I. Introduction

1: The Objectives and Structure of this Book

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During the last decade, increasing international attention has been directed towards the environmental problems of the humid tropics, with the focus on the fate and management of the surviving tropical rain forest. In terms of water management (also termed water resource management in this volume), several rigorous reviews concerning the hydrological effects of tropical forest conversion to other land uses have emerged (Hamilton with King, 1983; Hamilton, 1988; Bruijnzeel, 1989, 1990) with particular emphasis on the changes in water yield and related land management issues connected with soil and nutrient loss.

The possible impacts of large-scale conversion of forests on climate have also been elevated in research priority within the Amazon Basin. Of particular interest are the changes in the land surface's energy balance and water vapour transfer. This new attention has led to the establishment of more ambitious field experiments in the Basin in conjunction with remote sensing. The data obtained from both sources are being used to calibrate General Circulation Models (GCMs) (Shuttleworth, *et al.*, 1991).

These developments, however, only cover a relatively narrow part of the spectrum of water management issues. Within the developed world, the remaining problems have received less publicity, based on the false perception that being the humid tropics, the supply of potable water is more than adequate to meet the needs of the region. As a later presentation by Manton & Bonell (this volume) will outline, the distribution of tropical rainfall can still be highly variable over space and time, arising from various mechanisms that disrupt the atmospheric pressure patterns. Consequently, droughts are not unknown.

The cores of the region's environmental problems, however, are essentially socio-economic, resulting from the escalation in population across the humid tropics. By the year 2000, it is anticipated that 33% of the world's population will be living in this region and that this percentage will continue to rise dramatically well into the Twenty-First Century. The resulting biophysical impacts already are causing a series of water and related land management problems. A consequence is also a major reduction in the apparent plentiful supply of potable water.

Gradwohl & Greenberg (1988) provided a succinct review of the socio-economic causes inducing large-scale clearance of tropical forests. The "equation" is a complex one with over 30 variables involved. One key factor is the increase in demands on the water and land resources of the region for food production to meet the requirements of the escalating population. A consequence is poor land management over large areas which is resulting in degradation in the quality of both groundwater and surface water. Erosion is a prime cause but the concentration of various water-borne chemicals through irrigation and even poor waste management from rural communities also aggravate the overall water quality. There is an inevitable decline in agricultural productivity when erosion removes a large proportion of the plant-available nutrients stored in the top 20 cm of soil. The future of food production therefore, must depend to a great extent on better knowledge of intensified production and not simply on the continued expansion of production into previously unused (and more marginal) areas. Improved management in soil and water conservation and erosion controls are vital to the success of this area.

With the possible exception of Africa, a consequence of the population increase has been the rapid expansion in urbanization, most notably in South East and South Asia and Latin America, and the totally inadequate facilities to service the water management requirements of such urban centres. This includes storm drainage and both surface and ground water pollution induced by rapid industrialization and inadequate solid waste management. Urban development, with all of its social, economic and physical implications, may well be one of the most serious problems the region has to face.

Tropical islands also require special attention because their small area and limited water resources result in an exacerbation of the various management problems associated with both urban and rural areas.

Finally, a consequence of the contracting supply of potable water is that the linkage between water supply and health stands out as *the* most critical issue facing both the rural and urban areas.

