IMPETUS
West Africa

An Integrated Approach to the Efficient Management of Scarce Water Resources in West Africa:

Case studies for selected river catchments in different climatic zones

Final Report

Period: 1.5.2000 - 30.4.2003

An interdisciplinary project of the Universities of Cologne and Bonn

30.04. 2003

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Das diesem Bericht zugrundeliegende Vorhaben wurde mit Mitteln des Bundesministeriums für Bildung und Forschung unter dem Förderkennzeichen 07GWK02, mit Mitteln des Ministeriums für Wissenschaft und Forschung des Landes Nordrhein-Westfalens unter dem Förderkennzeichen 223-21200200 sowie durch die Universitäten Köln und Bonn gefördert. Die Verantwortung für den Inhalt dieser Veröffentlichung liegt bei den Autoren.

Contents

Zusammenfassung

Das Gesamtziel der 1. Phase des IMPETUS Westafrikaprojektes ist die Beschreibung, die Analyse und die Quantifizierung der wichtigsten Aspekte des hydrologischen Zyklusses zweier Flusseinzugsgebiete, das eine – des Wadi Drâa in Südostmarokko – nördlich, das andere – des Ouémé in Benin – südlich der Sahara gelegen. Dies wurde durch die einzigartige Konzentration einer Vielzahl von Wissenschaftlern sowohl der Natur- als auch der Geisteswissenschaften innerhalb des Projektes erreicht. Die im Verlauf des Vorhabens gewonnenen Erkenntnisse finden Eingang in die verschiedenen Modellansätze der einzelnen Disziplinen und dienen somit als Basis für die in der 2. Projektphase durchzuführenden Abschätzungen zukünftiger Entwicklung. Nachfolgend werden die wichtigsten Ergebnisse der ersten dreijährigen Förderphase aufgezählt.

Eine der grundlegenden Hypothesen zu Beginn des Projektes war die mögliche Existenz eines klimatischen Zusammenhangs zwischen den Regionen nördlich und südlich der Sahara. Dies bestimmte u. a. die Wahl der Einzugsgebiete. Wir fanden deutliche Anhaltspunkte für die Richtigkeit dieser Annahme aufgrund der Aufdeckung eines tropisch-extratropischen Wechselwirkungsmechanismusses, bei dem die Feuchtequellen für den im Atlasgebirge resultierenden Niederschlag im tropischen Westafrika zu finden sind.

Atmosphärische Modelle ließen die Bedeutung der Meeresoberflächentemperatur und der Vegetation für die lang anhaltenden Dürreperioden der 70er und 80er Jahre in der Sahelregion erkennen. Hochauflösende Modelle haben darüber hinaus gezeigt, dass ein beträchtliches Risiko für einen Rückgang der Niederschläge südlich des Sahel besteht, wenn die Vegetationsbedeckung schon um 50% reduziert wird. Ein multivariates Regressionsmodell unter Verwendung verschiedener Prädiktoren erbrachte zudem ein beträchtliches Vorhersagepotenzial für Niederschlag in dieser Region und wäre somit für eine operationelle Jahreszeitenvorhersage in Benin nutzbar.

Intensive Messungen im Agiuma-Testgelände konnten das hydrologische Prozessverständnis verbessern und die erforderlichen Modellanpassungen auf westafrikanische Bedingungen (subhumides Klima, Savannenvegetation, tropische Böden) ermöglichen. Gebietseigenschaften, bodenhydrologische Parameter und Aquiferparameter wurden durch Feldexperimente bestimmt sowie eine Bodenkarte des Agiuma-Einzugsgebietes erstellt. Ferner besteht eine signifikante Korrelation zwischen Erosionsraten und Anbaupraktiken der örtlichen Bauern.

Analysen der längerfristigen Veränderungen der Landnutzung und der Landoberfläche mit Hilfe der Fernerkundung zeigten, dass am Oberlauf des Ouémé die Hauptursachen für diese Veränderungen in der Neubesiedlung von Agrarland, in Waldrodungen und im Siedlungswachstum liegen. Zwischen 1986 und 2001 hat sich die Ackerfläche in der Region mehr als verdoppelt, während im gleichen Zeitraum die dichten Wälder um 40% reduziert wurden. Eine Regeneration des Waldes wäre möglich, wenn eine genügende Anzahl samenproduzierender Bäume mit einem Mindestdurchmesser von 45 cm geschützt würden. Ein für das tropische Afrika einzigartiger dendroklimatischer Datensatz mit einer Länge von über 200 Jahren wurde anhand von Holzbohrkernen erstellt, der die Rekonstruktion von Niederschlagsregimen zu vorinstrumentellen Zeiten erlaubt. Im Hinblick auf Nahrungssicherheit wurden die Wassernutzungseffizienz und die Biomasseproduktion der wichtigsten Anbaufrüchte untersucht. Dabei ergab sich, dass angepasste Anbaupraktiken eine bis zu dreimal höhere Ernte ergeben können.

