Springer Series in Physical Environment

William L. Graf

Fluvial Processes in Dryland Rivers

Springer-Verlag

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With 143 Figures

Springer-Verlag
Berlin Heidelberg New York
London Paris Tokyo

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ISBN 3-540-17591-1 Springer-Verlag Berlin Heidelberg New York
ISBN 0-387-17591-1 Springer-Verlag New York Berlin Heidelberg

Library of Congress Cataloging-in-Publication Data. Graf, William L., 1947– Fluvial processes in dryland rivers / William L. Graf ; cartography by Scott A. Lecce. p. cm. – (Springer series in physical environment ; 3) Bibliography: p. 1. Arid regions. 2. River channels. I. Title. II. Series. GB612.G73 1987 551.4–dc19

Media conversion: Daten- und Lichtsatz-Service, Würzburg
Offsetprinting and binding: Konrad Triltsch, Grapischer Betrieb, Würzburg
2131/3130-543210

For Dorothy and Lister,
who taught true appreciation
of the natural world.

Preface

From this high promontory, the landforms of the Sonoran Desert take on awesome proportions. The mesas, buttes, cinder cones, basalt flows, mountains, and valleys, all carved and modified by water in this dry place, must be measured in kilometers and millions of years. Even the colors are dazzling. The volcanic rocks, altered by ancient hydrothermal activity, glow a warm orange and yellow in the October sun. The bright, clear light illuminates each tiny crevice etched by weathering and erosion in the cliffs. Several hundred meters below and about a kilometer away the river rolls, a brown silt-laden ribbon on the floor of the gorge. The water rustles so quietly that I can hear it only when the wind dies. In the distance, sharp mountain peaks rake the bottom of the ocean of air where streamers of clouds stretch over the horizon to the ocean of water.

The field is a fitting place to write the preface for a book on geomorphology because of the importance of the field experience in the development of the science. Dramatic landforms and processes, especially in drylands, have excited the imagination and intellect of artists, writers, and scientists. Each observer has explored a different route to knowing and understanding this thin envelope that is the contact between sky and earth. Descriptions of these striking landscapes have appealed to cataclysmic forces, operation of machine-like processes, and even random occurrences governed by happenstance. The meanings attached to these places have included their definition as the homes of devils and gods, as wastelands or wonderlands, as places of desolation or of beauty. While meaning may reside in the experience of the individual, from a collective scientific perspective it is possible to begin the process of explanation.

If geomorphology is to progress to the stage of a mature and useful science that can successfully explain water-related processes in drylands, it must combine the field experience of perception, classification, description, and measurement with effective theory building. In the analysis of fluvial processes in dryland environments, geomorphology has produced a wealth of basic data in most subject areas (although relatively few geographic areas are included). Enough research is available to make possible the search for generalizations and the development of embryonic theory. That theory can take a variety of forms, but as with all theory it should include a language, a series of law-like statements, and a body of supporting testable data.

The primary purpose of this book is to begin the development of a geographic theory for modern dryland rivers by organizing the generalizations available from previous research into a connected intellectual framework. From this assembly of ideas comes a broad perspective on dryland rivers as manifestations of the interactions of three landscapes: a landscape of energy, a landscape of resistance, and a landscape of geomorphic work. The interactions among these landscapes (or the spatial distributions of relevant physical measures) produce water and sediment processes and resulting landforms. Vegetation and direct human intervention are major modifications to the landscapes that alter the processes and forms. This perspective forms the outline of a general theory and is the outline of this book.

The book is not a literature review. The twelve hundred references following the text do not exhaust the relevant literature even in English. I have attempted to sample research from non-English-speaking parts of the world, but of necessity many works are not included here. I have also included a critical evaluation of some humid-region literature from a dryland perspective because the development of theory for dryland rivers depends in part on the importation of ideas developed for humid regions.

A secondary purpose of this book is to put my own research into some context. After a decade and a half of research on dryland rivers, with the results published in journal articles, book chapters, a monograph, research reports, and legal testimony, it seemed that I had produced a series of sketches that were linked together in my own mind, but perhaps not in anyone else's. This book represents an attempt to assemble and organize those intellectual sketches into a single landscape painting. It was my intention to produce a volume for use by other scientists, engineers, planners, environmental decision-makers, students, and educated laypersons.

