainage basin. A plot of mean annual discharge from 1100 rivers in our database (Fig. 2.1) shows that basin area alone explains (statistically) 68% of the variance in Q. Big rivers as a rule tend to have greater discharge than smaller rivers, but for any given basin area, discharge can vary by two to three orders of magnitude. The Fortescue River in Australia, for instance discharges <0.2% that of the Rajang River in Malaysia (0.23 km^3/yr vs. 110 km^3/yr) even though the two rivers drain similar-size areas (49 000 vs. 51 000 km^2). Similarly, the Haast River (South Island, New Zealand) discharges as much water annually (6 km^3) as the Brazos River (Texas) although draining < 1% the watershed area (930 vs. 120 000 km^2). In both cases the critical variable defining discharge is climate; specifically, the drainage basin's hydrologic budget.

The hydrologic budget

Although runoff (R) and discharge (Q) are sometimes used interchangeably, the former is defined as discharge normalized by basin area: $R = Q/A$, which allows one to distinguish the roles of basin area (A) and climate in defining discharge. Referring to the previous paragraph, runoff from the Haast River exceeds 6000 mm/yr (6 km^3/yr/ 930 km^2) whereas Brazos runoff is 50 mm/yr (6 km^3/yr/ 120 000 km^2).

In meteorological terms, runoff is defined as the difference between water gain (via precipitation) and water loss:

$$R = P - \sum (ET + S + C)\cdot$$

That is, runoff (R) = precipitation (P) minus the sum of evapotranspiration (ET), water storage (S), and water consumption (C). Evapotranspiration is the water loss via physical evaporation and plant transpiration. Storage refers to the loss of water to both surface (lake) and subsurface (groundwater) reservoirs. In a natural drainage basin unaffected by anthropogenic activities, long-term storage is assumed to be zero; short-term groundwater storage can vary but is difficult to quantify. Globally groundwater plays a secondary role in freshwater discharge to the ocean. Hydrologic models suggest that groundwater may represent only 5–6% of the total freshwater discharged directly to the global ocean (Zekster and Dzhamalov, 1988; Zekster and Loaiciga, 1993), but in terms of the seaward transfer of dissolved ions

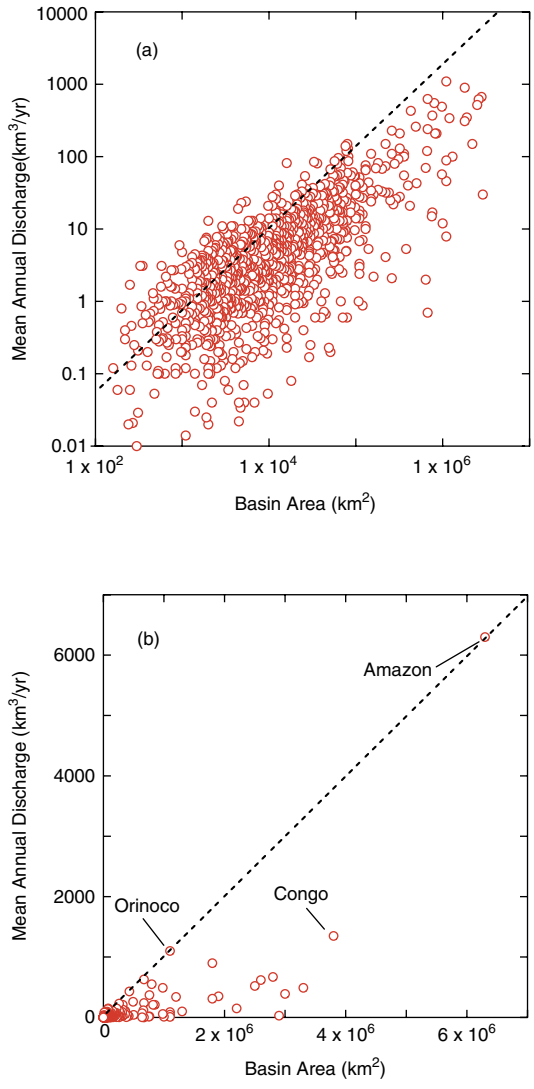

Figure 2.1. Mean annual discharge vs. basin area for more than 1100 rivers that discharge to the coastal ocean. Data come from the appendices at the back of the book. The log–log presentation (a) allows us to display data over many orders of magnitude, whereas the linear plot (b) relegates most rivers to the blob of circles in the lower left corner. But the linear plot underscores the global prominence of the Amazon River in terms of both basin area and discharge, its ~6400 km^3/yr exceeding the combined discharge of the next seven largest rivers. Diagonal dashed lines indicate 1000 mm/yr runoff.

and nutrients to the coastal ocean, groundwater plays an important regional and global role (Moore, 1996; Church, 1996). Dzhamalov and Safronova (2002) estimate 1 billion tons (Bt) of dissolved solids are discharged globally each year via groundwater, about 25% that of fluvially discharged dissolved solids (see below).

Water consumption is the loss of water by human use (e.g. evapotranspiration from irrigated cropland). It differs from "water withdrawal," which is the total amount of water withdrawn from the watershed, some of which may return to the system (e.g. via sewage outfall). Although consumption can be considerable in heavily regulated watersheds (Milliman *et al*., 2008), in natural systems it generally represents a minor loss.

Precipitation

Precipitation occurs when water-laden air is cooled. This can occur along a front separating warm from cold air masses or through the upward convection of warm, humid air into the cooler atmosphere, resulting in localized thunderstorms. Not surprisingly, global and regional precipitation patterns reflect latitudinal circulation cells that transport momentum and energy from low to high latitudes, but also longitudinal wind patterns. The highest rates of global precipitation occur around the climatic equator, ~10N (Figs. 2.2 and 2.3), and on the windward sides of continents. Orographically controlled precipitation occurs when warm moist air cools as it rises over mountains, thus releasing water. The most commonly cited example of orographic control is the cooling of moisture-laden air as it rises over the Himalayas during the SW monsoon season, but similar processes are noted in other regions bordering high mountains, such as the California Sierra Nevada and the Colorado Rockies (Fig. 2.4). Viviroli *et al*. (2007, and references therein) state that mountains, which they term "water towers," are particularly important in arid climates, as they can produce ~five-fold greater runoff than the surrounding lowlands.

Oceanic circulation also can play a key role in regional precipitation. As warm air associated with the Gulf Stream and Kuroshio currents reaches higher latitudes, for instance, both precipitation and latent heat are released, one result being the warming of subpolar coastal Norway and Alaska. The combined effects of orography and oceanography help explain the longitudinal asymmetry in runoff between the eastern and western Americas (see Fig. 2.5).

Atmospheric circulation – and its domination by latitudinal cells – means that tropical areas tend to have high rainfall, subtropical mid-latitudes (~30N and S) low rainfall, and subpolar regions (latitudes ~60°) slightly higher precipitation (Fig. 2.3). Superimposed upon this picture is a longitudinal variation in atmospheric circulation (E to W at tropical and subpolar latitudes; W to E in mid-latitudes). In addition, topographic/orographic controls of rainfall and the oceanographic influence of warm oceanic waters transported to higher latitudes on the eastern sides of ocean basins (via the Gulf Stream and Kuroshio) help dictate both regional and global precipitation and evaporation (Figs. 2.2, 2.4a–2.6).

Combining the effects of these factors, precipitation varies globally from <10 mm/yr to >5000 mm/yr. Basin-wide

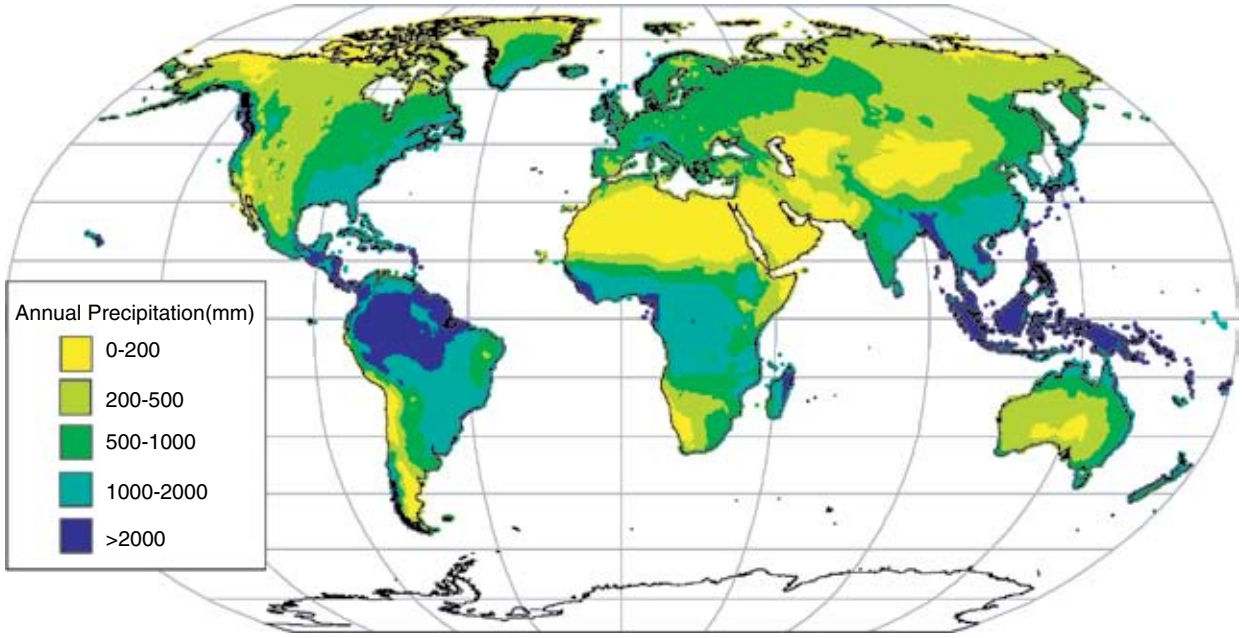

Figure 2.2. Global distribution of annual precipitation, 1901–2000, based on 0.5-degree grid data from the Climate Research Unit (CRU), East Anglia University.

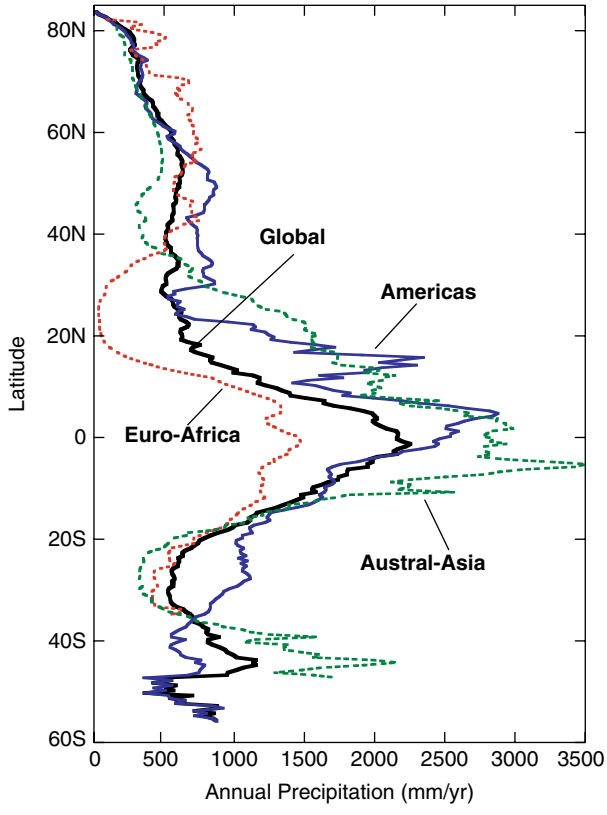

Figure 2.3. Latitudinal distribution of global precipitation (bold black line) and in the Americas (blue line), Euro-Africa (red dashed line), and Austral-Asia (green dashed line). Note the significantly lower Euro-African precipitation between ~20N and 25S. Data from CRU, East Anglia University.

precipitation in some of the New Guinean mountains can approach or exceed 10 000 mm/yr, whereas mean annual precipitation in some arid regions is nil except for rare storms (see Chapter 3).

