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978-0-521-87987-3 - River Discharge to the Coastal Ocean: A Global Synthesis
John D. Milliman and Katherine L. Farnsworth
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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 One outcome of this diversity of approaches is an ever-expanding database and an even wider range of published and unpublished literature.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.

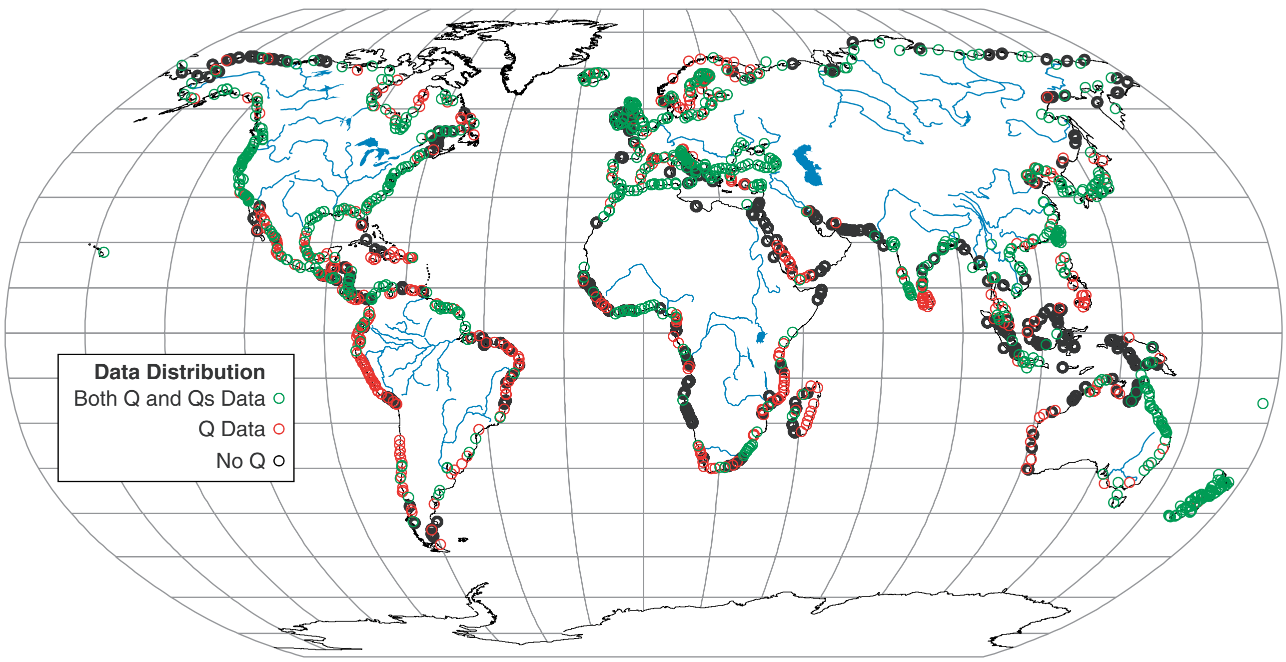

Figure 1.1. Locations of the 1534 rivers represented in our global database. Green circles represent rivers for which mean annual discharge and sediment and/or dissolved solid discharge are available; red circles represent those rivers for which only discharge is available; and black circles rivers for 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.

