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Avijit Gupta
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PART I

THE TROPICAL ENVIRONMENT

1 Introduction

The tropics are my element, and I have never been so constantly healthy as in the last two years.

Alexander von Humboldt

1.1 Geomorphology in the tropics

In tropical geomorphology we are constantly surprised by new discoveries. Currently, we have a limited understanding of the geomorphic processes, landforms and sediment in the tropics. Furthermore, the rapid, ongoing anthropogenic development in the tropics continues to modify landforms and operating processes and change the rates of erosion and sedimentation from the expected natural norms. Geomorphology in the tropics provides twin opportunities to discover new facts and to apply such information to managing the environment for a sustainable future. Tropical geomorphology thus has a tendency to look forward rather than look back exclusively at past landforms.

The tropics are in essence a climatic region, although the only shared meteorological component across the belt of low latitudes is high temperature. Considerable climatic variations exist across the tropical zone: the most impressive of which is the variation in rainfall. The annual total, the seasonal pattern and occasional synoptic disturbances all vary across the tropics. The Amazon lowlands, the Rift Valley of Africa, Raub al Khali of the Arabian Peninsula, the Ganga–Brahmaputra Delta, the wetlands of eastern Sumatra and a considerable part of the Red Heart of Australia are all areas of low elevation in the tropics, but they exhibit huge differences in rainfall.

The tropics can be divided into two primary units based on annual rainfall: the humid tropics and the arid topics. The transition between the two can be sharp (for example, where an orographic barrier prevails), or gradational (with a subhumid zone in between). About half of the tropical land surface is humid, with the annual rainfall exceeding annual evapotranspiration. The rest is subhumid or arid. Certain climatic characteristics, such as high temperature, high intensity of rainfall and high potential evapotranspiration are generally associated with the tropics but do not occur with the same intensity everywhere.

Formally, the tropics can be defined as an area of radiative surplus at the Earth–atmosphere interface, bounded by anticyclonic circulations near the 30° north and south latitudes (Reynolds, 1985). The margin of the tropics is best perceived in a pragmatic fashion as a fluctuating boundary, between 30 and 35 degrees of latitude. It is an area

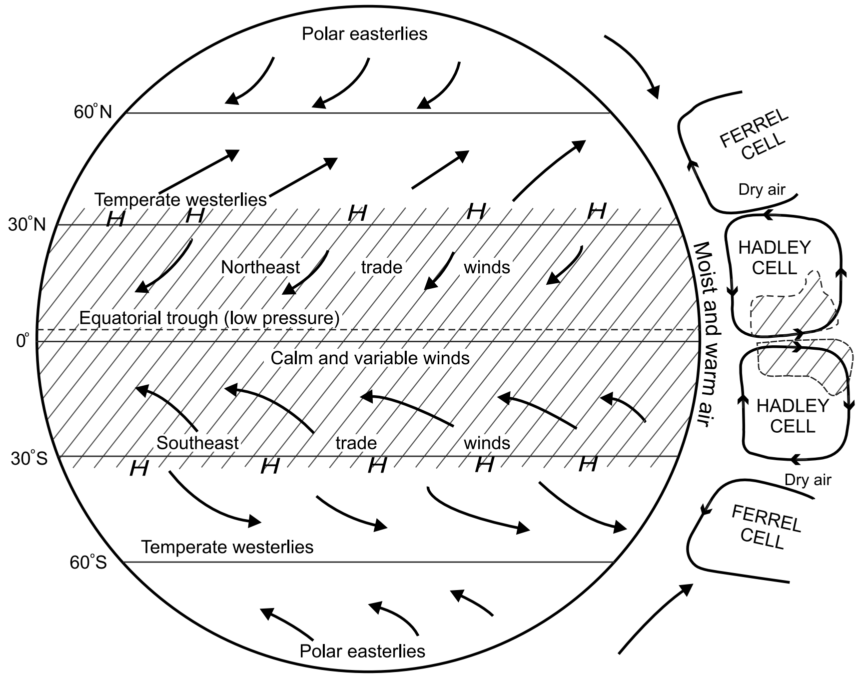

Fig. 1.1 Major pressure belts and wind systems of the Earth. Shaded area approximately indicates tropics and subtropics. The vertical circulation of air is shown diagrammatically towards the right of the figure

over which the Hadley Cell operates, and the three-dimensional pattern of air movement shows a distinct separation between the Hadley and the Ferrel Cells at these latitudes (Fig. 1.1). The two traditional latitude markers, identified as Tropic of Cancer and Tropic of Capricorn, are not effective boundaries. Thus, the tropics, as defined in this book, also include areas conventionally identified as the subtropics.

