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Impacts of Global Change on the Hydrological Cycle in West and Northwest Africa

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Foreword

Securing an adequate food supply and safe drinking water for people around the world is undoubtedly one of the greatest challenges of the 21st century. As much as 50% of the world's population relies on water supplied from transnational water systems. Additionally, water availability may be compromised by large-scale climate and land use changes that have significant impacts on global and regional water cycles. Together, these issues present a series of new challenges that necessitate developing sustainable strategies for water management and livelihood security.

The German Government and its Federal Ministry of Education and Research (BMBF) have played an active role in addressing these global challenges. To address these global issues, BMBF launched the Global Change and Hydrological Cycle (GLOWA) pilot program in 2000 as a part of the BMBF framework program on sustainability research. The objectives of GLOWA are to develop, test, and apply new integrative, interdisciplinary methods and models in individual projects. The methodologies and simulation tools developed under the program will contribute to long-term sustainable water management at the local and regional (river basins of approximately 100,000 km²) scales, taking into account global environmental changes and socio-economic conditions. Hence, Germany reaffirms its commitment to the United Nation's International Decade for Action "Water for Life" and to the Millennium Development Goals of halving the proportion of people without access to safe drinking water by 2015 and of eradicating extreme poverty and hunger. GLOWA is a prime example of programs intended to achieve these goals.

Two of the five GLOWA projects, GLOWA IMPETUS and GLOWA VOLTA, focused on river catchments in Africa, a continent which is generally considered highly vulnerable to adverse impacts from Global Change. Both projects successfully demonstrated the benefit of targeted research on application-oriented solutions to imminent water-related and food-related problems resulting from Global Change.

In this book, GLOWA IMPETUS provides a thorough overview of the wealth of its research results, how they were implemented into models and how meaningful projections of future developments can be established in sectors such as climate, water, agronomy, socio-economics, anthropology, and health. It has long been recognized that sustainable development must be based on scientific knowledge. The present book provides a good example of how GLOWA IMPETUS transferred interdisciplinary and integrated research into application-oriented, decision support tools. A coherent presentation of research results in this comprehensive publication will help to make its approaches, results, and "lessons-learned" known to a range of researchers and to the public.

Rainer Müssner
Federal Ministry of Education and Research / Germany

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It has to be underlined at this point that this work would not have been possible without the help, cooperation, and support of many individuals, colleagues, government/non-government organizations, and institutions too numerous to list here. For further details, see: www.impetus.uni-koeln.de/projekt/kooperationspartner.html.

We would like to extend a special thanks to the German Embassies in Benin and Morocco for their advice and support, to Thierry Lebel and Christian Depraetere from the CATCH/IRD project for their generous help in setting up the project in Benin, and to all members of the respective Steering Committees in Benin and Morocco for their valuable contributions during numerous meetings. Finally, we would like to thank all the reviewers of the IMPETUS project. Their constructive comments and guidelines significantly contributed to the success of IMPETUS.

Cologne and Bonn, March 2010 The Editors

Preface

Africa is an economically poor continent, contributing less than 2% to the world gross national product while holding more than 15% of the world population, with the population growing rapidly. Despite efforts by African countries, the amount of freshwater and food available per capita has steadily decreased over the past several decades. The reasons for this are numerous and complex. Africa has suffered from continual neglect over the centuries, both from the socio-economic and scientific points of view. Thus, it would be quite unrealistic to believe that solutions to water-related problems could be simple and achieved quickly. We are convinced that sustainable solutions to Africa's most pressing problems have to be science-based and implemented in a holistic and integrated approach that involves relevant disciplines from the natural, socio-economic, and health sciences. Another important element of sustainability is the efficient transfer from *science to application*. The IMPETUS research project has pursued this pathway successfully for almost 10 years and was structured into three research phases, as described below.

The first project phase was dedicated to data acquisition and to the comprehensive assessment of the *status quo* (i.e., the identification of existing water-related problems together with their underlying physical processes and interdependencies). In the second phase, qualitative and quantitative models were adapted or newly developed. Projections of future developments were derived from scenario calculations and from expert knowledge. In the third phase, tailored tools for local decision makers were developed to enable sustainable natural-resource management. A supplementary phase concentrated on the implementation and operationalization of research results. The transfer of knowledge and the intense capacity development undertaken were intended to facilitate African citizens to take responsibility for sustainable development.