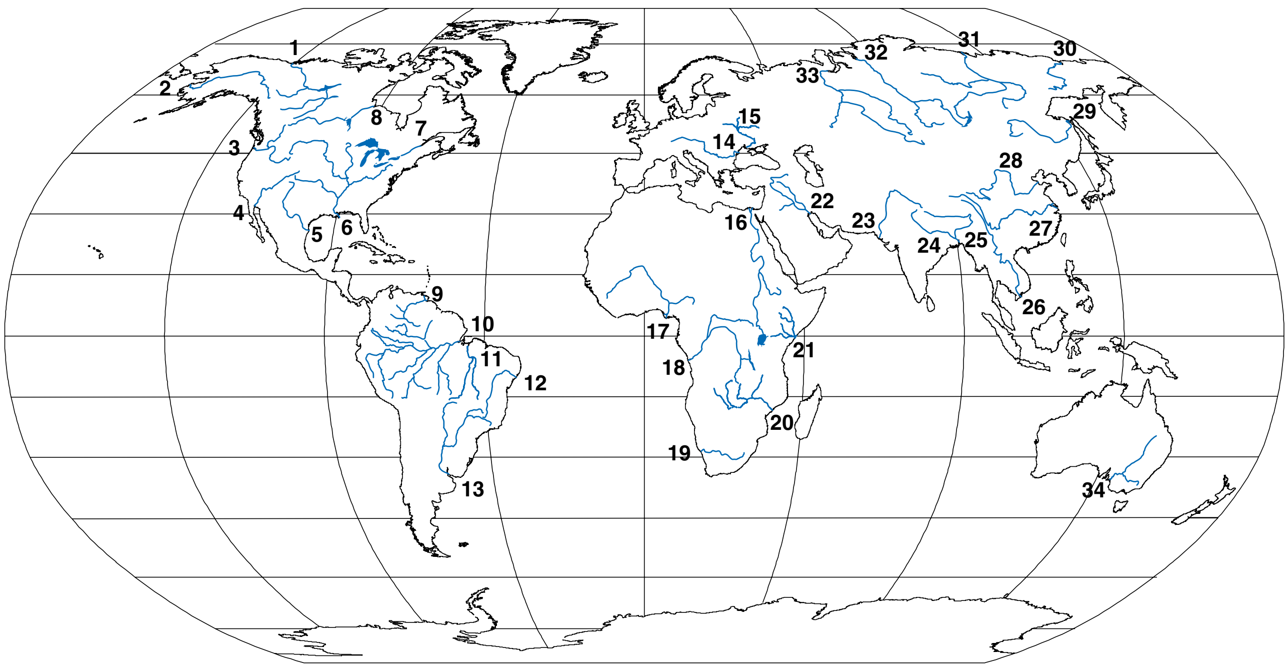

Figure 1.2. Locations of the 34 rivers with basin areas greater than 500 000 km^2; collectively these drainage basins account for half of the land area draining to the global ocean. 1, MacKenzie; 2, Yukon; 3, Columbia; 4, Colorado; 5, Rio Grande; 6, Mississippi; 7, St. Lawrence; 8, Nelson; 9, Orinoco; 10, Amazon; 11, Tocantins; 12, Sao Francisco; 13, Parana; 14, Danube; 15, Dniepr; 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

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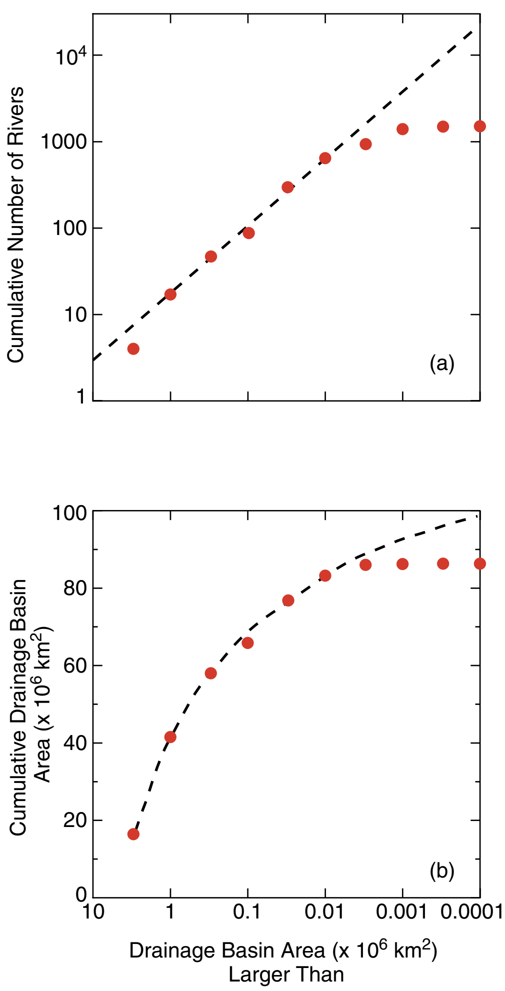

Figure 1.3. (a) Calculated number of global rivers (dashed line) and number of rivers in our database (red dots) vs. drainage basin size. The algorithm (# rivers = 16.92*(basin area in millions of km^2)$^{-0.7903}$) on which the calculation is based was derived from rivers in our database larger than 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

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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)	ΣQ (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**