Nearly 60 per cent of the total surface area of our planet lies between the 35° N and S latitudes. The tropical oceanic expanse is huge and plays an important role in influencing the climate of the world (Graham *et al.*, 1994). In spite of such extensive coverage, case studies from the tropics have contributed very little to mainstream theories in geomorphology.

Like climate, landforms and operating geomorphic processes are not the same across the tropics. The tropics are an assemblage of active tectonic belts, ancient cratons, alluvial valleys and subsiding deltas (Fig. 1.2). The early tropical geomorphologists did not always recognise such wide-ranging geologic variations, putting too much emphasis on the hot and humid climate as the prime controlling factor. As a result, the tropics used to be perceived as a set of climo-morphogenetic landforms, where physical features are primarily controlled by the ambient climate. The characteristics of the landscape were generally explained by assuming that they evolved in a hot and humid location over a very long period of time. The arrival of the theory of plate tectonics finally destroyed such concepts.

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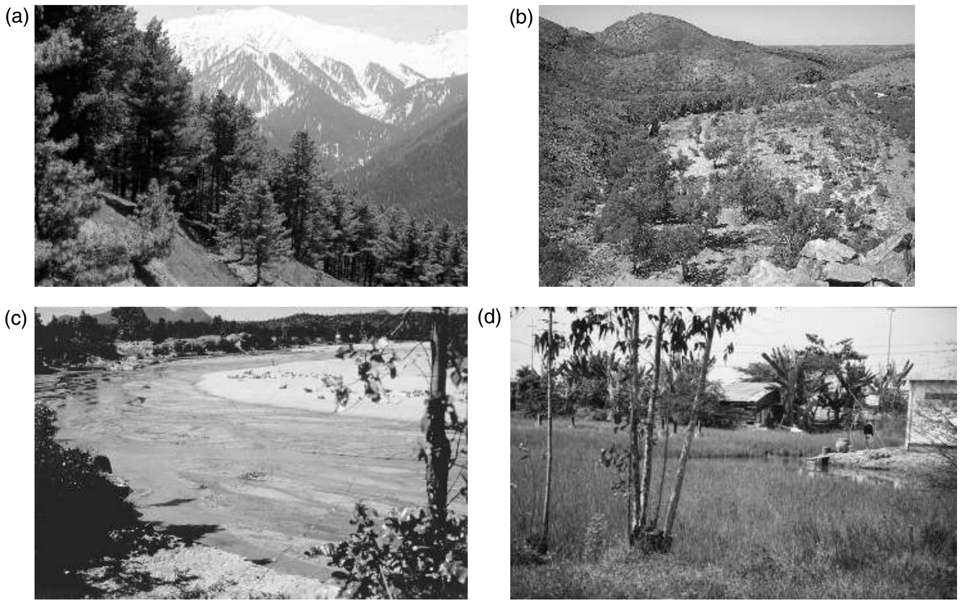

Fig. 1.2 Varieties of tropical landforms: (a) Western Himalaya Mountain (high tectonic mountains); (b) arid Central Australia (arid landscape on ancient craton); (c) Auranga River, India (seasonal river on Gondwana rocks). From Gupta and Dutt, 1989. (www.borntraeger-cramer.de); (d) Mekong Delta (river-dominated part of a Holocene delta). Photographs: A. Gupta

Landmasses that are now in the tropics were once part of a single large continent on Earth, known as Pangaea, before its break-up about 200 million years ago. The present tropical landmasses (Australia, part of Southeast Asia, the Indian subcontinent, Africa, South America) and a number of islands of various dimensions together with the cold Antarctica constituted the southern part of Pangaea, known as Gondwana or Gondwanaland (Box 1.1). The present physical landforms reflect the entire geological history from Pangaea. This includes the break-up, the nature of drifting of the separated landmasses towards the equator, the geomorphic processes that began to operate once they reached the tropical zone, and the current highly active anthropogenic modification of both landforms and processes. Traditionally, the Indian Peninsula was viewed as an excellent example of an assemblage of tropical landforms that had developed over a long period of time in a warm humid climate. The peninsula, however, had a near-polar location before the disintegration of Pangaea. It then drifted through a wide range of latitudes to reach its present position and collided with the Eurasian Plate to form the Himalaya Mountains and fuse with the Asian landmass (Fig. 1.3). The present monsoon system and operating geomorphic processes developed mostly after the collision. Landforms and subsurface sediment in the tropics were also modified by climate and sea-level changes during the Pleistocene. Like elsewhere on Earth, landforms in the tropics are multifactorial in origin. The history of the landmasses goes back in time beyond Pangaea, but we will start our narrative from this particular supercontinent.