The present publication entitled, "Impacts of Global Change on the Hydrological Cycle in West and Northwest Africa", is based on the long-term applied research experience of IMPETUS in two African watersheds: the Ouémé catchment in Benin and the Drâa catchment in Morocco. This publication is targeted for the following audiences: (i) scientists interested in state-of-the-art interdisciplinary research on the hydrological cycle who would like to obtain insight into neighboring disciplines; (ii) application-oriented scientists interested in knowledge transfer to application from an exemplary integrated research project, including how such a project could be designed conceptually, and (iii) decision makers with some scientific background who wish to learn how sound research results can be incorporated into the decision making process in the context of natural resource management and Global Change.

We hope this publication is welcomed and accepted in both scientific and non-scientific communities, and that it spurs interest in application of water management principles to aid Africa.

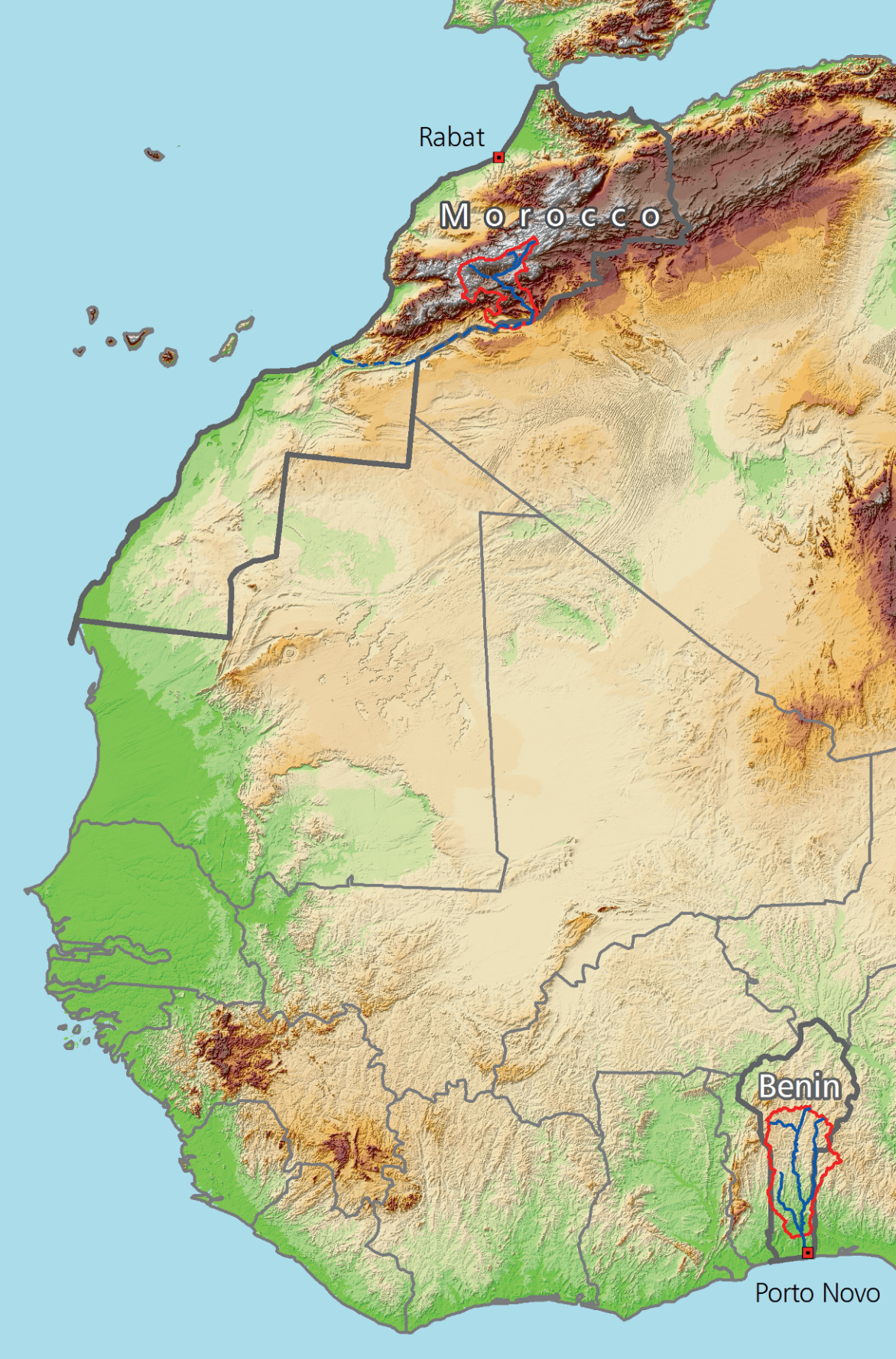
Cologne and Bonn, March 2010 The Editors