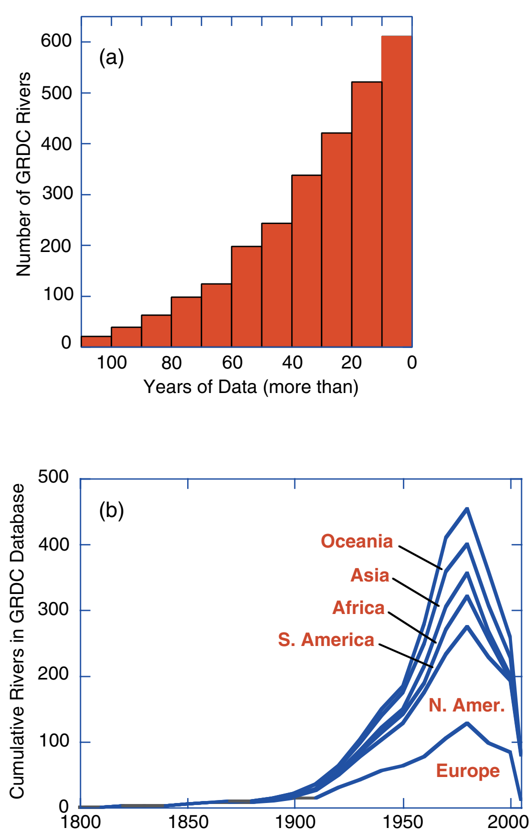

Figure 1.4. (a) Number of years of data for the 611 rivers in the GRDC database that discharge directly into the global ocean. Relatively few rivers are represented by more than 50 years of data. (b) GRDC discharge data, 1800–2005. Much of the steep decline of between 1980 and 2000 reflects a decrease 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

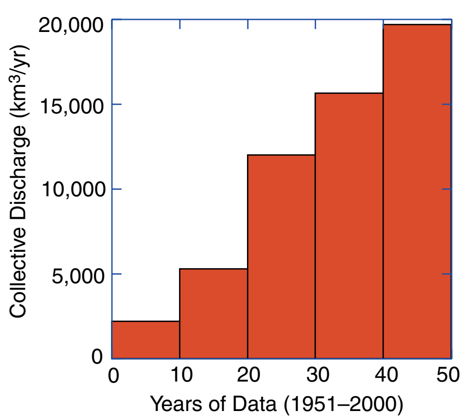

Figure 1.5. Length of record, 1951–2000, for the world's 50 largest rivers in terms of annual discharge; the collective 19 700 km^3/yr represent ~55% of the global total. Of this total, ~60% (12 000 km^3/yr) is represented by <30 years of GRDC-accessible data.

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 × 10^6 km^2, and the Nile's from 1.8 to 3.8 × 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.

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.

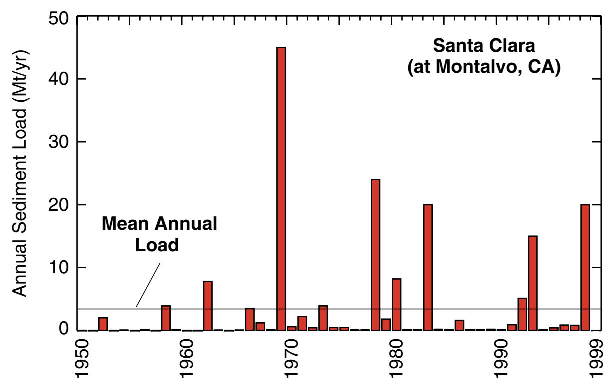

Figure 1.6. Annual sediment discharge from the Santa Clara River, as measured at the Montalvo gauging station, southern California. Note that the calculated mean load (3 Mt/yr) stems largely from flood-derived discharges in 1969, 78, 83, 93 and 98. Ignoring these one- to three-day events, collectively 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.

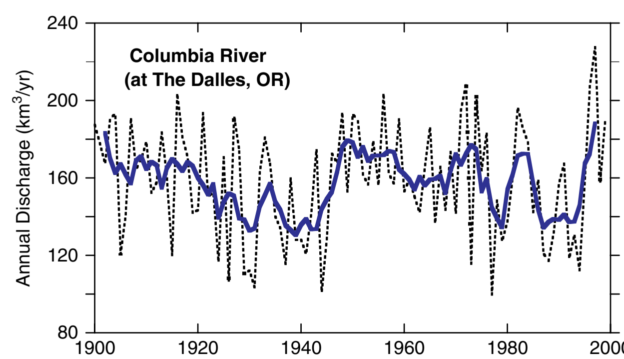

Figure 1.7. Annual discharge of the Columbia River (at The Dalles, Oregon), 1900–2000. The red dashed line shows annual discharge, the blue solid line shows the five-year running mean. Although long-term record shows no significant trend in annual discharge, interannually it deviated by more than 50%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