Box 1.1 Gondwana/Gondwanaland

From the Upper Palaeozoic to the Cretaceous, the entire continental landmass of the Earth formed a single continent called Pangaea. The southern half of Pangaea is collectively known as Gondwana or Gondwanaland, both names being used interchangeably. Gondwana was located south of the equator and a very large part of it stretched to high southern latitudes near the South Pole, which, as expected, was a very cold location.

As Pangaea broke up, Gondwana disintegrated into several units which moved away from each other. These fragments of Gondwana are now known as Antarctica, Australia, India, part of western Asia, Africa, Madagascar and South America. Except for Antarctica, all land masses drifted towards the equator and to warmer locations. The evidence of their former connections lies in the similarity of the rocks of the Permo-Carboniferous age found on all these continents.

At the base of such rocks is a glacial sediment, clay with boulders, the lithified form of which is called a tillite. This occurs on all continents that were part of Gondwana, indicating the former cold location and presence of glacial ice. The rocks also contain a characteristic cold-weather flora called *Glossopteris* (from the Greek for tongue-like, as the leaves of the flora resembled long tongues) and other associated flora such as *Gangamopteris*. *Glossopteris* is found in rocks of this age on the continents that constituted Gondwana, thereby indicating their past union and the shared glacial climate. From the Upper Carboniferous to the Jurassic, similar climatic conditions and rock types occurred on the continents that formed part of Gondwana. Such rocks were studied in central India by H. B. Medlicott, who first used Gondwanaland as a term in 1872 in an unpublished report (Krishnan, 1982). The name is derived from a part of central India which carries the diagnostic geology and used to be the kingdom of the Gonds. The tillites were followed by thick deposits of fluviatile or lacustrine origin, in places deposited in structural basins and bearing coal seams. These in turn were followed by other sedimentary rocks but without coal. Volcanic lavas are found on top of the Gondwana rocks in a number of places. The similarity of geology in locations now widely separated from each other indicates the existence of a single landmass which later disintegrated.

The present physical features reflect geological history. For example, extensive areas in Australia, the Indian Peninsula, Africa and South America are inherited from Gondwana. As a result these areas are underlain by old, hard, generally metamorphosed rocks on which weathering, soil formation and erosional processes operate very slowly. These are the cratons. Elsewhere the edges of the continents may reflect the history of their passage and collision with other plates. The Himalayan range was formed following the collision of India with Eurasia. The Andes was formed by subduction of the Cocos, Nazca and Antarctic Plates underneath the South American Plate. These active margins now form tectonic mountains which are the source areas of big rivers that drain the continents. The rivers flow from high active margins across the continent towards the continental margin that is tectonically passive. These are quiet places where the big rivers deposit their sediment and build deltas. The Amazon, the biggest of all, is an excellent example. The present river came into existence after the formation of the Andes to flow eastward along a structural low and to build a huge delta on the passive side of the continent into the South Atlantic Ocean. In contrast, Africa has not drifted much and its margins are passive, with tectonic mountains occurring only at the extreme northern and southern ends. Africa, therefore, is a continent with old surfaces at various levels. The present landscape on any continent thus reflects its past history inherited from Gondwana, marginal modifications that reflect the nature of its movement since the break-up of Pangaea, and other happenings over time such as large eruptions of basalt (western India) or the formation of rift valleys (East Africa).