Evapotranspiration

Unlike precipitation, which is easily measured by a rain gauge (although the gauge's trapping ability can depend on wind speed as well as the form of the precipitation – e.g. rain or snow; Bogdanova *et al*., 2002), evapotranspiration (commonly termed *ET*) is difficult to quantify. *ET* represents the integration of two interrelated processes: (1) physical evaporation, which is a function of air temperature, humidity, and wind velocity, can be measured by pan evaporation; (2) plant transpiration also depends on the ecosystem and the plants within that ecosystem (e.g. grassland vs. climax forest; deciduous vs. conifer), thus making it difficult to measure. Because of the difficulty in quantifying evapotranspiration, *ET* is often reported as potential evapotranspiration – *PET* (Fig. 2.6) – the adjective "potential" indicating how much would be evaporated given sufficient precipitation.

Evapotranspiration tends to decrease with increasing latitude (Figs. 2.6 and 2.7) in response to decreasing temperature and changing vegetation (e.g. deciduous vs. evergreen trees). The pronounced latitudinal fluctuation in fluvial runoff (Fig. 2.5) thus reflects both variations in precipitation (Figs. 2.2 and 2.3) and evapotranspiration (Figs. 2.6 and 2.7). According to Budyko (1974), *ET* in humid regions is controlled primarily by *PET*, whereas in more arid regions *ET* is

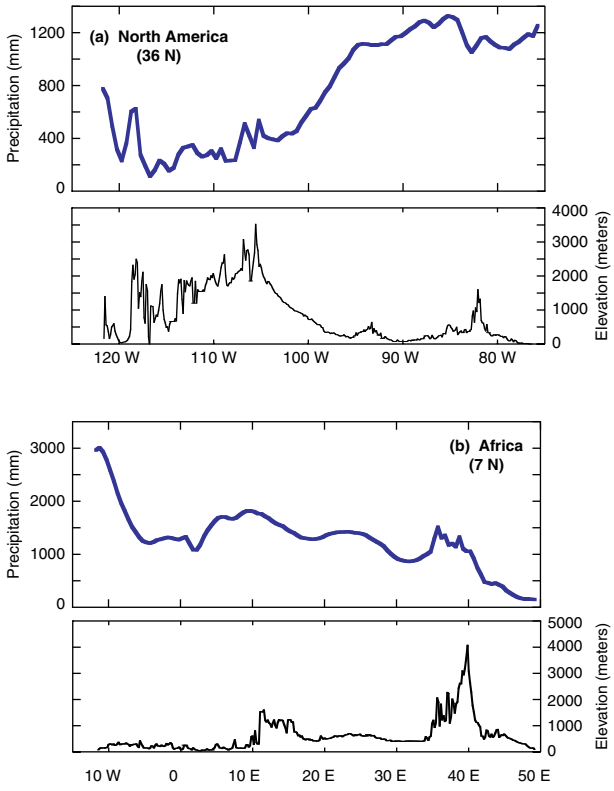

Figure 2.4. Longitudinal variation in precipitation across USA (at latitude 36N) (a) and equatorial Africa (latitude 7N) (b), illustrating the influences of orography (as shown by topography) and longitudinal atmospheric circulation on precipitation. The orographic control is particularly obvious in the western USA, where the windward (western) sides of the Sierra Nevada and Rocky Mountains receive greater precipitation than the leeward (eastern) sides. Precipitation data from CRU, University of East Anglia.

controlled more by the level of precipitation. In the Sahara Desert, for example, *PET* exceeds 2000–2500 mm/yr, whereas *P* averages only 200 mm/yr. The fact that the few scattered Saharan rivers exhibit any runoff – at least in some years – reflects the fact that precipitation often falls during short, intense storms, allowing short-term *P* to exceed *ET* (see Chapter 3).

River runoff

Unlike many climate classifications that are based on annual precipitation (e.g. Köpper–Geiger, 1954; Meigs, 1953), we categorize rivers on the basis of their annual fluvial runoff (see appendix). We recognize four classes of rivers: arid (runoff <100 mm/yr), semi-arid (100–250 mm/yr), humid (250–750 mm/yr) and wet or high-runoff rivers (>750 mm/yr). This classification differs from that used by Meybeck (2003; Meybeck and Vörösmarty, 2005): arheic (runoff <3 mm/yr), digoheric (< 30 mm/yr), mesorheic (30–300 mm/yr), hyperheic (runoff >300 mm/yr). Thus, although discharge for the Amazon (basin area of 6 300 000 km^2) is three orders of magnitude higher than that of the Choshui (basin area of 3100 km^2) – (6300 km^3/yr vs. 6.1 km^3/yr) – both rivers are classified as wet (R = 1000 mm/yr and 1900 mm/yr, respectively). The Congo (R = 1300 km^3/yr per 3 800 000 km^2 = 355 mm/yr) is a humid river, whereas the adjacent Niger (R = 190 km^3/yr per 2 200 000 km^2 = 86 mm/yr) is an arid river.

Greatest runoff is noted in small rivers that drain wet, mountainous terrain (orographic effects facilitating high precipitation); seven of the ten greatest runoff rivers listed in Table 2.1 have basin areas <2000 km^2. All low-runoff rivers listed in Table 2.1, in contrast, drain arid or subarid climates. Even though the southern hemisphere accounts for a relatively small portion of the global landmass, more than half of the low-runoff rivers listed in Table 2.1 are located south of ~10S, supporting the suggestion that southern hemisphere arid rivers have a different runoff character than northern hemisphere rivers (Finlayson and McMahon, 1988; McMahon *et al*., 1992). Peel *et al*. (2001) have hypothesized that this difference, particularly apparent in temperate arid rivers, may reflect the dominance of evergreen trees in southern hemisphere watersheds, which leads to greater evapotranspiration (relative to northern hemisphere deciduous-dominated watersheds), particularly during winter months.

In considering global runoff, we are impressed by the dominance of arid drainage basins – much of the Arctic, most of Africa (coastal west Africa and some Madagascar watersheds being the only areas where R >750 mm/yr), essentially all of Australia, the Middle East, and parts of western North and South America (Fig. 2.8). High-runoff watersheds are located predominantly in northern South America and southwestern Asia/Oceania; rivers draining SW South America, NW North America, Labrador, Iceland, and Norway also tend to have high runoff.

Because most large rivers (>500 000 km^2 in area) drain arid or semi-arid continental interiors (see Fig. 1.2) – with the notable exceptions of the Amazon, Orinoco and Brahmaputra rivers – many large rivers are classified as arid or subarid. Collectively these large arid to semi-arid rivers drain nearly twice as much global area as large humid and wet rivers (Table 2.2). Even though rainfall near the mouth of the Niger River exceeds 1000 mm/yr, for example, most of the river's watershed lies in arid east Africa; mean annual runoff for the entire Niger watershed is only 86 mm/yr. Similarly, much of the Mississippi drainage basin lies within the arid and semi-arid Missouri and Arkansas watersheds (see Chapter 4); its annual runoff (150 mm/yr) classifies it as a semi-arid river even though the tributary Tennessee and Ohio rivers have runoffs exceeding 500 mm/yr.

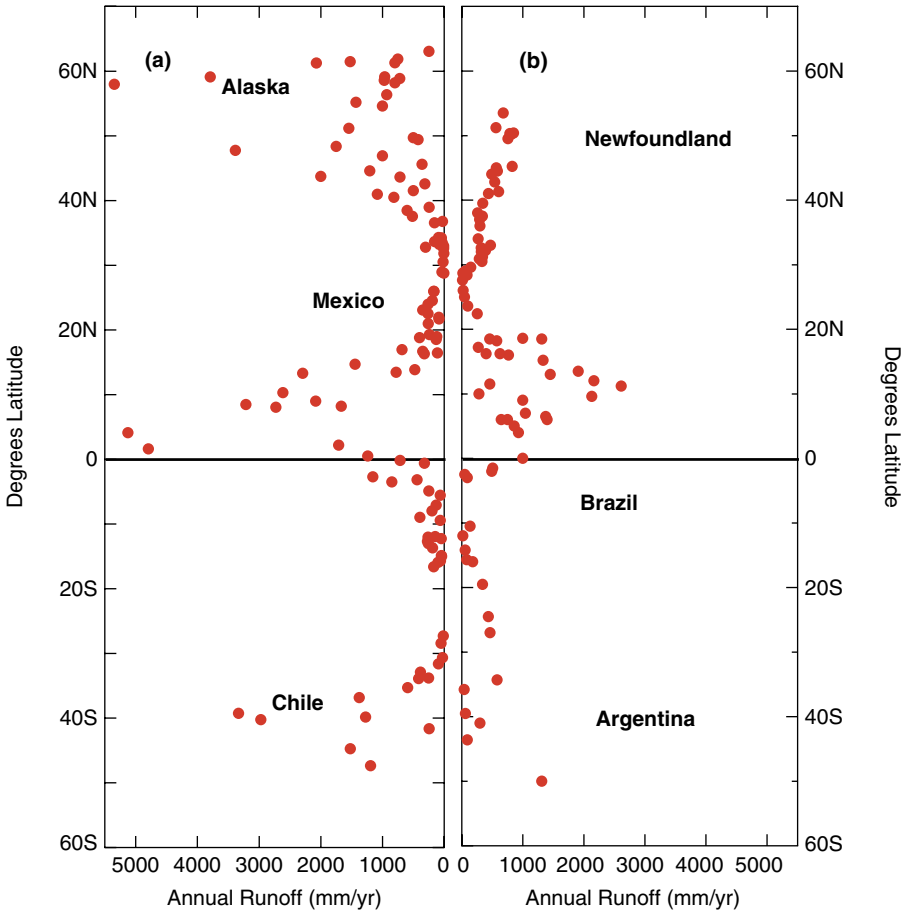

Figure 2.5. Latitudinal variation in hydrologic runoff from western (a) and eastern (b) North, Central and South America (NCSA), reflect the control that latitudinal circulation cells have on precipitation. Topography, oceanography, and evapotranspiration help explain local and regional variations in these patterns. Note that eastern NCSA runoff peaks (~2700 mm/yr) at ~10N, while along western NCSA it peaks at ~5N (reaching >5000 mm/yr). Mid-latitude runoff on both sides of NCSA is <100 mm/yr, but increases at higher latitudes. High Alaskan runoff is explained by both oceanic circulation and orographically controlled precipitation.