None of the ideas expressed in the following pages is strictly my own. Interchange with my colleagues in the geographic, geologic, engineering, agricultural, planning, and legal communities produced this work. A complete list of all those to whom I owe a debt of gratitude would be a lengthy one. I hope that the citations in this work perform three functions for my professional colleagues: first, to recognize this connection of my work to theirs; second, to compliment them; and third, to express my appreciation to them.

Four people early in my career had profound but perhaps not obvious influences on this work. Norbert P. Psuty introduced me to the excitement of geomorphology, and invested his time and effort in me at a very early stage of my career. Donald R. Currey guided my early field research in the American West. George H. Dury educated me in the art and science of scholarly writing. James C. Knox taught me science as practiced by the geomorphologist. I can never adequately thank these people for what they have given me except to say that my life has been richer for having known them, and to offer this book as an expression of appreciation.

Patricia Gober, my wife and colleague on the faculty at Arizona State University, has also contributed to this work through numberless philosophical discussions. Her intellectual and personal support during the production of this volume have been sources of strength and happiness. I am deeply grateful to her for all this and much more.

Superstition Mountains, Arizona
October 1987 WILLIAM L. GRAF

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1.1 Fluvial Geomorphology

1.1.1 An Overview

One of the most startling paradoxes of the world's drylands is that although they are lands of little rain, the details of their surfaces are mostly the products of the action of rivers. To understand the natural environments of drylands, deserts, arid, and semiarid regions of the earth is to understand the processes and forms of their rivers. Because over one third of the earth's surface is generally considered arid (Cooke et al. 1982, p. 5), and because at least one fifth of the world's population lives in such areas, the subject of fluvial geomorphology in arid environments has direct significance for human welfare. The purpose of this book is to relate the present understanding of fluvial processes in arid environments in a manner that specifies our present knowledge as well as our uncertainties.

Practical considerations of an economically developing world community are balanced by another major benefit of the exploration of river processes and forms in drylands. The natural beauty of dry ecosystems and the landscapes that support them have stimulated the mind of mankind from earliest times. If it is true that to know and understand a thing is also to admire and appreciate it, then the study of fluvial geomorphology of dry environments is an esthic as well as a scientific pursuit.

Although fluvial geomorphology of dry environments may seem to be a hopelessly limited topic, the explosion of natural scientific knowledge makes the limitation practical and desirable. Studies of the earth-surface processes have been under way since the time of Herodotus almost 25 centuries ago, but the present conception of the field of "geomorphology" developed only after about 1890. According to Roglic (1972) and Tinkler (1985) the word first appeared in German literature in 1858 and later in American works (McGee 1888a, b). Defined as the study of earth surface forms and processes, geomorphology is largely an intellectual child of the twentieth century. For example, a survey of 12 leading earth-science journals that published geomorphologic papers shows that during a 5-year period, there were about 4,540 papers pertaining to geomorphology (Costa and Graf 1984).

With the general subdivisions into fields of study related to dominant processes, more geomorphologists probably study fluvial phenomena (those related to running water) than any other, so that the extant body of literature is now enormous. Fluvial geomorphic literature reflects the input primarily of geographers and geologists, but closely related work also occurs in the fields of engineering, planning, forestry, soils, agriculture, and hydrology. Twenty years ago it was possible to produce a volume largely subsumming the knowledge about fluvial processes (Leopold et al. 1964, as an example), but now treatises must be more limited in scope.

In addition to limiting treatment of fluvial geomorphology to dry environments to make the subject more manageable, a special approach to river processes is important for arid regions because many of the basic concepts in the larger field of fluvial studies were developed in humid regions. The transfer of these humid-region concepts, theories, and practices to arid regions is problematic because the magnitude and frequency of many environmental processes in general are not similar between the two regional types. Therefore, a review of fluvial processes in arid environments is in part a critique of the applicability of knowledge gained in humid regions.