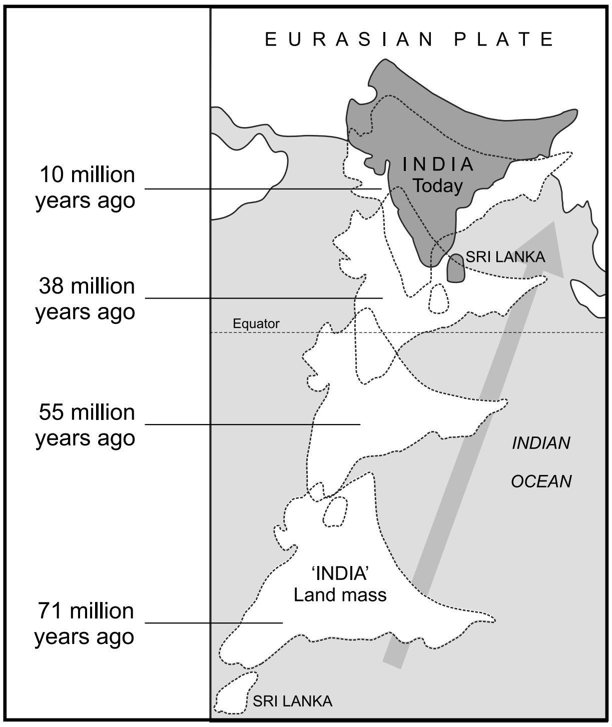

Fig. 1.3 Drifting of the Indian plate. Adapted from US Geological Survey figure

1.2 Traditional tropical geomorphology

We know very little about the geomorphological knowledge that existed before the arrival of the Western maritime powers in the tropics. There must have been some, given the widespread successful utilisation of water as a resource, often with designed structures. After the establishment of global maritime sailing routes, the tropics were visited from the last decade of the eighteenth century with astonishment, enthusiasm and insight by Western scientific explorers including Alexander von Humboldt, Alfred Russel Wallace and Charles Darwin. This revolutionised primarily the biological sciences, but remarkable observations on regional geology and geomorphology were also registered. We may recall Humboldt's work in tropical South America or Wallace's description of the landforms of Southeast Asia. In 1859, the year *On the Origin of Species* was published, Darwin was honoured by the Royal Society for his research, and the citation listed his contribution to the geology of the Andes. We should also recognise the work of German geologists in various parts of the tropics: Sapper, Passarge, Bornhardt and others, and that of Dana (1850) from the United States in the Pacific. Dana provided a very early discussion on fluvial processes in the tropics. Later, as part of colonial governance, land- and soil-related information was collected, processed and published in a number of countries. Some of these are now classics, such as reports by Buchanan on Indian laterite, and Mohr and Van Baren on tropical soils (Buchanan, 1807; Mohr and Van Baren, 1954). Topographical maps and official geological reports also started to appear. All these later became very useful for studying local geomorphology.

Up to the second half of the twentieth century, or even later, the teaching of geomorphology in the tropical countries was carried out using standard textbooks written for European or North American students (Gupta, 1993). These did not reflect the ambient landscape and local or regional examples were rarely furnished. Large Andean landslides, coral reefs or tropical karsts were mentioned, but the common reference to tropical geomorphology was the climo-morphogenetic regions of Peltier (1950) or De Martonne (1951) or Büdel (1982). Krynine's (1936) approach was different; he studied the relationship between geomorphology and sedimentology in the humid tropics. The general emphasis was on landforms, and climatic characteristics were used to explain their nature and distribution. For years, geomorphological studies in the tropics were driven by two concepts: the climo-morphogenetic region and the Davisian cycle of erosion. The typical tropical landscape was perceived as a stable erosion surface, studded with low hills (called inselbergs or bornhardts) and underlain by soil and deeply weathered rock. Geomorphology was a description of landforms.