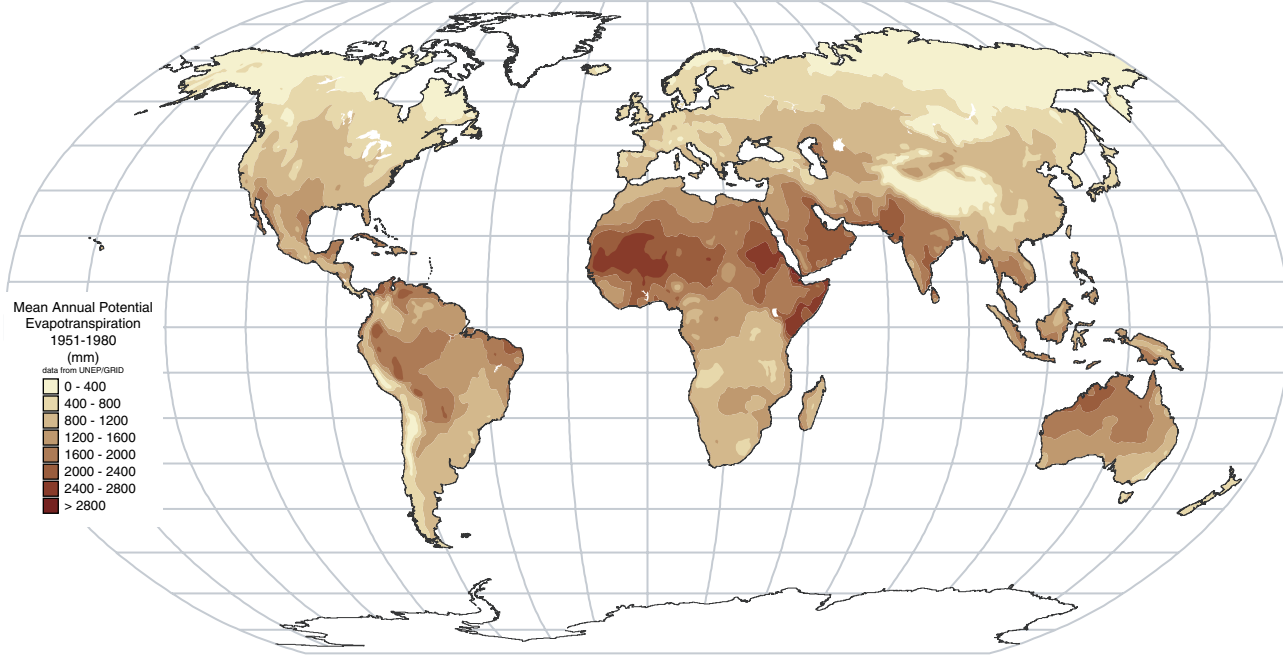

Figure 2.6. Global distribution of potential evapotranspiration (PET). Note the dependence of PET on air temperature and humidity (see Fig. 2.2).

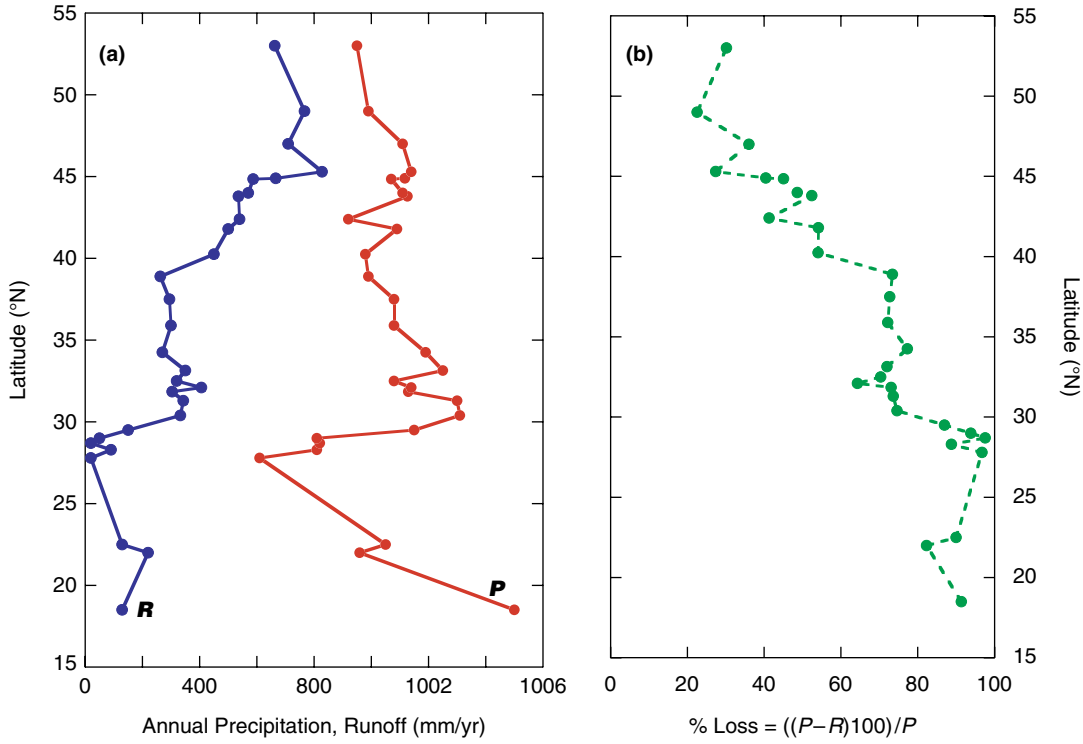

Figure 2.7. (a) Latitudinal variation in river runoff (*R*) and basin-wide precipitation (*P*), and (b) % water loss [(*P*–*R*)*(100)]/*P* in eastern Central and North American river basins. Assuming minimal storage and consumption, water loss essentially reflects evapotranspiration (*ET*).

The 12 rivers that individually discharge more than 400 km^3 annually (Table 2.3) occupy about 25% of the total land area emptying into the global ocean and collectively account for more than 35% of the total fluvial water annually discharged to the global ocean. Other than the Amazon and Orinoco, most high-discharge rivers are characterized by either high runoff offsetting relatively small drainage basins (e.g., Irrawaddy) or by large drainage basins that offset low runoff (e.g., Yenisei, Lena).

Freshwater discharge to the global ocean

We calculate that rivers discharge ~36 000 km^3 of water to the global coastal ocean (Fig. 2.9); the mean global runoff is ~350–360 mm/yr. This discharge estimate is similar to those made by Nace (1967), Baumgartner and Reichel (1975: ~37 700 km^3/yr discounting Antarctic and Greenland ice-melt runoff, the latter alone accounting for >250 km^3/yr; Hanna *et al*., 2009; Mernild *et al*., 2008), Berner and Berner (1987: 36 000 km^3/yr), Milliman (1990: 35 000 km^3/yr), Dai and Trenberth (2002: 37 000 km^3/yr), and Fekete *et al*. (2002: 37 500 km^3/yr). Our estimate is somewhat lower than the 38 500–41 000 km^3/yr calculated by Fekete *et al*. (1999), Oki (2006), GRDC (www.grdc.bafg.de), Shiklomaov (in Gleick, 1993) and Peucker-Ehrenbrink (2009), and substantially lower than the 43 000–47 000 km^3 discharge reported by Korzoun *et al*. (1977), L'Vovich (1974) and Shiklomanov and Rodda (2003) (see also summary in Oki, 1999). The differences in calculated global discharge are best explained by differences in the databases and differences in the methods used to extrapolate the runoff from 40% of the world's surface for which discharge data are lacking. Estimates in cumulative global discharge are likely to contain errors equivalent to at least one Congo – i.e. 1000–1500 km^3/yr (R. H. Meade, personal communication).

Given the latitudinal distribution of global precipitation (Figs. 2.2, 2.3, and 2.7), it is not surprising that rivers draining northern South America and southern Asia/Oceania account for about half of the total freshwater (~19 000 km^2/yr) discharged to the global ocean (Figs. 2.9 and 2.10a). By virtue of its extensive drainage basin and high runoff, the Amazon's discharge (6300 km^3/yr) exceeds the combined discharge of the next eight largest rivers (Table 2.3). Arctic rivers, by contrast, collectively drain about 20% of global watershed but account for "only" about 4800 km^3/yr; their mean annual runoff is less than 200 mm/yr. Of the 11 regions shown in Fig. 2.9, only NE South America and parts of western South America (see Fig. 2.10a) can be regarded as being high-runoff (mean runoff 860 mm/yr). Three other regions (western South and North Americas, southern Asia/Oceania) have runoffs greater than the global average (360 mm/yr), whereas most of Australia and Africa are semi-arid to arid (Fig. 2.10b). Rivers draining

Table 2.1. *Greatest and smallest runoffs (in bold) of rivers within our global river database; global mean is 360 mm/yr. Most high-runoff rivers (>4000 mm/yr) drain tropical or temperate mountains (see Fig. 2.5), and with exception of the San Juan River all have small watersheds. In contrast, rivers with runoffs <5 mm/yr drain a variety of elevations, but many in the southern hemisphere. Climate is represented by three groups of letters: first group refers to mean basin temperature: Tropical (Tr), Subtropical (STr), and Temperate (Te); the second group refers to mean annual runoff: Arid (<100 mm/yr: A) and Wet (>750 mm/yr: W); and the third group refers to season of maximum discharge: Summer (S), Autumn (Au) and Winter (W), Continuous (C), and Desert (D).*

River	Country	Basin area ($\times 10^3$ km^2)	Climate	Discharge (km^3/yr)	Runoff (mm/yr)
Hokitika	New Zealand	0.35	Te-W-C	3.1	**8900**
Esk	New Zealand	0.25	STr-W-W	1.7	**6800**
Naya	Colombia	2	Tr-W-W	13	**6500**
Haast	New Zealand	0.93	Te-W-C	6	**6450**
Speel	USA (Alaska)	0.58	Te-W-S	3.1	**5300**
San Juan	Colombia	16	Tr-W-C	82	**5100**
Taramakau	New Zealand	1	Te-W-C	4.8	**4800**
Baudo	Colombia	5.4	Tr-W-Au	24	**4400**
Micay	Colombia	4.4	Tr-W-C	19	**4300**
Global					**360**
Besor	Israel	3.7	STr-A-W	0.01	**3**
Casamance	Senegal	37	Tr-A-S	0.1	**3**
Loa	Chile	33	STr-A-W	0.1	**3**
Holgat	South Africa	1.6	STr-A-D	0.003	**2**
Murchison	Australia	82	STr-A-S	0.2	**2**
Spoeg	South Africa	1.6	STr-A-D	0.003	**2**
Dasht	Pakistan	36	STr-A-S	0.04	**1**
Omaruru	Namibia	14	STr-A-D	0.02	**1**
Swartlinjies	South Africa	1.7	STr-A-D	0.002	**1**
Hoanib	Namibia	18	STr-A-D	0.01	**0.5**
Ugab	Namibia	33	STr-A-D	0.01	**0.3**