PART I - Fundamentals and process understanding

PART II - Future projections and decision support

Part I

Fundamentals and process understanding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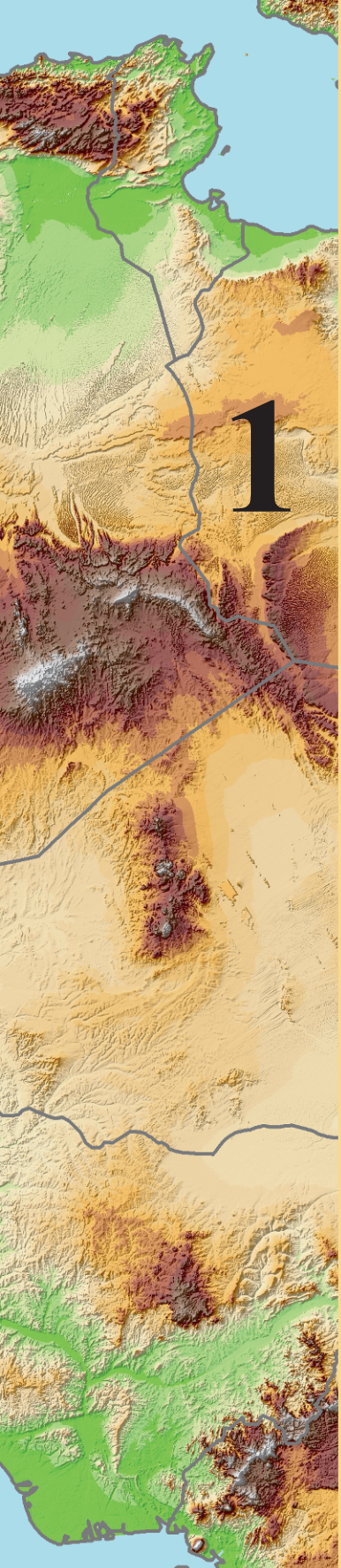

1 Introduction

I-1 Introduction

P. Speth and A. H. Fink

Human activity affects the Earth's climate mainly via two processes: the emission of greenhouse gases and aerosols and the alteration of land cover. Climate research conducted in the past several years indicates that most of the observed increase in global average temperatures over the past few decades is *very likely*[1] due to the observed increase in greenhouse gas concentrations from human activities. It is *likely* that without the cooling effects of atmospheric aerosols, greenhouse gases alone would have caused a greater global temperature rise than has actually been observed. Research also indicates that human influences on the climate are expected to increase in the future, mainly because greenhouse gas emissions will continue to rise. Consequently, global average surface warming is projected for the 21st century. These projections depend largely on the scenarios used to represent greenhouse gas emissions. In general, however, the projected warming is greatest over the land and most high northern latitudes, with relatively less change over the Southern Ocean and parts of the North Atlantic Ocean. Warming is typically projected to be greater in arid regions than in humid regions. Projected precipitation increases are *very likely* at high latitudes, while decreases are *likely* over most subtropical land regions. This projected change in precipitation is a continuation of recent trends.

The above-mentioned projections for Climate Change are based on coarse-grid, global-scale climate models with a spatial resolution that is typically greater than 200 km. These models only consider greenhouse gas forcing and usually do not consider land use changes (or at least only do so in a cursory manner). Climate Change is part of Global Change, which consists of three components: demographic change, global environmental change, and globalization impacts. In this context, environmental change refers to climate variability and Climate Change, land use and land cover change, changes in water availability and loss of biodiversity. Processes behind Global Change are interdependent and interrelated, and they interact in complex ways. Thus, interdisciplinary[2] studies are necessary to find solutions to Global Change-related problems.