Finally, geomorphology is like all sciences in that its object is to determine generalizations about known phenomena so that predictions can be made about unknown phenomena. In recent decades, however, investigations of fluvial processes in arid environments have all too often appeared piece-meal, so that it would appear that a contribution might be made by attempting the construction of integrated theory in the subject. Such formulations are in part the objective of this book, though the effort represents only a tentative first approximation. The following pages therefore represent an attempt to impose an admittedly arbitrary order on a sometimes chaotic body of research.

1.1.2 Distribution of Drylands

Theoretical definitions of dryland regions are many and varied, but their general application results in similar regions on the surface of the earth (UNESCO 1979). Most hydro-climatic definitions relevant to the problem of regionalizing fluvial processes rely on the analysis of precipitation and temperature or some combination of the two. Although the Koppen climatic classification system is a widely used approach for the regionalization of climates (see Espenshade 1978, pp. 8–9 for a simplified example), a more sophisticated system proposed by Thornthwaite and modified by Meigs (1953) is most commonly used to define drylands.

In Thornthwaite's view, the most significant aspect of climate is the interaction among rainfall and its seasonality, soil moisture, and potential evapotranspiration (reviewed by Oliver 1973, pp. 58–59). Thornthwaite and Mather (1955) proposed a climatic index defined by

$$Im = [(s-d)/PE]100, \tag{1.1}$$

where Im = the index value, s = excess of monthly rainfall over potential evapotranspiration and storage in the soil during wet months, d = deficit of rainfall plus available soil moisture below potential evapotranspiration in dry months, and PE = potential evapotranspiration (Adams et al. 1979, p. 16). Thornthwaite's index is essentially the aridity index of Budyko, the ratio of radiational energy available for evaporation to the total energy required to evaporate the actual rainfall (Sellers 1965, p. 90).

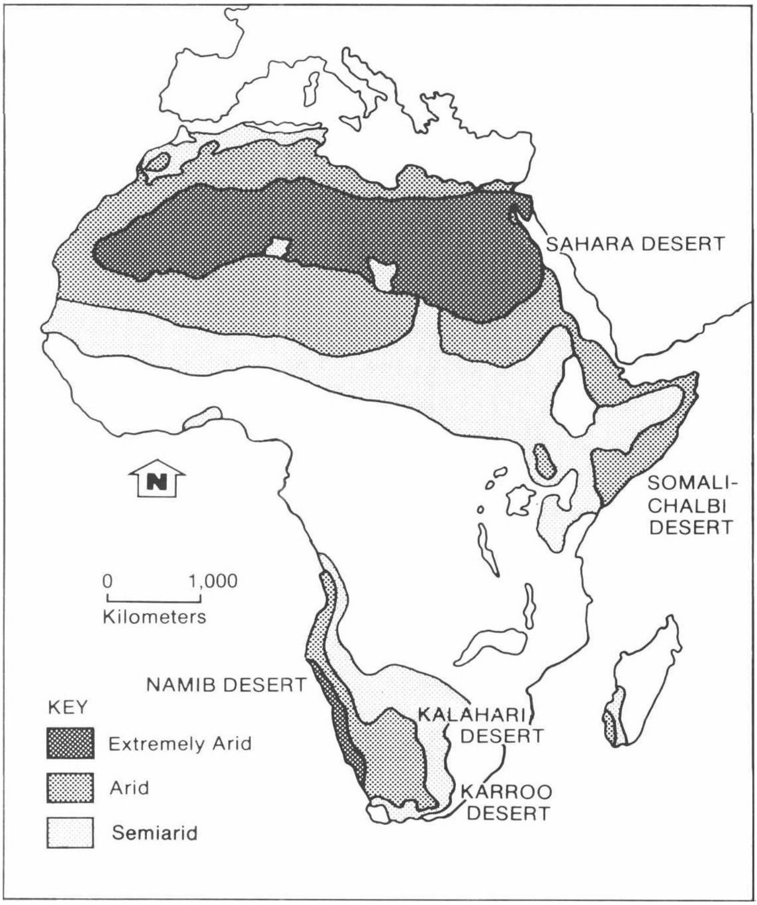

Fig. 1.1. Drylands of Africa. (After Adams et al. 1979)

Meigs (1953) established an interpretive scale of values for the Thornthwaite index, and named various classes according to specific values of the index. The maps of the regions Meigs defined as extremely arid (where 12 or more months without rainfall is the record), arid (where the index Im < −40), and semiarid (−40 < Im < −20) are the most widely used geographic definitions of drylands (Cooke et al. 1982, p. 5), and are adopted for use in this book (Figs. 1.1–1.6).