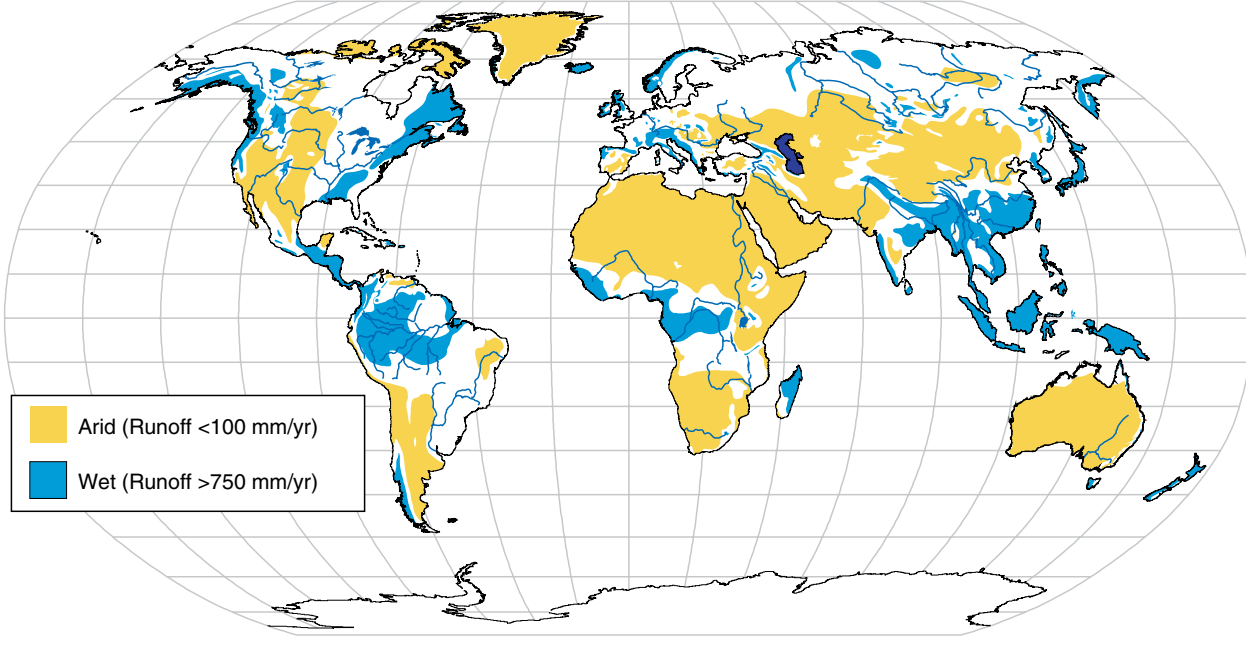

Figure 2.8. Global distribution of arid (R <100 mm/yr) and wet (R >750 mm/yr) watersheds; after Baumgartner and Riechel (1975).

Table 2.2. *Hydrologic classification, based on fluvial runoff (discharge/basin area), of world rivers with watershed areas >500 000 km². Numbers in parentheses refer to the watershed area in millions of km². The cumulative basin area of 52 900 000 km² represents slightly more than half of the total land area draining into the global ocean. See Fig. 1.2 for location of these rivers.*

Arid (<100 mm/yr)	Semi-arid (100–250 mm/yr)
Colorado (Mexico) (0.64)	Amur (1.9)
Huanghe (0.75)	Dnepier (0.58)
Indus (0.98)	Kolyma (0.66)
Murray–Darling (1.1)	Lena (2.5)
Nelson (1.1)	MacKenzie (1.8)
Nile (2.9)	Mississippi (3.3)
Niger (2.2)	Ob (3.0)
Orange (1.0)	Parana (2.8)
Rio Grande (0.67)	Sao Francisco (0.63)
Shebelle–Juba (0.8)	Yenesi (2.6)
Zambesi (1.4)	Yukon (0.85)
Total land area: 13.6×10^6 km²	**Total land area: 21.7×10^6 km²**
Humid (250–750 mm/yr)	Wet (>750 mm/yr)
Changjiang (1.8)	Amazon (6.3)
Columbia (0.67)	Brahmaputra (0.67)
Congo (3.8)	Orinoco (1.1)
Danube (0.82)	**Total land area: 8.1×10^6 km²**
Ganges (0.98)	
Mekong (0.8)	
St. Lawrence (1.2)	
Tocantins (0.76)	
Total land area: 10.8×10^6 km²	

Africa, in fact, discharge only 2700 km³/yr, a continent-wide runoff of 90 mm/yr (Figs. 2.9 and 2.10).

North and Central America

Runoff in North and Central American rivers ranges from <100 mm/yr in the SW USA and Mexico to >1000–2000 mm/yr in southern Central America (Fig. 2.11a). Because of large watersheds and locally high runoff (in coastal Alaska), rivers in the James Bay–Hudson Bay region of northern Canada and central and southeastern Alaska discharge 1300 km³/yr and 960 km³/yr, respectively. Rivers discharging into the Gulf of Mexico, Gulf of St. Lawrence, and the Arctic Ocean have low runoffs, but their large drainage basins allow them to discharge 990 km³/yr, 750 km³/yr, and 660 km³/yr, respectively. We have few data for Puerto Rico, Hispaniola, Cuba, Newfoundland, and Baffin and Victoria islands, but their collective size exceeds 1000 km², necessitating that we include them in our calculations even though, at best, they are rough estimates.

South America

The fluvial character of South America is dominated by two large river systems, the high-runoff Amazon in the north and the moderate-runoff Parana/Uruguay system in the south (Fig. 2.11b). Together with the Orinoco and coastal rivers, NE South America discharges 8200 km³ of freshwater to the coastal ocean; the Magdalena and coastal rivers draining northern Colombia and Venezuela discharge an additional 350 km³. Rivers draining eastern and southern Brazil, much of Argentina and southern Peru and northern Chile stand in stark contrast, with runoffs of <100 mm/yr. Perhaps most interesting are the rivers draining western Colombia and northern Ecuador, a number of which have runoffs exceeding 3000 mm/yr (e.g. San Juan River); collectively these NW rivers discharge an estimated 400 km³ of water to the equatorial eastern Pacific. Southern Chilean rivers discharge roughly an equal amount as the NW rivers, whereas rivers along the arid central western coast contribute essentially no fresh water to the global ocean.

Table 2.3. *Global rivers that discharge more than 400 km³ of water annually; annual discharge in bold. Collectively these drainage basins account for ~25% of the total land area draining into the global ocean, and they discharge ~35% of the freshwater reaching the ocean. Most rivers are high mountain (>3000 m maximum elevation), but climates vary widely; runoffs for the 12 rivers range from <200 mm/yr (Mississippi) to 1000 mm/yr (Amazon, Orinoco, Irrawaddy).*

River	Country	Basin area (× 10^3 km²)	Climate	Discharge (km³/yr)	Runoff (mm/yr)
Amazon	Brazil	6300	Tr-W-S	**6300**	1000
Congo	Congo, DR	3800	Tr-H-S	**1300**	340
Orinoco	Venezuela	1100	Tr-W-S	**1100**	1000
Changjiang	China	1800	Te-H-S	**900**	500
Bramaputra	Bangladesh	670	STr-W-S	**630**	940
Yenisei	Russia	2600	A-SA-S	**620**	240
Mekong	Vietnam	800	Tr-H-S	**550**	690
Lena	Russia	2500	A-SA-S	**520**	220
Ganges	Bangladesh	980	STr-H-S	**490**	500
Mississipppi	USA	3300	Te-SA-Sp	**490**	150
Parana	Argentina	2600	STr-SA-C	**460**	180
Irrawaddy	Burma	430	Tr-W-S	**430**	1000
Totals		**27 000**		**13 800**	500

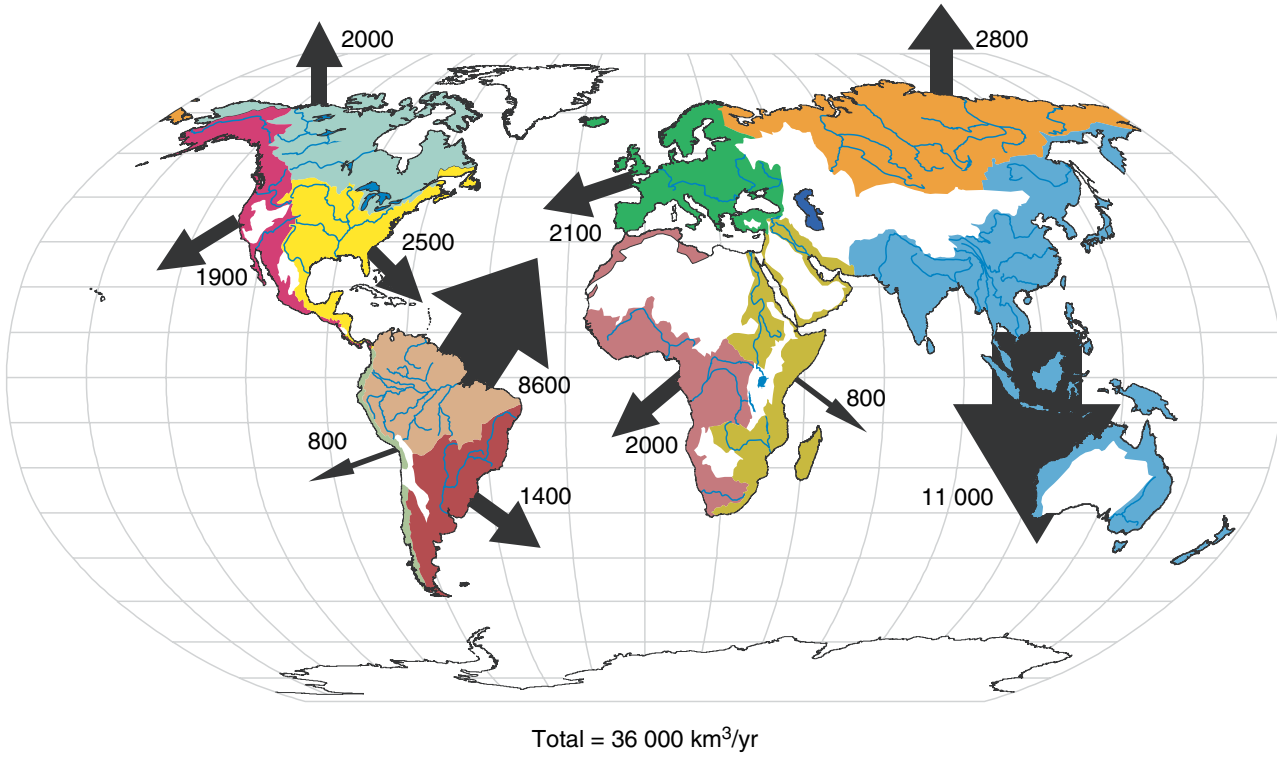

Figure 2.9. Fluvial discharge of freshwater to the global coastal ocean. Numbers are mean annual discharge (km³/yr); the arrows are proportional to these numbers. Cumulative arrow width is the same for subsequent global maps in this chapter, thus facilitating comparison of the relative fluvial discharge of freshwater, suspended solids (Fig 2.29), dissolved solids (Fig.2.38), and dissolved silica (Fig. 2.49).