Observational evidence shows that many natural systems are affected by Global Change, among which the hydrological system is predominantly influenced. Because of the aforementioned projected large-scale patterns of precipitation and warming, it can be postulated that Global Change will impact the hydrological

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[1] In The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (2007) the likelihood of an outcome or result where this can be estimated probabilistically is defined as follows:
very likely: > 90% probability;
likely: > 66% probability.

[2] An *interdisciplinary field* is a field of study that crosses traditional boundaries between academic disciplines or schools of thought as new needs and professions have emerged.

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cycle and the availability of fresh water. A shortage of fresh water is expected to be the dominant water problem of the 21st century. Water shortages coupled with reduced water quality may jeopardize efforts to secure sustainable development. This may lead to social and political instability in some cases. Fresh water has already become critically scarce in many regions of the world. The global mean water withdrawal per capita has decreased significantly in recent decades. Some countries have renewable fresh water resources under 1000 m^3 per capita per year, which is a value that is commonly accepted as a benchmark for fresh water scarcity. It is estimated that one quarter of the world's population will suffer from severe fresh water scarcity during the first quarter of the 21st century. Therefore, this book focuses on the hydrological cycle in West and Northwest Africa for the following reasons: i) these regions have experienced the most pronounced inter-decadal climate variability of anywhere in the world during the 20th century; (ii) climatic alterations in Africa may impact the European climate via complex atmosphere-ocean interactions in the area of the tropical and extratropical North Atlantic Ocean; and (iii) the study regions contain sub-regions to the north and south of the Sahara that are linked by atmospheric teleconnection processes with regard to precipitation anomalies[3].

Investigations were carried out through an initiative named IMPETUS ('An Integrated Approach to the Efficient Management of Scarce Water Resources in West Africa', in German: '**I**ntegratives **M**anagement-**P**rojekt für einen **E**ffizienten und **T**ragfähigen **U**mgang mit **S**üßwasser in West Afrika'), which was a joint venture of the Universities of Cologne and Bonn, Germany. The work done under IMPETUS was part of a German research program on the global water cycle (GLOWA). GLOWA was launched by the German Federal Ministry of Education and Research (BMBF) and its aim was to develop strategies for sustainable future water management at regional levels while taking into account global environmental changes and socio-economic framework conditions.

Past and present situation

Tropical West Africa has suffered from declining rainfall since the late 1960s. Severe drought periods occurred in the early 1970s and in the first half of the 1980s. The average rainfall deficit from 1971-1990 was about 180 mm/year compared to the 1951-1970 interval. All climatic zones in West Africa have been affected, ranging from the semi-arid Sahel and the sub-humid Sudanese zone south to the humid Guinea coast. In addition, areas to the north of the Sahara desert have experienced a number of dry years since the 1970s. By the end of the 20th century, river discharges in West Africa had decreased by about 40-60% compared to 1951-1970, resulting in water shortages for domestic and agricultural

[3] For the existence of such a link by atmospheric moisture transports out of the area of the Inter-Tropical Convergence Zone (ITCZ) over the Western Sahel zone northward across the Sahara towards the Atlas Mountains, see fig. I-5.2.7.

purposes. These precipitation changes have led to extensive migration. During the rain-rich 1950s and 1960s, water power stations were built along the Guinea coastal zone to supply a substantial amount of energy to West African countries. Low discharges from major tributaries are the main reason for the recent frequent shortages in energy production. The decadal drought at the end of the 20th century clearly demonstrated that climate deterioration can cause a profound decline in the economic and social development of West African countries. A slow recovery of rainfall to near normal conditions has been observed in parts of the Sahel since about two decades. However an unabated drought period has been experienced in the western Sahel. Population growth and projected rainfall declines linked to anthropogenic Climate Change may provide no relief to pressing water problems in the long term – despite the present climate amelioration.

Apart from the per capita decrease in the availability of fresh water, the current situation to the north and south of the Sahara is also characterized by growing populations (e.g., population growth rates greater than 3% per year in Benin), increasing degradation of natural vegetation due to overgrazing (Morocco[4]), increasing demand for firewood, and shifting cultivation patterns (e.g., Benin). Soils have rapidly eroded in Morocco (and to a lesser degree in Benin), and salt content has risen due to intensive irrigation practices. In combination, these issues are likely to accelerate degradation and desertification processes in the coming decades. This situation is aggravated by increasing water demands, mainly associated with high population growth, which dramatically reduces the per capita water availability.