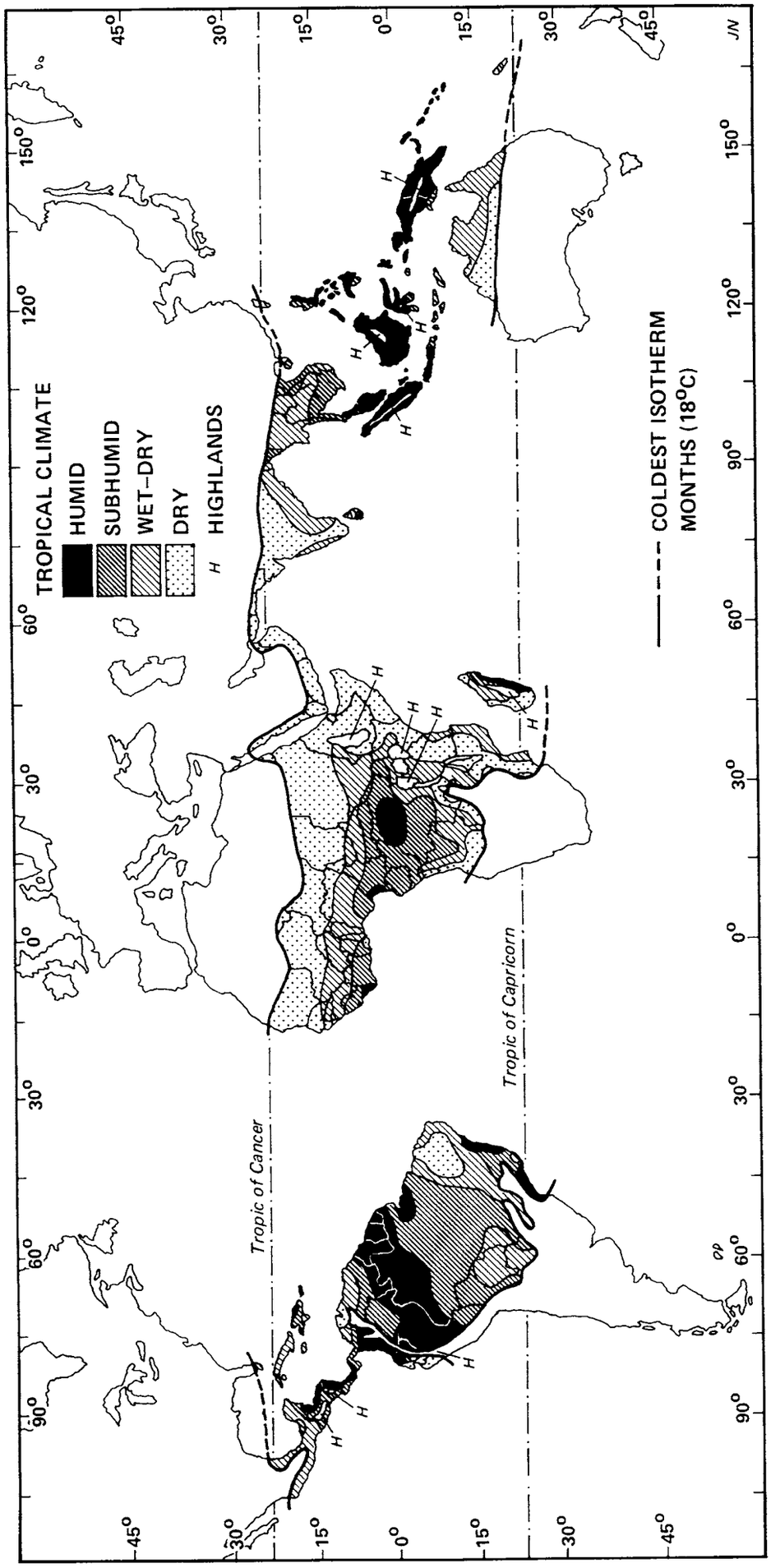

Figure 1: World map showing the distribution of the three climatic sub-types (humid, subhumid, wet-dry) of the humid tropics. Also shown is the dry tropical region.

THIS BOOK

This book is divided into seven Sections, including this Introduction. The initial sections of the book provide the physical basis of the humid tropics through a consideration of various systematic areas. A holistic approach is also adopted by the inclusion of the regional hydrology of the continents and islands. The interface between physical processes and human issues is later described as a basis for evaluating the complex water management issues of the region.