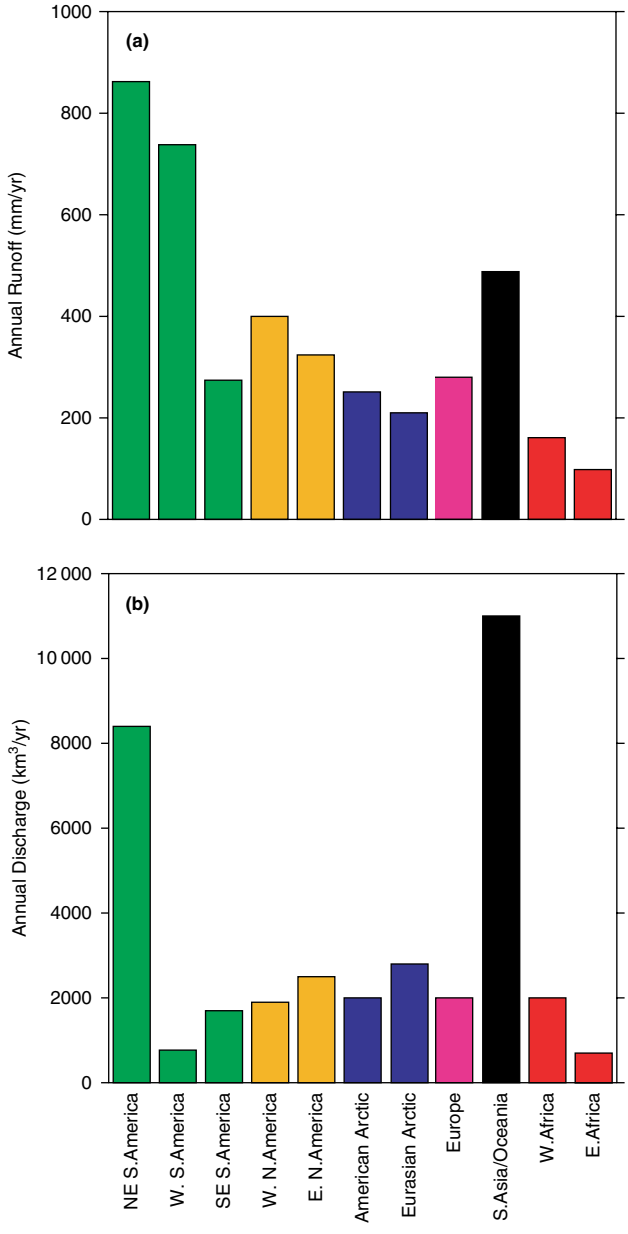

Figure 2.10. Annual discharges (a) and runoffs (b) to the global ocean from the 11 regional areas portrayed in Fig. 2.9. Note that only northern and parts of western South America can be classified as wet (>750 mm/yr), whereas the Eurasian Arctic and Africa are semi-arid or arid.

Europe

If one were to judge only from the small arrows in the panel in Figure 2.11c, one would assume that European rivers are rather uniform and, to someone used to working in the New World or Asia – to put it kindly – rather boring. While it is true that the runoff from many northern and central Europe rivers can be viewed as being monotonously semi-arid (<250 mm/yr), the contrasts, in fact, are stark. Watersheds influenced by the Gulf Stream (Iceland and Norway) have runoffs >750 mm/yr, Albanian and western Greek rivers have runoffs >1000 mm/yr; in contrast, far eastern Mediterranean rivers are semi-arid (Fig. 2.11c). Nowhere is the disparity in runoff more apparent than in the Black Sea drainage basin: northern rivers, such as the Don and Dniepr, have runoffs <100 mm/yr, whereas some Georgian rivers in the southeastern part of the region have runoffs exceeding 1500 mm/yr (Jaoshvili, 2002; Milliman *et al*., 2010).

Africa

One reason that we have not included detailed maps of Africa or the Russian Arctic is that rivers draining both areas are rather consistent. Of the large African rivers, for example, only the Congo (runoff 340 mm/yr) is non-arid; pre-dam runoffs for the Nile, Niger, Zambesi, Orange, and Shebelle averaged only about 50 mm/yr. Many of Africa's major secondary rivers (e.g. Limpopo, Volta, and Senegal) are also arid.

Asia and Oceania

Southern Asian and Oceania rivers collectively account for about 30% of the fluvial discharge to the global ocean, but the contrasts between various areas within southern Asia and the high-standing islands are noteworthy (Fig. 2.11b). Runoff from the major Himalayan rivers, for example, ranges from 91 mm/yr for the Indus in the west to 940 mm/yr and 1000 mm/yr for Brahmaputra and Irrawaddy farther east. Highest runoff is seen in Taiwan, the Philippines, and Indonesia, runoff in some rivers exceeding 3000 mm/yr. In contrast, many Australian rivers, including the Murray–Darling, have runoffs less than 50 mm/yr.

Eurosian Arctic

The very large Russian Arctic rivers (Ob, Yenisei, Lena, and Kolyma; combined drainage basin area 8.8×10^6 km^2) are all semi-arid, with an average runoff of 185 mm/yr. Because the shorter Russian rivers (Severnaya Dvina, Khatanga, Indigirka, Pechora, etc.) drain less of the arid Eurasian interior, their runoff is somewhat higher (260 mm/yr), but only the Severnaya Dvina and Pechora (310 mm/yr and 410 mm/yr, respectively) in the far west can be considered humid rivers.

Another perspective

The Arctic Ocean accounts for less than 5% of the global ocean (17×10^6 km^2), but the watershed draining into the Arctic totals 21×10^6 km^2, about 20% of the land area draining into the global ocean. The drainage area/ocean ratio is 1.2. By contrast, the South Pacific accounts for 1/4 of the global ocean area, but combined watersheds draining into the South Pacific total only 5×10^6 km^2, giving a drainage area/ocean area ratio of ~ 0.05 (Table 2.4). The greatest freshwater input is to the North Atlantic (largely because of the Amazon and, to a lesser extent, the Orinoco and Mississippi), but the

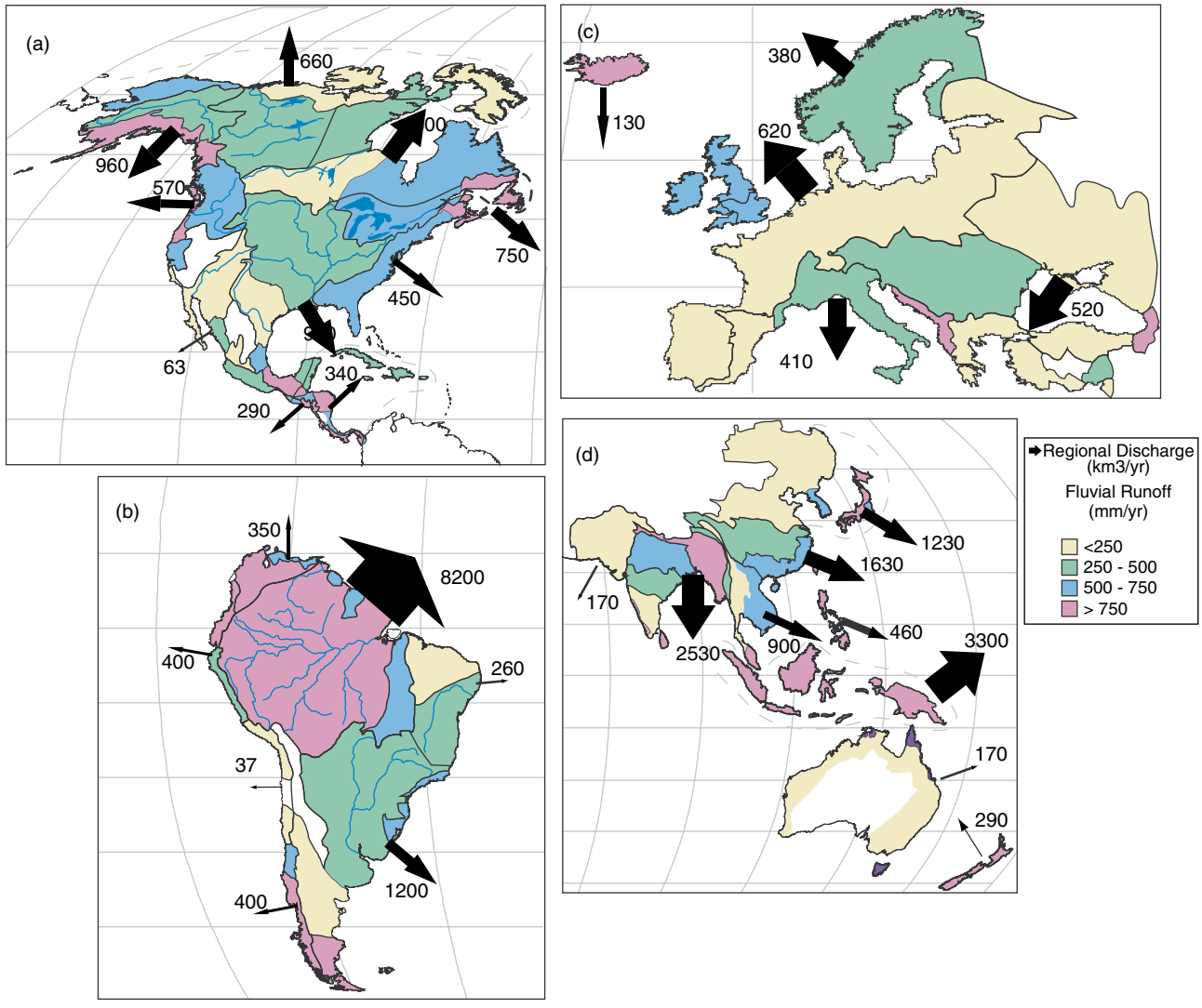

Figure 2.11. Regional discharge from (a) North America, (b) South America, (c) Europe, and (d) Austral-Asia. Runoff for the various polygons is color-coded, from arid to wet. Arrows in each panel are proportional to water discharge within that area. Where discharge data are meager, we rely on data from adjacent polygons. Areas with generally similar physiography, geology, and climate are delineated by bold black borders. Africa and the Eurasian Arctic are excluded from this analysis because of the general uniformity of their physiography, geology, and climate.

greatest input per unit basin area is to the Arctic (280 mm/yr if distributed evenly over the entire basin). The lowest input per unit area is the South Pacific (45 mm/yr) (Table 2.4). The timing of discharge to the various basins, however, shows stark seasonal contrasts, peak discharge to the Arctic and Pacific occurring in June, versus May for the Atlantic and August for the Indian Ocean (Dai and Trenberth, 2002).

Sediment: erosion and discharge

Introduction

Fluvial sediments can be transported in suspension or as bedload along the river bottom. The term suspended sediment normally refers to solids coarser than 0.45–0.62 μm, depending on the nominal pore diameter of the filter; finer material is considered dissolved if one disregards colloidal matter. Suspended sediment includes wash load, the fine fraction that remains more or less continuously in suspension, and bed material load, the sediment incorporated into the suspended load during higher flow. The dividing line separating bed material load from bed load varies with time and flow conditions: as river flow increases, what is normally transported as bed load can be resuspended and incorporated into the bed material load.