West Africa is one of the most vulnerable regions to desertification in the world. Desertification is characterized by land degradation that decreases agricultural productivity, reduces biodiversity, and degrades the environment, all while diminishing ecosystem resilience. Desertification is creating economic, environmental, and social hardship for millions of poor farmers practicing subsistence agriculture in fragile environments. The desertification of West Africa fuels the migration of people from the north to the south, thereby exacerbating problems in sub-Saharan Africa. This chain of events could potentially lead to social and political instability. Arable lands in this region are estimated to decline by 61% to 0.63 hectare per capita between 1990 and 2025.

Regionalization of climate projections

The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) projected an overall warming trend in Africa and a substantial drying of subtropical North Africa based on global circulation models that use different emission scenario runs to the end of the 21st century. The rainfall trend

[4] This book deals with the water balance in two catchments in Benin and Morocco. Sometimes in the text, it is referred to these countries rather than to the catchment names (see below).

over tropical West Africa for this century is uncertain. For example, a comparison of individual global climate models used in the AR4 reveals considerable differences in their projections of rainfall trends in West Africa. A regional downscaling[5] of global climate models that takes into account land use changes (e.g., deforestation, desertification, vegetation loss, and soil degradation) indicates that a general decrease in rainfall together with prominent surface warming can be expected for sub-Saharan Africa[6]. Although rainfall will decrease north of the High Atlas Mountains and the Antiatlas Mountains, a somewhat wetter climate south of these massifs is suggested for the coming decades[7]. The projected wetter climate is a consequence of tropical-extratropical interactions (TEIs)[8] across the Sahara desert and is in contrast to the trends predicted by the IPCC global models.

The projected rainfall decline in sub-Saharan Africa indicates that the hydroclimate in tropical and subtropical West Africa will be impacted. This change suggests a weakening of the hydrological cycle. The implication of this precipitation reduction is that the decrease in fresh water availability will occur simultaneously to an increasing water demand. Agricultural production and food access are anticipated to be severely compromised. Decreases in agriculturally suitable areas, growing season lengths, and potential crop yields are expected, particularly along margins of semi-arid and arid areas. This condition would further adversely affect food security and exacerbate malnutrition.

Choice of catchments

During the IMPETUS project, thorough investigations of all aspects of the hydrological cycle were carried out along a transect between the High Atlas Mountains and the Gulf of Guinea for two river catchments in West and Northwest Africa: the river Ouémé in Benin and the wadi Drâa in the southeast of Morocco (see fig. I-1.1). These river catchments were chosen according to the following criteria: feasibility (< 100,000 km^2), availability of pre-existing data sets, political stability, relevance, and representativeness. Specifically, the Drâa catchment is typical of a gradient from humid/sub-humid subtropical mountains to arid foothills. The Ouémé basin in Benin is typical of a sub-humid climate ("Guineo-Soudanien") of the outer tropics with distinct dry and wet seasons embedded in a transect that extends from the Sahelian to the Guinean coastal climate.

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[5] For the different downscaling methods see subsections II-3.2.5 - II-3.2.7.

[6] See fig. II-3.2.6.

[7] See fig. II-3.2.12.

[8] See sect. I-5.2.