The Koppen and Thornthwaite methods of climatic classification are those most commonly used in the literature. We have followed, however, the definition of the humid tropics as developed by Chang and Lau (1983) as part of the UNESCO International Hydrological Programme's Projects IHP-II Projects A1.10 (Hydrology of Humid Tropical Regions) and IHP-III Project 4.2 (b) (Hydrology of Humid Tropical Areas). The definition is summarized in Appendix A.

In that definition, the region is subdivided into three climatic sub-types on the basis of the number of their "wet" months, viz, Humid Tropical (9.5 to 12 months), Subhumid Tropical (7 to 9.5 months) and Wet-Dry Tropical (4.5 to 7 months). Figure 1 presents the world map of these climatic subregions.

It is significant that the Humid Tropical sub-type is only the most geographically extensive across the "maritime continent" (Ramage, 1968) of the Indonesian archipelago, and is particularly limited in distribution within Africa. Each of these three climatic sub-types not only serve to differentiate vegetation and agricultural land-use patterns, but also have implications for hydrological research. Each sub-type may be considered as a possible climate analogue where at least some of the hydrological characteristics are sufficiently similar to permit the successful transfer of methodology from one area to another.

SECTION II: HUMID TROPICS SETTING

A summary by Manton & Bonell initially presents the various meteorological systems which control the climate and rainfall variability across the humid tropics. Several points emerge from this chapter. Rain-producing synoptic systems are different between the monsoon and non-monsoon regions, and it important to define each system rigorously through an understanding of the atmospheric circulation. Of great interest to hydrologists is the description of various mechanisms producing rainfall at a mesoscale, and various oscillations (30–60 day, Southern Oscillations, Quasi-Biennial) which cause rainfall to be more variable in time and space than commonly credited, especially within hydrological literature. An underlying theme of this chapter is the consequences of high net radiant energy available which produce more severe storms, e.g., tropical cyclones, higher rainfall intensities and a higher frequency of devastating floods in comparison with the temperate areas.

A major problem for both meteorological and hydrological research, and water resource management is the relative absence of comprehensive datasets within the humid tropics. Manton & Bonell introduce this issue, but the following chapter by Manley & Askew provides a detailed assessment of the operational problems involved with data collection. Their contribution provides various environmental and socio-economic reasons why gaining good quality data is difficult in most humid tropical countries, in contrast to developed countries, where such databases are taken for granted. The location of this chapter near the front of the book serves to bring to the reader's immediate attention the basic hydrometric needs of the region – a subject of increasing neglect in the increasingly adverse socio-economic climate and yet highly significant if we are to improve our understanding of the climatology and hydrology. The chapter also serves as mandatory reading both for economists and politicians who are responsible for decision-making. It is also appropriate for the emerging generation of younger scientists, who were recently criticized by Philip (1991) for placing too much faith in computer modelling at the expense of supporting field data collection and experimentation to validate such models.

The concluding chapter of Section II by Klemeš provides a personal philosophy of the current inadequacies of existing hydrological methodology with its roots in hydraulic engineering and the challenges in producing an improved methodological framework for the humid tropics. He particularly focuses on three areas. First, the need for greater consideration of non-stationarity over time in the major geo- and bio-physical processes to more appropriately address the hydrological impacts of the population explosion within the region, through increasing urbanization and conversion of forests into agricultural land. Second, he examines the development of quantitative eco-hydrology, given the importance of vegetation in the hydrology of the humid tropics. A thorough understanding of the quantitative relationships across the soil-vegetation-atmosphere spectrum is particularly highlighted by Klemes, including adequate parameterization of the land-surface processes for modelling the dynamics of water and energy fluxes. His third point logically follows, with the call for a dynamically sound understanding of macrohydrology to address the needs of atmospheric General Circulation Models (GCMs), and the problems of scale within many existing methodologies associated with process hydrology.

Klemes particularly stresses the inadequacies of many water resource engineering techniques, both from a philosophical standpoint and as to their suitability for application to water management problems of the humid tropics. He calls for a new avenue in hydrological education with alternative roots in the earth sciences to produce specialists who can meet the water-related geo- and bio-physical problems of the humid tropics.