Many, if not most, fluvial sediment data refer to suspended sediment rather than total load, in large part because measuring bed load is, at best, problematic. Bed load measurement, for example, can alter surface roughness of the

Table 2.4. *Cumulative oceanic areas, drainage basin areas, discharge, and runoff of rivers draining into various parts of the global ocean. For this compilation, it is assumed that Sumatra and Java discharge into the Indian Ocean, and that the other high-standing islands in Indonesia discharge into the Pacific Ocean. Rivers discharging into the Black Sea and Mediterranean are assumed to be part of the North Atlantic drainage system.*

	Ocean area ($\times 10^6$km^2)	Drainage basin ($\times 10^6$km^2)	Discharge (km^3/yr)	Sediment flux (Mt/yr)	Dissolved flux (Mt/yr)
North Atlantic	44	30	13 200	2500	1350
South Atlantic	46	12	3400	400	240
North Pacific	83	15	6100	7200	660
South Pacific	94	5	4100	3900	650
Indian	74	14	4000	4000	520
Arctic	17	21	4800	350	480
Total	360	98	36 000	18 000	3800

riverbed, whether by installation of a recording instrument on the bottom or digging a pit to record the speed at which it is filled. Although new non-intrusive laser and acoustic Doppler techniques offer some hope for less intrusive measurement, most workers continue to assume that bed load represents a relatively small fraction of the total sediment load, perhaps only ~10% (C. Nordin, cited by Milliman and Meade, 1983). The 10% estimate is probably too high for most larger meandering rivers (e.g. 1–2% for the Yukon River, Brabets *et al.*, 2000; <5% for the lowermost Mississippi River, Nittrouer *et al.*, 2008). For smaller rivers, particularly short mountainous rivers, on the other hand, 10% may be too low. Rovira *et al.* (2004), for instance, estimate that 75% of the sediment load discharged by the Tordera River (basin area 894 km^2), in southern Spain, is as bed load, which is transported almost exclusively during floods.

Sediment discharge, often termed sediment load, refers to sediment transport: mass per unit time. Some workers appear to confuse discharge or load with sediment concentration, thus writing such statements as "…average sediment load is 35 mg/l…" (reference here purposefully deleted). A particularly useful – but sometimes confusing – term is sediment yield, which we define as the sediment discharge divided by drainage basin area upstream of which discharge is measured, in much the same way that runoff is water discharge normalized for basin area. Some workers use the term synonymously with sediment load; Phillips (1990), for example, defines yield as "sediment transport out of the drainage basin." For those workers equating yield and load, what we consider as sediment yield is termed specific sediment yield. As with runoff, sediment yield allows one to compare the loads of disparate-sized rivers, for example the Congo River (12 t/km^2/yr) vs. the Choshui River (13 000 t/km^2/yr). Waythomas and Williams (1988) have cautioned that plotting sediment yield vs. basin area (as we do in this chapter) is statistically invalid since area is common to both axes. Nevertheless, sediment yield helps us to delineate the key environmental factors that control sediment erosion and fluvial transport.

Although it is often equated with denudation rate (e.g. Gilluly, 1955; Judson and Ritter, 1964; Li, 1976; Harrison, 1994), sediment yield refers to sediment delivery averaged over the area of the entire drainage basin. But in reality, denudation is never uniform throughout the entire basin. In large drainage basins, in fact, sediment often is stored downstream, thereby resulting in a high up-basin denudation and negative down-basin denudation. Holeman (1980), for instance, calculated that only ~10% of the total erosion in the conterminous United States actually reaches the ocean, and Wasson *et al.* (1996) state that only ~1% of the eroded soil in Australia is discharged to the ocean. As will be seen at the end of this chapter, sediment storage, both temporary and long-term, is critical to understanding the correlation between sediment yield and basin area. To add to the confusion, human influence on solid and dissolved denudation cannot be minimized; present-day sediment yields in the eastern USA, although relatively low, are ~four to five times greater than they were prior to European settlement (Meade, 1969). Chapter 4 deals in greater detail with anthropogenic impacts on sediment erosion and delivery.

No matter the scale – watershed-specific, regional or global – freshwater discharge can be measured in a relatively straight-forward way by measuring river height; the margin of error is relatively small – perhaps no more than 5–20% in extreme cases. Water discharge only requires frequent measuring a river's gauge height (stage) above an arbitrary datum, and referring the gauge height to a previously constructed graph (rating curve) of gauge height vs. measured discharge (Fig. 2.12a), corrected in response to changes in river channel configuration. Moreover, because most river flow is measured in similar ways, often with uncertainties of no more than 10% (Fekete *et al.*, 2002; Shiklomanov *et al.*, 2006), we

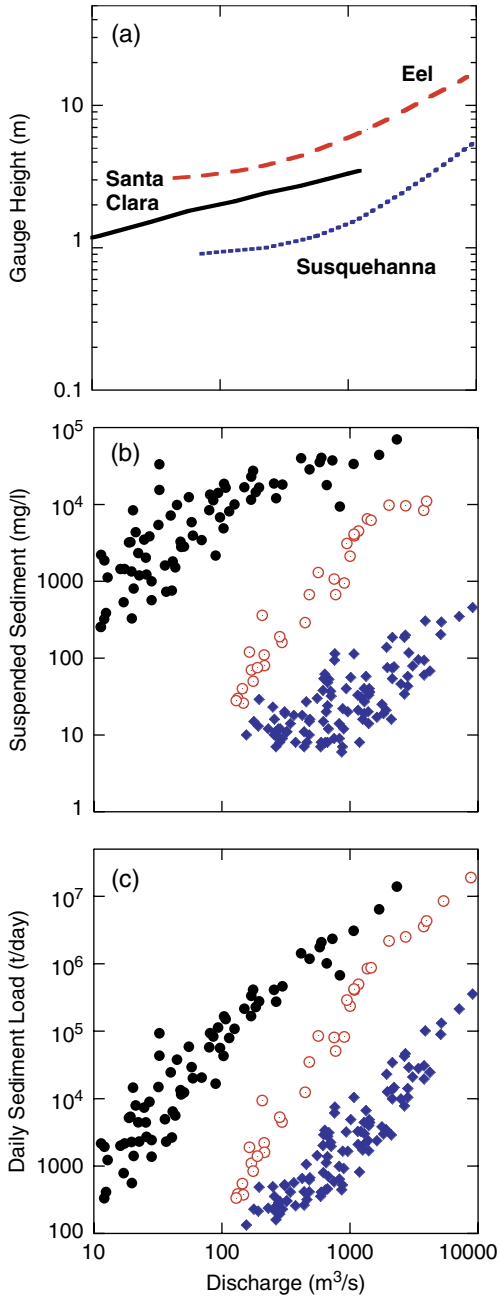

Figure 2.12. Discharge- and sediment-rating curves for the Santa Clara (at Montalvo, California: 4100 km^2 basin area, 100 mm/yr runoff; black notations), Susquehanna (at Harrisburg, Pennsylvania: 71 000 km^2, 450 mm/yr; blue notations), and the Eel (at Scotia, California: basin area 8000 km^2, 900 mm/yr; red notations) rivers. Water discharge is calculated by comparing measured gauge height to rating curves shown in (a). Measured suspended-sediment concentrations can be correlated with river discharge to derive a sediment-rating curve (b), from which sediment load (c) (i.e. concentration times water discharge) can be calculated. As water discharge appears in both terms, sediment-rating curves tend to follow a close-fitting power function. Data from the USGS.

can compare and contrast discharges of various rivers with a fair degree of certainty.

Sediment discharge is more difficult to quantify. Suspended sediment can be sampled in a diversity of ways, from long-term depth- and point-integrated cross-channel sampling used by the US Geological Survey (e.g. Edwards and Glysson, 1999; Carvalho, 2008) to a one-time dip-bucket sample, which is almost guaranteed to misrepresent both spatial and temporal variations in sediment concentration, and hence sediment discharge. The expense and difficulty in obtaining suspended sediment samples mean that even well-monitored rivers are often sampled too infrequently to catch important short-lived events, such as floods or landslides.

Historically, the most reliable monitoring of suspended sediment concentrations has combined periodic suspended sediment sampling with closely spaced sampling during major discharge events (Walling and Webb, 1988; Robertson and Roerish, 1999; Bridge, 2003). But in contrast to some larger rivers that have had long-term monitoring, many rivers have been sampled only long enough to allow workers to construct an operational sediment-rating curve, after which sampling often has been reduced or eliminated, the assumption being that the constructed curve can adequately represent the river's sediment discharge as well as the watershed's erodibility. Assuming no temporal change in watershed character, of course, is often based more on hope than on reality; the watershed's response to natural occurrences such as fire or landslides (Chapter 3) or to a change in landuse (Chapter 4) can greatly alter the erosion and/or subsequent transport of eroded sediments. In Taiwan, for example, rapidly changing annual and interannual conditions require semi-annual revisions of the sediment rating curves (Kao *et al.*, 2005; Kao and Milliman, 2008). At the opposite end of the scale, the oft-cited 260 Mt/yr discharge of the Irrawaddy River (Burma) published by Gordon (1885) was based on measurements made in 1877–78, and almost certainly is an underestimate. Reanalysis of Gordon's collection techniques and data led Robinson *et al.* (2007) to increase Gordon's estimate by nearly 40%, which more recent measurements confirm (Furuichi *et al.*, 2009).

Published sediment loads for most rivers are derived from the algorithms produced from sediment-rating curves, but anyone who has carefully considered the multitude of inherent problems with these curves cannot help but question how accurately they represent the river's actual sediment discharge. In addition to the sampling problems mentioned above, one has to worry about how the rating curve is constructed, particularly the wide degree of scatter that often characterizes such curves (Fig. 2.12b). Hysteresis seen in many rating curves reflects the varying capacity of a river to transport more sediment during its rising stage than

during its falling stage, by which time much of the available sediment has been removed. In other words, many rivers evolve seasonally from transport-limited to supply-limited (Hudson, 2003). Hysteresis loops also can reflect different timing of sediment and water contributions from various tributaries within a river system. Depending on the number of major tributaries flowing into a river, this may result in several hysteresis loops within a single year; the convoluted corkscrew pattern of Mississippi River's pre-dam rating curve in 1950 (see Fig. 4.37c) is perhaps an extreme example.

Even if one disregards hysteresis, creating a meaningful rating curve can be disconcerting. For example, does one use a stratified seasonal rating curve or not, have there been sufficient sediment measurements during peak flow, etc.? Taking into account such uncertainties, Walling (1978; Walling and Webb, 1981) and Warrick and Farnsworth (2009) suggested that a 50% error in estimated annual suspended sediment loads is not only possible but perhaps acceptable. Given these problems, one should not place too much faith in many (most?) published sediment loads. Of the 75 rivers whose mean annual sediment loads are estimated to exceed 20 Mt/y shown in Table 1.3, for example, we consider only ~25% of the estimates to be good, whereas ~50% are considered to be poor, out of date, or non-existent.