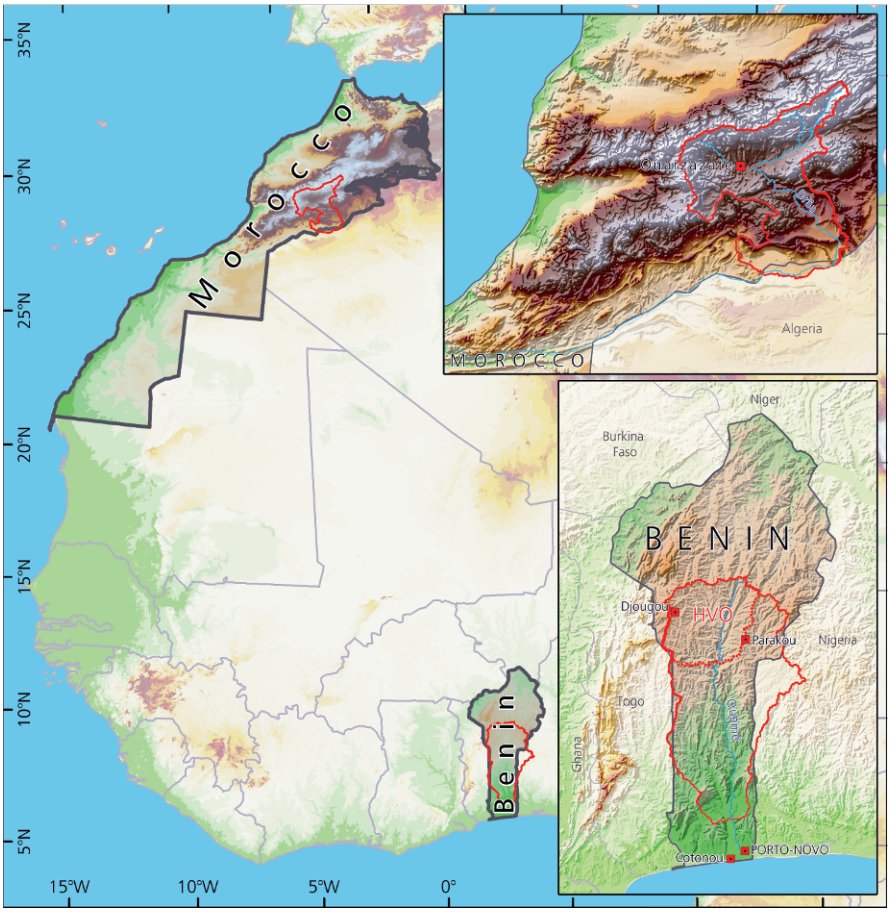

Fig. I-1.1: The two river catchments considered in this study, the Drâa catchment in Morocco and the Ouémé catchment in Benin, are outlined in red. A subcatchment of approximately 100x100 km west of Parakou has been chosen as an area of focused investigations (Upper Ouémé Valley / in French: *Haute Vallée de l'Ouémé* - HVO).

Options for a sustainable development

The overarching goal of IMPETUS was aimed at developing an interdisciplinary, integrative approach to mitigate regional-specific risks of Global Change as they relate to the hydrological cycle of the Drâa and Ouémé catchments. Ultimately, decision makers in Benin and Morocco were given tools that helped them to analyze decision-making problems and the underlying phenomena. This then allowed these parties to assess the impact of their decisions and to implement sustainable management options for the water resources that are so vital to life. The results of these different options can be compared and evaluated for different

scenarios, mainly with the aid of *Spatial Decision Support Systems (SDSSs)* but also with *Information Systems (ISs)* and *Monitoring Tools (MTs)*.

Outline of the book

This book adopts the interdisciplinary and holistic approach necessary to solve present and potential future problems regarding fresh water supplies. Interdisciplinary, application-oriented tasks were accomplished with the help of a unique mix of scientists from the social sciences, natural sciences, and medicine.

Feedback mechanisms in the atmosphere, hydrosphere, biosphere, and anthroposphere were studied under IMPETUS to better understand complex interactions leading to deteriorations in fresh water supplies in West and Northwest Africa. The aim was to identify the steering natural and anthropogenic factors (driving forces) that affect the water cycle, to establish an understanding of the underlying processes, and to assess the extent of their impacts.

Key findings on the basic subjects are presented in Part I of the book, entitled, "Fundamentals and process understanding". Part I begins by providing a detailed overview of the regional impacts of Global Change and of the regional geography. The scarcity of hydro-meteorological and vegetation data for the considered catchments necessitated the design of a customized measurement concept, which is described subsequently. Thereafter, the scientific background of the process understanding, together with the identification of driving forces are provided for the atmosphere, hydrosphere, biosphere, and anthroposphere. Part I forms the basis for Part II of the book, entitled, "Future projections and decision support". Part II focuses on findings surrounding the decision support with regard to future impacts of Global Change on the two catchments. Results are based on special climate and socio-economic scenarios.

2 Impacts of Global Change