SECTION III: REGIONAL HYDROLOGY

The six chapters of the Regional Hydrology section attempt to present a summary of the hydrology and water resources of the

world's major humid tropic regions. Chang's chapter dealing with the Asian region presents information concerning the variability of rainfall, including the reasons for the presence of droughts in what is normally considered to be a very moist area. Chang notes that in this region, studies of evaporation in mountain areas also are scarce, and that, as the temperature and psychrometric parameters decrease with elevation, the energy term rapidly loses its importance as the aerodynamic term assumes a dominant role in high mountains. Furthermore, although the monsoon atmospheric circulation governs the variability of the river flows in this region, there are still significant regional variations. From the standpoint of river regimes, four general regions may be recognized: (1) typhoon-prone, (2) equatorial, (3) tropical, with a distinct and prolonged dry season, and (4) areas affected by intense tropical cyclones (bordering the Bay of Bengal). In addition, heavy soil erosion poses a serious problem in this region, as evidenced by the exceedingly high sediment loads in many rivers. Besides the very high rainfall erosivity, rapid conversion of forests in recent years has been a major contributing cause to such sediment loads.

The chapter by Stewart looks specifically at the hydrology and water resources of the Wet-Dry Tropical region of northern Australia and makes contrasts with Papua New Guinea, which is mostly in the Humid Tropical Region, except for the Highlands and parts of the southern coastal strip. Stewart notes that while northern Australia's rainfall is markedly seasonal, occurring during the summer monsoon, and can be highly variable, Papua New Guinea, by comparison, receives very reliable rainfall from the four major rainfall-producing mechanisms (convection, convergence, orographic and cyclonic). An inverse association between evaporation in northern Australia and median annual rainfall is also noted. In Papua New Guinea, evaporation measurements have been made only in limited areas and for limited time periods so that extrapolation to other parts of the country are questionable. The mean annual runoff in Papua New Guinea has been estimated at 2,100 millimetres, with the runoff coefficients ranging from 0.25 to 0.75. The variability of the annual runoff in northern Australia is greater than other humid tropical regions, with the annual values ranging from over 1,000 millimetres on the east coast to under 25 millimetres inland.

Griesinger and Gladwell discuss the hydrology and water resources of the Latin America and Caribbean region. They note that this region is probably the world's most humid of the world, although the Humid Tropical sub-type is only the most extensive in the northern part of the Amazon Basin ,with smaller patches elsewhere. South America has some of the highest rainfall and runoff amounts of any continent. And because most of the rivers of the region are rainfed, the seasonal river regimes are mostly directly related to the rainfall distribution. In the Northern hemisphere, the incidence of tropical hurricanes can confuse the regionality of the rainfall amounts because of the random occurrence with which the islands and mainland are impacted by these cyclonic systems. Throughout the mainland of Latin America, the major physiographic factor affecting the water resources is the mountain chain that runs from Mexico to Chile. This causes the rivers generally to be longer and larger on the Atlantic side, and shorter and with much higher gradients on the Pacific side. Notable exceptions are to be found in Brazil, and in northern Bolivia and Paraguay where several rivers have their headwaters in the Central Plateau of Brazil.

Up to the present, the various human impacts on water resource uses have been mainly concentrated along the coastal areas of South America. Lesser impacts have been observed on the larger river systems, except primarily the response to regulation of the rivers for irrigation and hydroelectric power development. Nevertheless, the major land-use changes now occurring within the Amazon Basin suggest that, in the future, the various impacts on the surface waters will intensify and become of more serious concern.

The chapter by Molion looks specifically at the Amazon region. He notes that the hydrological processes in Amazonia vary widely from year to year due to natural changes in the atmospheric conditions. The chapter reviews the dynamic mechanisms that produce rainfall in the region. Subsequently, the characteristics and fluctuations of rainfall arising from the inter-annual variability of the large-scale atmospheric circulations associated with the El Niño - Southern Oscillation (ENSO) phenomenon are discussed along with the effects of blocking patterns within the atmospheric circulation, both of which cause variability in space as well as time. The effects of large-scale deforestation on local hydrology as well as the possible impacts on global climate are also considered.