A sediment load reported to three or four digits, say 10.83 Mt/yr, should be treated with particular suspicion. One can achieve a greater sense of reality by using only the first two digits, say 11 Mt/yr, although it can be argued that only the first digit is actually meaningful, in this case, 10 Mt/yr. Depending on the sampling techniques and sampling scheme used to derive the sediment load, in fact, reporting a range between 6 and 16 Mt/yr might be closer to the truth. Throughout the book and in our database we report values to the second digit.

Of particular concern to us are the reported loads for rivers draining Indonesia and the Philippines, since, as discussed later in this chapter, the few published data suggest that these rivers collectively are a major source of fluvial sediment to the global ocean. Many of the Indonesian and Philippine data come from second- and third-hand sources, and most presumably reflect short-term measurements of unknown quality. The Sumatra river sediment data that we cite in the appendix and use in many of the following calculations, for instance, may be too high according to colleagues who have worked on eastern rivers that flow through the island's broad coastal lowlands (B. Cecil and T. Jennerjahn, personal communication). A similar problem is seen in the Mahakam River, which drains ~80 000 km^2 in eastern Borneo. Using preliminary data, Allen *et al.* (1979) estimated the Mahakam's annual load to be ~10 Mt/yr, which equates to an annual sediment yield of ~120 t/km^2/yr, somewhat lower than the global mean. Douglas (1996), in contrast, estimated that the rivers draining the Tertiary mudstones in eastern Borneo should have annual yields of ~1000 t/km^2/yr, which would give the Mahakam an annual sediment load of 50–100 Mt/yr. As new data become available, estimates for Indonesian and Philippine sediment discharge almost certainly will need to be re-evaluated.

Compounding the problem of quantifying sediment flux is that reported discharge, no matter its accuracy, represents measurements upstream from any tidal influence, which in some cases may lie hundreds of kilometers upstream from the river mouth. For example, the Yangtze River's downstream-most gauging station at Datong is 400 km upstream from the East China Sea. Almost certainly sediment is deposited downstream of Datong and perhaps new sediment introduced, so that the reported sediment load may not represent the actual amount of sediment that reaches the coastal ocean.

Environmental controls on sediment delivery to the coastal ocean

It is almost axiomatic to state that sediment erosion and subsequent transport are controlled by drainage basin size and topography/gradient, bedrock geology, climate (particularly precipitation/runoff), rainfall severity, vegetation cover, and anthropogenic activity (Ludwig and Probst, 1998; Leeder *et al.*, 1998; Meybeck, 2003; Syvitski *et al.*, 2005; Syvitski and Milliman, 2007; Kao and Milliman, 2008), the basic variables used in the Universal Soil Loss Equation. Thus, unlike river discharge, we need to look not only at precipitation and evapotranspiration (i.e. river runoff) but we also must figure in the influences of basin morphology and source-rock lithology as well as temporal change and the impact of events (Chapter 3) and human activity (Chapter 4). The continuing debate, as witnessed by the wide range of interpretative and predictive models, has been over which of these factors play primary and secondary roles in determining a river's sediment discharge.

All published interpretative and predictive models regarding fluvial sediment loads are based on factors that control sediment supply (erosion), transport (discharge), or a combination of the two. Early studies by Fournier (1949, 1960) and Langbein and Schumm (1958) concluded that precipitation is the dominant factor controlling sediment load. Douglas (1967) found a good correlation between rainfall variability and sediment load, and Jansson (1988) suggested that climate (temperature and precipitation/runoff, particularly "rainfall aggressiveness") was the determining factor in soil erosion. Using a larger database, Wilson (1973) concluded that precipitation has relatively little influence on sediment yield; rather, he argued, basin area and land use

Table 2.5. *Highest and lowest average suspended-sediment concentrations (in bold), in descending order, of the 700+ rivers in our database. Global average is 500 mg/l. Rivers with highest concentrations tend to lie in subtropical arid to semi-arid climates, the Erhjen (Taiwan) and Jaba (Bougainville) being stark exceptions. Rivers with lowest concentrations, by contrast, are located in Europe, many of them draining erosion-resistant shield-dominated terrain.*

River	Country	Area ($\times 10^3$ km^2)	Climate	Runoff (mm/yr)	Sed. load ($\times 10^3$ t/yr)	Sed. yield (t/km^2/yr)	Sed. concentration (mg/l)
Miliane	Tunisia	2	STr-A-D	10	0.9	450	**45 000**
Agrioun	Algeria	0.66	STr-H-W	260	4.8	7300	**28 000**
Wadi Sihan	Yemen	4.9	STr-A-D	20	2.8	570	**28 000**
Isser	Algeria	4.2	STr-A-W	86	8.3	2000	**23 000**
Erhjen	Taiwan	0.14	STr-W-S	3600	10	71000	**20 000**
Jaba	Bougainville	0.46	Tr-W-S	2800	26	56000	**20 000**
Huanghe	China	750	Te-A-S/Au	57	1100	15000	**19 000**
Draa	Morroco	110	STr-A-W	7	14	13	**17 500**
Dalinghe	China	23	Te-A-S/Au	91	36	1600	**17 000**
Santa Clara	USA	4.1	STr-A-W	44	3	7300	**17 000**
Ventura	USA	0.48	STr-SA-W	110	0.38	1700	**15 000**
Global							**500**
Dalaven	Sweden	29	SA-H-S	520	0.03	1	**2**
Fluvia	Spain	1	Te-SA-W	300	0.002	10	**2**
Ljungan	Sweden	13	SA-H-S	340	0.01	1	**2**
Lule	Sweden	25	SA-H-S	640	0.04	2	**2**
Skellefte	Sweden	12	SA-H-S	410	0.009	1	**2**
Rane	Sweden	4.1	SA-H-S	320	0.002	0.5	**1**
Rhine	Netherlands	220	Te-H-C	340	0.07	0.3	**1**
Siikajoki	Finland	4.4	SA-H-S	320	0.002	0.4	**1**

are the primary forcing functions. Ahnert (1970) agreed, stating that "…mean precipitation has a negligible effect on denudation rate," whereas local basin relief plays a major role, a suggestion supported by Gunnell's (1998) study of denudation rates on the southern Indian shield. Catchment gradient, suggested Phillips (1990), accounts for 70% of the contribution to maximum expected variations in erosion rates, a conclusion similar to that of Summerfield and Hulton (1994).

Jansen and Painter (1974) suggested that sediment yield could be related to temperature, discharge (i.e. precipitation) or basin relief, whereas Pinet and Souriau (1988), Milliman and Syvitski (1992), Summerfield and Hulton (1994), and Syvitski and Milliman (2007) concluded that basin elevation (rather than climate) is a primary determinant. Milliman and Syvitski (1992) also confirmed Schumm and Hadley's (1961) observation that sediment yield is inversely proportional to watershed area, although there are regional contradictions to this global trend (de Vente *et al*., 2007). Milliman and Syvitski (1992) and Montgomery and Bandon (2002) pointed out that tectonism and the rate of tectonic uplift, rather than local relief per se, may play key deterministic roles in landscape degradation. In Taiwan, for example, earthquake-generated landslides create the source of sediment that is subsequently eroded during typhoon-forced rains (Dadson *et al*., 2004; Milliman *et al*., 2007; Goldsmith *et al*., 2008).

Ludwig and Probst (1996, 1998) were among the first to propose a numerical model that could extract the relative importance of the environmental factors controlling sediment discharge. Runoff intensity, rainfall variability, basin slope, and rock hardness were considered the primary factors, although the Ludwig and Probst model also suggested (wrongly, as discussed later in this chapter) that erodibility increases with aridity. One problem, which the authors readily acknowledged, was that the Ludwig and Probst model was based on a rather slim database (60 rivers) that was weighted towards large rivers, many in Europe, even though most European rivers have very low yields. The high-yield landscape in southeast Asia and Oceania was represented by only 11 rivers.

In recent years James Syvitski and his co-workers (Syvitski and Alcott, 1995; Syvitski and Morehead, 1999; Syvitski *et al*., 2003, 2005) have been particularly active in developing dimensional analyses to predict long-term sediment loads. Syvitski and Milliman (2007) presented the BQART model, utilizing a database of 488 rivers from

Table 2.6. *Highest and lowest average annual sediment loads, in descending order (in bold). 13 of the 15 highest loads are in rivers whose headwaters exceed 3000 m in elevation; 7 drain the Himalayas. Rivers with the lowest sediment loads are located in Scandinavia and the British Isles, most with headwaters <1000 m (upland rivers), many <500 m (lowland rivers).*

River	Country	Area ($\times 10^3$ km^2)	Elevation	Runoff (mm/yr)	Sed. load (Mt/yr)	Sed. yield (t/km^2/yr)	*Q*sc (g/l)
Amazon	Brazil	6300	High Mt	6300	**1200**	190	0.19
Huanghe	China	750	High Mt	15	**1100**	1500	19
Brahmaputra	Bangladesh	670	High Mt	630	**540**	810	0.86
Ganges	Bangladesh	980	High Mt	490	**520**	530	1.1
Changjiang	China	1800	High Mt	900	**470**	260	0.52
Mississippi	USA	3300	High Mt	490	**400**	120	0.82
Irrawaddy	Burma	430	High Mt	430	**260**	600	0.6
Indus	Pakistan	980	High Mt	<10	**250**	250	2.8
Orinoco	Venezuela	1100	High Mt	1100	**210**	140	0.14
Godavari	India	310	Mountain	92	**170**	550	1.8
Mekong	Vietnam	800	High Mt	690	**150**	190	0.27
Magdalena	Colombia	260	High Mt	230	**140**	540	0.61
Fly	Papua New Guinea	76	High Mt	180	**110**	1100	0.44
Song Hong	Vietnam	160	High Mt	120	**110**	690	0.92
Skellefte	Sweden	12	Lowland	410	**0.009**	1	2
Welland	England	0.53	Lowland	210	**0.007**	13	63
Conon	Scotland	0.96	Mountain	1600	**0.006**	6	4
Slaney	Ireland	1.8	Upland	610	**0.006**	3	5
Teith	Scotland	0.52	Mountain	1400	**0.005**	10	7
Liffey	Ireland	1.4	Lowland	335	**0.004**	3	8
Karjaanjoki	Finland	2	Lowland	320	**0.002**	1	3
Rane	Sweden	4.1	Upland	320	**0.002**	0.5	1
Siikajoki	Finland	4.4	Lowland	320	**0.002**	0.4	1
Mandalselva	Norway	1.7	Upland	880	**0.001**	1	1

which they quantified the importance of river discharge, basin area, relief, temperature, as well as the combined effect of glacial erosion, basin-wide lithology, trapping by lakes and reservoirs, and human-induced erosion. Geological factors (basin relief, basin area, lithology, and ice/glacial erosion), they concluded, explain 65% of the variation in sediment loads; climatic and anthropogenic factors collectively explain an additional 30% of the variability.