1.3 Modernisation of tropical geomorphology

Tropical geomorphology started to lose its essentially climate-based approach in the second half of the twentieth century. The writings of L. C. King (1951, 1962) on the South African scenery led the practitioners to think in terms of rock types and geological history as important explanations for the ambient landscape. About this time, a number of case studies started to appear that were more in line with process-based approaches prevalent in other parts of the world. Early examples include Ruxton and Berry (1957) on granite weathering in Hong Kong, Fournier (1960) on erosion rates, Simonett (1967) on earthquake-generated landslides that eroded the mountains of New Guinea, and Coleman's study (1969) on the morphology and sedimentation of the Brahmaputra River. These papers highlighted rationality, methodology and excitement in tropical geomorphology. Case studies became easily available from this time, due to the publication of several regional collections (Jennings and Mabbutt, 1967; Davies and Williams, 1978; Dardis and Moon, 1988; Warner, 1988). Prior to these, regional studies were difficult to find as they were published in local journals, commonly with a limited circulation. All this overlapped with the diffusion of modern mainstream concepts, techniques and textbooks (Horton, 1945; Strahler, 1952a, 1964; Leopold *et al*., 1964; Young, 1972) to the practitioners in the tropics. From the 1970s, such diffusion, along with the presence of process-oriented geomorphologists in the tropics, led to a tremendous increase in the quantity and quality of papers in tropical geomorphology. Textbooks in process geomorphology with a tropical slant started to appear (Douglas, 1977; Faniran and Jeje, 1983; Thomas, 1994), and tropical case studies also were mentioned in mainstream textbooks (Schumm, 1977). The new research indicated that the same geomorphic processes operate in the tropics as elsewhere, but they operate at different rates and with varying intensities (Selby, 1993). Research publications were generally in English but, given the large number of tropical countries, research and institutional reports were also published in a number of other languages. This at times constituted linguistic demands on the tropical geomorphologist. For example, a researcher on the lower Amazon Basin is handicapped without knowledge of Portuguese. The diffusion of ongoing research across the tropics was limited before electronic communication became common. The free distribution of the *Tropical Geomorphology Newsletter*, published from 1986 to 1996, used to help. As computer-based searches became common, the problem of inadequate diffusion of knowledge largely disappeared.

1.4 Structure of tropical geomorphology

Tropical geomorphology highlights three areas:

1. geology, landforms and geomorphic processes across the tropics
2. the passage of water and sediment from the mountains to the coast, mainly via river systems: a large volume of moisture is in circulation over the humid tropics
3. anthropogenic alteration of the natural rates and processes, associated environmental degradation, and related geomorphic principles for better environmental management.

We can break these down to a list of specific topics that should be studied (Table 1.1). As this table indicates, a combination of common and exotic factors characterises tropical geomorphology.

It is necessary to emphasise that although climate acts as an important control on landforms and processes in both humid and arid tropics, the operating processes and the characteristic landforms at a particular location reflect a diversity of causes. Gardner *et al*. (1987), writing on locations in Central America and the Caribbean, focused on three selected topics among a diversity of regional geomorphic processes and landforms: karst; alluvial fans; and tectonism along convergent plate margins. This was justified, as these three are the most characteristic of the region, representing the dominance of lithology, a rapid fluvial depositional process and neotectonics. Elsewhere in the Caribbean, other factors such as hurricanes or volcanoes dominate local geomorphology. The fascination and challenge of present-day geomorphology in the tropics lies in the recognition of such regional diversity.

Geomorphological rates are high in the humid tropics, especially in high-relief areas (Fig. 1.4). A number of world maps of suspended sediment yield have been published since the 1980s (Milliman and Meade, 1983; Walling and Webb, 1987; Milliman and Syvitski, 1992). All such maps show elevated rates for most of the humid tropics. Working with a data set of 280 rivers, Milliman and Syvitski found very high sediment rates for South Asia and high oceanic islands, and identified basin relief as a very important factor behind the high sediment yield. They interpreted relief as a surrogate for tectonism and proposed that 'the entire tectonic milieu of fractured and brecciated rocks, oversteepened slopes, seismic and volcanic activity … promotes the large sediment yields from active orogenic belts' (Milliman and Syvitski, 1992: 539–540). The high sediment yield is also due to intense tropical rain falling on such mountains, for at least part of the year.

Table 1.1 A summary description of tropical geomorphology

Topic	Description
Major controls in geomorphology	Location of tectonic belts, volcanoes, cratons, alluvial valleys, deltas, etc. as determined by plate tectonics Wind pattern and rainfall systems (especially tropical storms) Distribution of vegetation cover Deforestation, agricultural expansion, urbanisation and channel controls
Major operating processes; same as in other parts of the world, but different in rates and relative importance	Tropical weathering, and its effect on slope material and river load Mass movements on tropical slopes Rivers, a number of which are seasonal and prone to flooding Glacial, glacio-fluvial and fluvial processes operating on high mountain slopes Fluvial and aeolian processes in the arid tropics Coastal processes, presence of mangroves, salt marshes and coral reefs Tectonic movements and volcanism
Quaternary inheritance	Pleistocene glaciations of the tropical mountains Climate change Sea-level changes affecting coasts and lower river reaches
Present and future changes	Common anthropogenic changes Global warming and climate change