Ayibotele identifies data availability and accuracy as major constraints in defining the hydrology and water resources of Africa. He also notes that except for their physical characteristics, information on the African lakes is also inadequate. Likewise, while a generalized knowledge about the sediment yield for the African region has been put forward, it is only tentative because of the data constraints. These conclusions reinforce the earlier operational problems described by Manley & Askew.

The high rates of population growth are also increasing the areal extent of land degradation within Africa – in response to the basic food requirements. As a result, Ayibotele discusses the impact of this land-use change on the water balance components and linkages with severe floods and droughts, increasing erosion and the deterioration of water quality.

Falkland and Brunel describe the hydrology and water resources of tropical islands. They note that island water resources (especially of the smaller ones) are often very limited. Many have no surface water resources and rely on limited groundwater resources in the form of thin fresh water lenses. They examine some of the major hydrological and water resource issues of small islands, with the main topics discussed being water resource assessment, water use, and water resource development and management. Approaches to resolving some of the major problems are also provided.

SECTION IV: PHYSICAL PROCESSES

Section IV provides the scientific basis of the book through an examination of the physical processes related to the hydrological cycle, erosion and sedimentation, water quality and freshwater biology.

Bonell with Balek systematically reviews process research connected with the water balance components: rainfall, evaporation, water movement in the unsaturated zone, groundwater and runoff generation. The broad field of the subject matter requires a more extensive coverage than found in other contributions of this Section.

The application of process hydrology within the context of various land-use conversions and their impact on the water balance are then considered. This includes some consideration of "physically-based" modelling techniques which have potential for application in land management issues. Throughout this review, several gaps in research are identified. Consequently, a large proportion of this chapter considers the technology-transfer of various methodologies and research findings from mostly temperate latitudes which need further testing in different humid tropical environments. Bonell with Balek conclude by describing the early results from macrohydrology projects connected mostly with the Amazon Basin. In accordance with an underlying theme of this chapter,this final section particularly highlights the meteorological and climatological linkages with process hydrology at different scales.

As indicated in Section V by Wurzel, groundwater is an important source of potable water (with its chemical and microbiological quality) for reducing the transmission of water-borne diseases. The modest pumping and reticulation costs, and the minimal treatment required are causing an increasing interest in the development of groundwater resources in the humid tropics. A separate chapter devoted to the physical basis of groundwater is therefore presented by Foster and Chilton. The principal features of five main types of groundwater system are described, viz, major alluvial formations, basement regoliths, intermontane valley-fill, active volcanic areas, and karstic limestones. Furthermore, the problems which arise in their exploitation and management are also highlighted. Foster and Chilton appropriately conclude on the vulnerability of shallow groundwater to pollution from a range of human activities.

Natural freshwater wetlands and lakes have a broad range of management applications such as flood control, groundwater discharge and water supply. Bullock initially presents material pertaining to natural lakes such as long-term changes in water levels, aquatic weeds and modelling of lake/river interactions. Greater emphasis, however, is placed on the status of tropical wetland research – drawing on the author's own experience in southern Africa. Different modelling strategies, empirical water balance studies and wetland influences upon downstream flows are considered. Linkages between hillslope hydrology processes (Bonell with Balek, this volume) and the hydrology of wetlands are also clearly demonstrated by Bullock. The author concludes by addressing the appropriate strategies for optimal wetland management and associated research needs.