The diversity of opinions cited above, often derived by different workers using many of the same data, clearly emphasizes the difficulty in prioritizing the factors controlling sediment erosion, transport and discharge to the ocean. As pointed out by Hovius and Leeder (1998, p. 2):

It should therefore not come as a surprise that empirical studies of modern drainage basins… have not so far produced a reliable universal relationship between sediment yield and catchment characteristics. Although strong relations between erosion rates and one or more catchment characteristics can be found locally, the search for universality, in this form, is futile. The principal reason for this is that sediment efflux of a catchment is the integrated effect of a series of tectonic, climatic and geomorphic processes…

Of 760 rivers for which we have sediment data, we find a great range in average suspended sediment concentrations (1–45,000 mg/l, with a global mean of 500 mg/l; Table 2.5), sediment loads (0.001–1200 Mt/yr; Table 2.6), and annual sediment yields (0.3–71 000 t/km^2/yr, with a global annual mean of 190 t/km^2/yr; Table 2.7). The relative plethora and range of values within our database allow us the "luxury" of sorting out the relative importance of the various environmental factors, which we attempt to do in the following pages. Because our database includes only rivers that discharge directly into the ocean, it is not compromised by data "double-dipping," in contrast to Wilson's (1973) database of 1500 rivers, which included more than 1200 tributaries to larger rivers.

Before we proceed in this discussion, we should warn the reader that we recap here many of our thought processes developed over the years as we have sought to delineate the relative importance of the various environmental factors controlling

Table 2.7. *Highest and lowest fluvial suspended-sediment yields (in bold) in descending order; global annual mean, 190 t/km². Many high-yield rivers drain mountainous elevations (<3000 m), more than half of them in Taiwan. Maximum elevation of the highest-yield river, the Erhjen (average annual yield 71 000 t/km²), however, is only 460 m. All high-yield rivers are small, with drainage basins <3000 km², and most have runoffs greater than 2000 mm/yr. Most low-yield rivers, on the other hand, drain lower elevations or erosion-resistant shield rocks; runoff for low-yield rivers tends to be <500 mm/yr.*

River	Country	Area (× 10³ km²)	Elevation	Runoff (mm/yr)	Sed. load (× 10³ t/yr)	sed. yield (t/km²/yr)	*Q*sc (g/l)
Erhjen	Taiwan	0.14	Upland	3600	10	**71 000**	20
Jaba	Bougainville	0.46	Mountain	2800	26	**56 000**	20
Hoping	Taiwan	0.55	High Mt	2200	16	**29 000**	13
Waiapu	New Zealand	1.7	Mountain	1600	35	**21 000**	12.5
Hokitika	New Zealand	0.35	Mountain	8900	6.2	**18 000**	2
Hualien	Taiwan	1.5	Mountain	2500	20	**13 000**	5.3
Choshui	Taiwan	3.1	High Mt	2000	38	**12 000**	6.2
Waiho	New Zealand	0.29	Mountain		3.4	**12 000**	
Cikeruh	Indonesia	0.25	Mountain		2.8	**11 000**	
Peinan	Taiwan	1.6	High Mt	2300	18	**11 000**	4.9
Tungkang	Taiwan	0.47	Mountain	2300	5.2	**11 000**	4.7
Tsengwen	Taiwan	1.2	Mountain	2000	12	**10 000**	5
Yenshui	Taiwan	0.22	Lowland	1400	2.2	**10 000**	7.3
Global						**190**	
Murray–Darling	Australia	1100	Mountain	22	1	**1**	42
Jaguaribe	Brazil	81	Upland	49	0.06	**1**	15
Guadiana	Spain	72	Upland	125	0.07	**1**	8
Kymijoki	Finland	37	Lowland	320	0.05	**1**	4
Iijoki	Finland	14	Lowland	360	0.014	**1**	3
Karjaanjoki	Finland	2	Lowland	49	0.002	**1**	3
Oulujoki	Finland	25	Lowland	320	0.024	**1**	3
Dalaven	Sweden	29	Upland	520	0.03	**1**	2
Ljungan	Sweden	13	Upland	340	0.01	**1**	2
Skellefte	Sweden	12	Lowland	410	0.009	**1**	2
Mandalselva	Norway	1.7	Upland	880	0.001	**1**	1
Rane	Sweden	4.1	Upland	320	0.002	**0.5**	1
Siikajoki	Finland	4.4	Lowland	320	0.002	**0.4**	1
Rhine	Netherlands	220	Mountain	340	0.07	**0.3**	1

sediment (and dissolved-solid) erosion (and weathering) and transport. The impatient or faint-hearted reader may prefer to skip the following pages and proceed directly to the concluding section at the end of this chapter. While many of the conclusions are understandably similar to those of Syvitski and Milliman (2007), here we assess, piece by piece, the relevant factors that control fluvial sediment discharge.

Drainage basin area and morphology

It seems reasonable to assume that sediment discharge is proportional to basin area, larger rivers having greater loads than smaller rivers. But the number of exceptions to this rule of thumb underscores the inexactitudes of such an assumption (Fig. 2.13a). The Waiapu River (North Island of New Zealand, basin area 1700 km²), for example, discharges far more sediment (26 Mt/yr) than the much larger (1 100 000 km²) Murray–Darling River (1 Mt/yr); the São Francisco (Brazil) and the Brahmaputra (Bangladesh) rivers drain similar size watersheds (640 000 and 670 000 km², respectively) but have drastically different annual sediment loads: 6 vs. 540 Mt/yr, respectively. Conversely, although sediment yield tends to increase with decreasing basin area (Fig. 2.13b), some large rivers have higher yields than smaller rivers (de Vente *et al*., 2007); for example, the Ganges (980 000 km²; annual yield 530 t/km²/yr) vs. the Karjaanjoki (Finland, 2000 km²; annual yield t/km²/yr).

We can deconvolve this relationship a bit further by factoring in drainage basin morphology. Following Milliman and Syvitski (1992), we have categorized sediment discharge and yield of 760 rivers on the basis of maximum

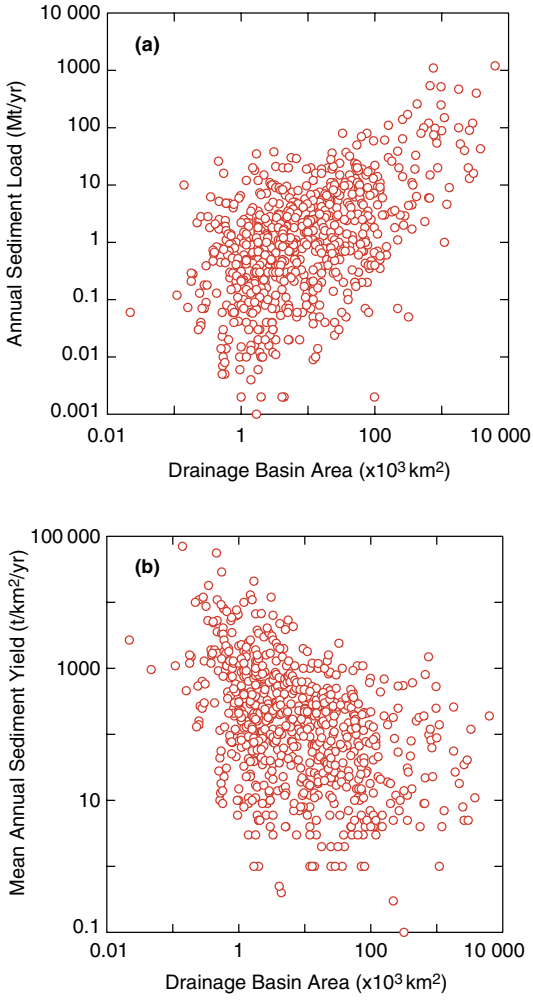

Figure 2.13. Variation of annual sediment discharges (a) and yields (b) relative to drainage basin area for 760 rivers discharging into the coastal ocean.

elevation of the drainage basin: >3000 m (high mountain), 1000–3000 m (mountain), 500–1000 m (upland), and <500 m (lowland). The resulting figures – 2.14 and 2.15 – show that sediment load and yield generally increase as maximum drainage basin elevation increases. This, of course, should be no surprise, as Ahnert (1970) and Pinet and Souriau (1988) previously suggested that relief is the main driving function of basin denudation. By categorizing rivers based on maximum elevation, Milliman and Syvitski (1992) found a reasonably workable relationship between basin area and sediment load and an inverse relation between basin area and sediment yield, much like those shown in Figs. 2.14 and 2.15. Summerfield and Hulton (1994) used a slightly expanded global database to derive the relation:

$$\text{denudation rate (mm/yr)} = 0.00721e^{(0.0015*\text{elevation})}$$

High-mountain rivers tend to have one to three orders of magnitude greater load/yields than similar-sized lowland rivers (Figs. 2.14 and 2.15). The inverse relation between yield and basin area shown in Fig. 2.13 also becomes clearer. A high-mountain, mountain or upland river with a 1000 km^2 drainage basin, for example, generally has one to two orders-of-magnitude greater sediment yield than a river whose watershed is greater than 1 000 000 km^2 in area (Fig. 2.15). Sediment discharges and yields of coastal plain rivers (maximum elevation <100 m), in contrast, show no correlation with basin area (Milliman and Syvitski, 1992, their Fig. 6G).

There are a number of reasons for the direct relationship between sediment discharge (or yield) and elevation. Most obvious, rivers that drain higher elevations have steeper average gradients (Fig. 2.16). Elevation also serves as a tectonic surrogate: lying within orogenic belts, mountains are more likely to experience earthquakes (Inman and Nordstrom, 1971; Audley-Charles *et al.*, 1977; Potter, 1978), which can play a greater role in denudation than elevation or relief per se (Milliman and Syvitski, 1992; Montgomery and Brandon, 2002; Dadson *et al.*, 2004). But not all mountains are equally susceptible to earthquakes – either in frequency or magnitude. Mountains that lie along the edge of tectonic plates – such as the western Americas, but especially along the south Asian plate (including Taiwan, Philippines and Indonesia) – are particularly susceptible to ongoing tectonism and thus frequent and large earthquakes (Fig. 2.17). Mountains produced from past tectonic events, such as the Rockies or Urals, often are not major producers of sediment; their present high elevations, in fact, give testimony to the relatively low rates at which they shed sediment (R.H. Meade, personal communication).

The orographic control on precipitation (see above) means that mountains also are more likely to experience increased precipitation (Reiners *et al.*, 2003), and higher elevations experience greater snow and ice cover. Some high mountains may have year-round ice cover, which can greatly increase both physical and chemical weathering (Dedkov and Mozzherin, 1992; Schmidt and Montgomery, 1995; Collins, 1996; Hallet *et al.*, 1996; Anderson, 2005; Green *et al.*, 2005), particularly if the snowpack or glacier is warm-based (Tomasson, 1991; Andrews and Syvitski, 1994; Syvitski and Alcott, 1993). Vezzoli *et al.* (2004), for instance, found a direct relationship between sediment yield and glaciated area in the western Alps. The breaching of ice-dams can also produce a Jokulhlaup (see Chapter 3), another unique feature of glaciated terrain that can have a major role in both erosion and sediment transfer. Because present-day glaciers are relatively restricted (<1% of the global land area), they probably do not play a major role in present-day global erosion or sediment discharge; but they almost surely played prominent role during and following