The natural rates of erosion, however, are not necessarily in operation everywhere. Parts of the tropics have a long history of intense human occupation leading to modification of the natural landscape. This process has accelerated since about 1950 and the present landforms and processes may be natural only in certain areas. For example, destruction of the tropical rain forest has increased the annual sediment yield in Southeast Asia from less than 10^2 tkm^{-2} to more than 10^3 tkm^{-2} (Gupta and Krishnan, 1994; Gupta, 2005a). Transfer and storage of this excessive sediment sequentially affect hillslopes, gullies, rivers and coastal forms. Satellite images, as on the cover of this book, show sediment plumes at the mouth of rivers whose basins are undergoing significant anthropogenic changes (Gupta and Krishnan, 1994). The high rate of erosion and sedimentation therefore is a function of relief, climate and land use – all three.

Destruction of vegetation cover and accelerated instability of slopes lead to excessive sediment transfer and storage in the river systems. In contrast, thousands of large dams globally block the passage of sediment downstream, the total world volume rising to about 50 km^3 of sediment each year (Mahmood, 1987). We need to keep all such modifications

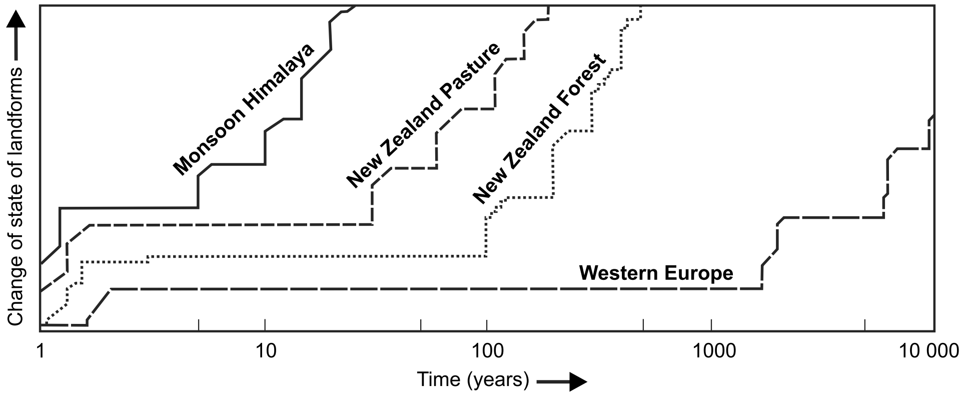

Fig. 1.4 Change of state of landforms. Note according to his estimate, a combination of high relief and climate leads to approximately the same amount of change in landforms in ten years in the Himalaya Mountains as has occurred since the end of the last glacial advance in Western Europe. The graphs for New Zealand compare the role of the third factor in accelerating geomorphic processes: land use. From Selby (1993). By permission of Oxford University Press

in mind. Environmental problems in the developing countries that constitute most of the tropics involve land and water degradation to a large extent. The recognition and solution of such problems depend on geomorphological knowledge of the area. Current tropical geomorphology therefore combines scientific research with the application of its findings for the betterment of people. Such a linkage will become crucial with climate change that is expected to alter the rate and intensity of operating geomorphic processes.

In one of the crime fictions of Ellery Queen (1934), a detective was described as a prophet looking backwards. A tropical geomorphologist frequently needs to be that in order to explain a particular landform. At the same time, the geomorphologist also needs to operate in the conventional prophetic fashion, predicting the future determined by anthropogenic alterations including climate change. It is a challenging but wonderful occupation.

1.5 Structure of the book

This book is divided into three sections. The first section introduces the physical background of the tropics against which the operating geomorphological processes are subsequently presented. An introduction to the geological framework of the tropics and landforms (Chapter 2) is followed by a discussion of tropical hydrology (Chapter 3), and an account of vegetation cover and land use including a brief introduction to anthropogenic modification of the land and water (Chapter 4).

Part 2, dealing with geomorphic processes, starts with weathering that prepares slope material and river sediment for subsequent soil formation and removal (Chapter 5). This is followed by chapters on slopes and slope processes (Chapter 6) and tropical rivers (Chapter 7–9). The coastal environment is discussed next: first as a general case (Chapter 10) and