Erosion and sedimentation by water-borne processes is a key element in land degradation following forest conversion. The chapter of Rose initially outlines the scientific issues involved in erosion and sedimentation, and subsequently presents arguments for a major change in direction concerning soil erosion modelling methodology beyond the commonly used Universal Soil Loss Equation. In this way, our present understanding of the physical processes are better represented in modelling for application at a hillslope scale. There is an acceptable bias in this account towards methodologies used in the development of the author's own model, which also has the advantage of being currently tested in the humid tropics of South East Asia. Nevertheless, how such theoretical developments within the Rose model relate to alternative methodologies are still discussed, with particular attention given to the Water Erosion Prediction Program (WEPP) in the USA. Evident from this review is that the field application of these new soil erosion models are at an earlier stage of development in contrast to hillslope hydrology models. Specific parameters, e.g. the J parameter of the Rose model, still require continued research effort under controlled experimental conditions to obtain a comprehensive understanding of their physical interpretability. In addition, at the present stage of technology, some of the parameters are difficult to measure during storms under field conditions. Rose concludes by considering erosion processes and modelling at a catchment scale, including the adaptation of physically-based hillslope hydrology models based on digital terrain models for predicting areas of erosion and deposition. The author also highlights developments using isotopic tracer methods for evaluating soil erosion and deposition, and recent work in the sediment behaviour and management within humid tropical catchments.

The standard of water quality has direct implications for health, agriculture and the environment. Roche isolates the main problem areas for scientific research and the related aspects of institutions and adverse management which have caused them. Water quality problems considered include the impact of industrialization through the introduction of microtoxics; organic (faecal) waste water from both urban and rural communities; and changes in salt and nutrient cycles plus the over-use of pesticides due to adverse land and water resource management. The impact on human health of water-borne pollution and aquatic vectors and larvae responsible for water-borne endemics is also one of the core messages of Roche's account. The problem of setting the appropriate water quality standards and even more important, the provision of adequate laboratory facilities to monitor such standards is strongly highlighted. A brief survey is also made of current experiences in water quality modelling within the humid tropics.

The final chapter of this Section by Golterman *et al.*, describes the water chemistry and freshwater biology of tropi-

cal surface waters. Initially, the chemical composition of river water and its variability, both in space and time, are considered. The utilization of freshwater nutrients for plant growth as well as photosynthetic activity are then considered. Various reactions on the water chemistry by plants are also reviewed in terms of dissolved oxygen, carbon dioxide and the recycling of plant decomposition products. The concluding part of this chapter concentrates on several aspects of the consumer's food web. They describe the web components, the invertebrate vectors of human disease and the various environmental factors controlling the food chain. Special consideration is also given to freshwater fisheries.

SECTION V: PHYSICAL PROCESSES – HUMAN USES – THE INTERFACE

This Section deals with the physical processes involved in the human uses of the water resources of the humid tropics, and their interactions. In the chapter by Lal, attention is primarily on the agricultural and forest hydrology aspects. He focuses primarily on the Humid Tropical and parts of the Subhumid Tropical regions associated with the narrow geographic band of latitudes 5°to 7° north and south of the equator, where tropical cyclonic influences are absent. The gaps in research knowledge related to the water balance, erosion and sedimentation and change in land-use are addressed. He also makes brief reference to the applications of remote sensing and geographic information systems, and to the problem of scale.

In the following chapter, Fleming describes the limited Australian experience in changes in land-use hydrology within the Wet-Dry Tropics, and also devotes some attention to temperate Australian work, e.g., the hydrology of eucalyptus trees, so as to evaluate the potential for technology transfer. He concludes that experimental data and design methods should be reviewed for their relevance to problems in tropical hydrology, using the simple balance equations for water, energy, salt and sediment. He stresses that an attempt should be made to develop predictive models that are parsimonious with respect to the detailed specification of environmental boundary conditions, but at the same time are realistic with respect to relevant processes. This, he suggests, should allow the extension of data from experimental sites concerned with manipulation of a limited suite of external variables.