In subsequent discussions, the specific terms extremely arid, arid, and semiarid will be used as defined by Meigs (1953). Drylands is a collective term referring to regions with any of these conditions. Generally, the term desert will be avoided, since it is more a botanical than a hydro-climatic concept.

Drylands occur in specific places because either they are isolated from ocean moisture sources or because they are located beneath semi-permanent high pressure systems (Figs. 1.1–1.6). In western North America, western South America, and Australia, interior lands are separated from oceans by some of the highest mountain ranges on the two continents. Prevailing on-shore winds

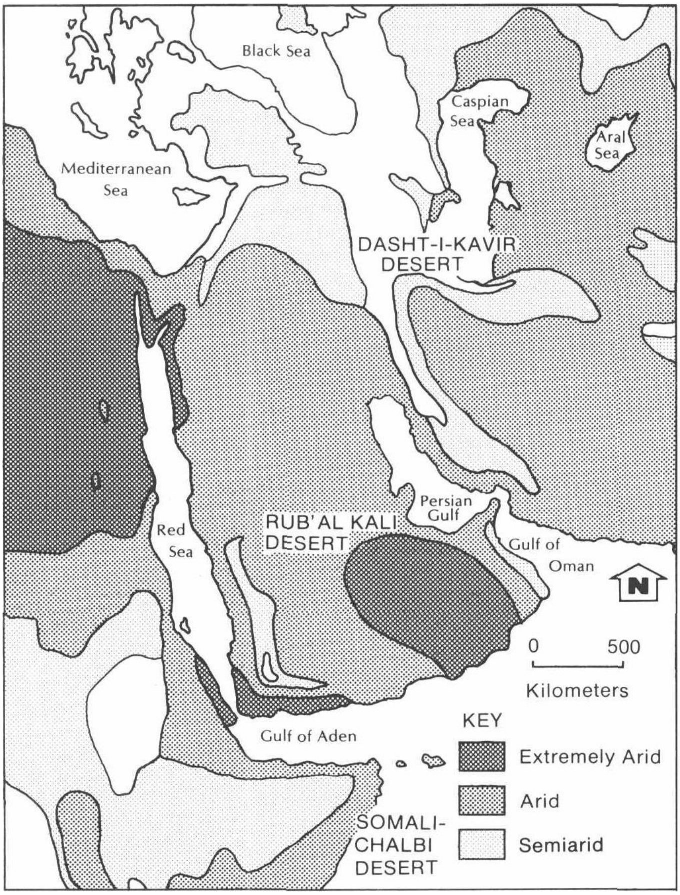

Fig. 1.2. Drylands of Southwest Asia. (After Adams et al. 1979)

cannot transport their moisture to the interiors because they are forced upward over the ranges, and concomitant cooling releases most of their moisture on the mountains (Gilman 1965). Hence, relatively rainy coastal zones contrast with arid inland zones.

Of equal importance are the belts of semi-permanent high pressure generally centered on the latitudinal lines 30 degrees north and south of the equator (Chang 1972, pp. 21–42). These high pressure zones are characterized by air decending from upper elevations as part of the global circulation system. The result is that cloud formation and precipitation mechanisms are suppressed, and rainfall is sparse irrespective of terrain conditions. Southwestern Africa, north Africa, Australia, and southwest Asia experience these atmospheric conditions and are locations of some of the most extensive arid regions of the world.

The boundaries of arid and semiarid lands are not sharply delineated on the landscape, but occur as highly mobile transition zones of uncertain location. These zones change from one year to the next as atmospheric circulation systems