The chapter by Gladwell reviews the situation currently to be found in the urban areas of the humid tropics. He argues that if the critical water management problems of these areas are to be successfully addressed, the water resources will have to be viewed as a continuum, rather than in a piecemeal manner – as is too often now done. The chapter reviews the various regions of the humid tropics, and presents the problems that have accumulated, their causes, and suggests directions in which the solutions will be found. Those directions include technical as well as nontechnical approaches. He concludes that unless both are considered in an integrated fashion, the outlook for the urban areas of the humid tropics is not good. Decision-makers, planners, engineers and the public need to be aware that the results of narrowly focused and limited approaches to the solution of the various water-related problems have consequences far beyond the obvious limits of the urban area.

In the chapter by Prost, it is argued that innovative approaches will be needed to overcome the professional barriers between health specialists, engineers and decision-makers. The main health benefits accrue, it is argued, from the availability of unlimited quantities of water, whatever its quality; and unnecessarily stringent quality standards may be counterproductive since they may reduce the quantities available, delay the supply or increase its cost. It is pointed out that despite the momentum created by the International Drinking Water Supply and Sanitation Decade, coverage of the world population with adequate supply services is far from satisfactory. Progress can hardly keep pace with the increases in population. The majority of rural people in poor tropical countries are not served and there is little prospect of achieving universal coverage in the foreseeable future. There is concern expressed that a shift in resources from other vital sectors such as nutrition and health could offset the benefits of a safe water supply. It is argued that engineering techniques and non-medical interventions in water management can be shown to be the most cost-effective measures for controlling diseases of economic importance.

Wurzel's chapter concentrates largely on rural water supplies and sanitation as they relate to health in the humid tropics. It is argued that by interrupting the transmission cycle of water-borne and water-washed diseases, these interventions can contribute significantly to improved health in the developing world. The issues, trends, strategies and philosophy for the future are explored, with the accent on low-cost and appropriate technologies – a number of which are evaluated. Particular emphasis is given to groundwater as the primary water resource. As in the chapter by Prost, emphasis is placed on the fact that the installation of drinking water and sanitation facilities has hardly kept pace with the increasing population. The unfortunate paradox is that it is the most affluent and accessible populations which have been the first to receive attention. Wurzel observes that those remaining will be progressively more difficult to reach.

SECTION VI: MANAGEMENT ISSUES

The special nature of the humid tropics and the serious problems arising from a rapidly expanding population and economic activity have important consequences for water resource management (alternatively termed water management in some chapters). As defined by Hufschmidt in the opening chapter, water resource management is a process through which water resources are put to beneficial uses of humans and actions are taken to reduce detrimental effects of pollution and

natural hazards on humans and natural systems. The management process consists of the key stages of assessment, planning, and implementation, each of which has its own problems and issues, and, taken together, provide the structure for developing the management strategy, as presented by Hufschmidt.

Water resource management issues in the rural resource-related context are analyzed in depth by Tejwani with a focus on watershed management. A historical perspective is used to examine the programmes and policies promoting water management. Selected management issues involving population pressure, integrated planning, research and financing are discussed. The urban context of water resource managment is treated in considerable detail in three additional chapters. Initially, Low examines urbanization trends and the accompanying water problems of the ASEAN region, primarily of Thailand, Malaysia, Indonesia and the Philippines. Water pollution, sedimentation, solid waste accumulation and flooding are important and growing problems of cities in this region. Lindh and Niemczynowicz subsequently emphasize the many obstacles to achieving effective and environmentally-sound management solutions. They call attention to innovative technical options involving recycling, wastewater reuse, and low-cost non-structural alternatives that are based upon sound ecological principles. The final urban contribution of Lee presents a revised urban water supply and sanitation strategy based on four lessons learned from the International Water Decade: technology alone is not enough, appropriate, low-cost technology is required, innovative cost recovery is a must, and community participation is a key element. The concluding chapter of this Section by LeMoigne and Kuffner emphasizes the particular issues of the humid tropics associated with excess water and flooding, the unique potential for hydroelectric power and the traditional emphasis on rice irrigation. Further details of the content of this Section are presented in the opening summary chapter on water resource management by Hufschmidt.

SECTION VII: APPENDICES

Section VII consists of four appendices. Appendix A contains the document prepared by Chang and Lau which provides the basis for the definition of the humid tropics used in this book. The report was originally presented at an IAHS Symposium in Hamburg, Germany in 1983, and later included in a May 1986 UNESCO Report entitled *Hvdrologv of Humid Tropical Regions.*

In Appendix B there are four reports compiled by the rapporteurs from the working groups developed during the International Colloquium at James Cook University of North Queensland, Townsville, Australia in July 1989. Each report deals respectively with the following topics: hydrological processes (Bullock), erosion and sedimentation (Nogueira), water quality (Stewart) and water management (McCauley and Van Beek).

Finally, Appendix C contains lists of the members of the Organizing and Co-ordinating Committees for the Townsville International Colloquium and Appendix D acknowledges the institutions who sponsored the Colloquium.

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II. Humid Tropics Setting

2: Climate and Rainfall Variability in the Humid Tropics

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ABSTRACT

Although the absolute variability of weather features in the tropics is less than that at higher latitudes, tropical weather and climate are rich in variation on time scales from the diurnal to decadal. Moreover, the climate of the tropics is closely linked to the behaviour of the upper oceans, which provide inertia to the climate system and which act as a moisture source for convective heating of the atmosphere. Latent heating from convection is a common factor in all aspects of variability in the tropical climate. The links between the major causes of variability are reviewed in the present work.

INTRODUCTION

Weather at the mid-latitudes is clearly associated with baroclinic fronts and other synoptic features that are controlled by the earth's rotation. It is, therefore, natural to assume that the tropics, where these Coriolis effects are small, should have weather with a distinctive lack of structure. Charney & Shukla (1981) quantify this effect by showing that the temperature variance increases away from the equator. This apparent lack of structure is supported by the observation that persistence is a useful weather forecast in the tropics. Indeed, operational short-range weather forecasting is generally no more accurate than persistence (Holland *et al.,* 1987). But this result suggests that the basically quiescent weather is punctuated by intermittent and unpredictable events. In this paper, these events, their interconnections and progress on improving our understanding of them are reviewed.

One manifestation of the apparent lack of features in tropical weather is the observation that the temperature generally does not vary greatly, even following the passage of a weather system. This lack of change occurs because there is normally a local balance between diabatic heating from condensation and adiabatic cooling from lifting as the air flows out through the weather system. Such a localized vertical response is restricted by the earth's rotation at higher latitudes.

Significant weather features are described in the present work in order of increasing time-scale. They are diurnal convection, easterly disturbances, tropical cyclones, the 30–60 day oscillation, monsoons, quasi-biennial oscillations, El Niño-Southern Oscillation (ENSO) events and the greenhouse effect. The time scales of tropical weather events stretch from hours to decades. The longer-term variations tend to modulate the local response of shorter-term features. Thus the Australian monsoon is weaker in an El Niño year and tropical cyclones are more likely to form when the environment is preconditioned by convective disturbances, such as the 30-60 day oscillation.

At all scales, the atmospheric behaviour is closely coupled to the behaviour of the upper ocean. The tropical oceans are the source of the moisture that condenses and so heats the atmosphere to drive the global circulation. Similarly, the wind stress and latent heating (or cooling) at the ocean surface due to the atmospheric fluxes drive the upper ocean circulations. Any explanation of the tropical weather and climate must account for this coupling between the ocean and atmosphere. The importance of this link is recognized in the establishment of such projects as the Tropical Ocean Global Atmosphere (TOGA) project by the World Climate Research Programme (WCRP) in 1985.

ATMOSPHERIC CIRCULATION IN THE TROPICS

A common component of all the weather features in the tropics is convection and associated rainfall. Because the tropical atmosphere is almost invariably near a state of conditional instability, the overall dynamics is essentially a balance between latent heating and radiative cooling. The background large-scale flow for the tropics is the Hadley circulation, which