Die unzureichende Verfügbarkeit von Wasser in den ländlichen Bereichen Benins wird anhand der langen Wasserholzeiten (ca. 6 Stunden pro Tag und Haushalt) deutlich aufgrund der großen Entfernungen. Während der Regenzeit ist diese Situation noch verschärft, da viele Wasserstellen trockenfallen. Obwohl Wasserarmut in 85% der Haushalte ein offensichtliches Problem darstellt, ist dies kein Grund für Migration. Die Migration in das IMPETUS-Untersuchungsgebiet liegt gegenwärtig in der Landknappheit in Nordwestbenin und Togo begründet und führt zu örtlichen Wachstumsraten der Bevölkerung von bis zu 11%. Die vorherrschende staatlich ungelenkte Agrarkolonisation lässt Intensivierungsmöglichkeiten bzgl. Ressourcenmanagement ungenutzt, beschleunigt den Entwaldungsprozess und führt zu Konflikten zwischen Neusiedlern und der autochthonen Bevölkerung. Weiterhin wurde ein Agrarsektormodell entwickelt, das die Bestimmung verschiedener Entwicklungspfade bzgl. Ressourcennutzung und Nahrungssicherheit in Benin erlaubt. Dieses Modell kann zu einem späteren Zeitpunkt zur agrarpolitischen Entscheidungsfindung herangezogen werden.

In Marokko wurde ein Netzwerk von zwölf Klimastationen entlang eines Höhen- und Ariditätsgradienten (350 km Länge, 2500 Höhenmeter) im Bereich des Drâa-Einzugsgebietes aufgebaut, um dort u.a. die Wasserverfügbarkeit zu quantifizieren und später zu modellieren. Der Transekt erstreckt sich von den ariden Bereichen des mittleren Drâa bis zu den zeitweilig mit Schnee bedeckten Bergen des Hohen Atlas im Norden. Charakteristisch für die Niederschlagssituation sind kurze, heftige, aber seltene Ereignisse im Süden und häufigere, aber schwächere Regen- und Schneefallereignisse in den bergigen Regionen im Norden. Aufgrund der zurückgegangnen Niederschläge wies der Stausee bei Ouarzazate in der jüngeren Vergangenheit niedrige Füllstände auf und die bewässerte Fläche degradierte zunehmend durch Versalzungen. Bodenerosion ist fast an allen Orten ein Problem aufgrund der sporadischen Niederschlagsereignisse, der geringen Vegetationsbedeckung und des Wegfalls der schützenden obersten Bodenschicht. Schneehydrologische Prozesse wurden im Hohen Atlas gemessen, besonders die Akkumulation und den Abbau der Schneedecke, und anschließend modelliert und validiert. Es hat sich gezeigt, dass Schnee nur wenig zum Grundwassersystem beiträgt, da das meiste davon durch Sublimation infolge niedriger Temperaturen und hoher Windgeschwindigkeiten verloren geht. Aus Satellitenaufnahmen war erkennbar, dass es im Winter keine kontinuierliche Schneebedeckung mehr gibt und die Schneedecke häufig zwischen einzelnen Ereignissen ganz verschwindet.

Eine Analyse der Vegetationsveränderungen anhand von LANDSAT-Daten ergab keinen klaren Langzeittrend für die südlichen Drâa-Oasen. Die Anbaufläche fluktuierte stark im Wechsel von trockenen und feuchten Jahren mit einem leichten Anstieg während der letzten 30 Jahre aufgrund des zunehmenden Einsatzes von Pumpen außerhalb der traditionellen Oasen. Die Vegetationsdynamik wurde auf 35 Weideausschlussflächen entlang des IMPETUS-Transektes permanent beobachtet. Der Anstieg der Biomasse ist signifikant unter Weideausschlussbedingungen im Atlasgebirge, während die Testgebiete am Rand der Sahara eine geringere Reaktion zeigten. Der Einsatz von Superabsorbern (Hydrogelen) in landwirtschaftlichen Experimenten führte zu einer verbesserten Etablierung perennierender Pflanzen und allgemein zu einer Produktivitätszunahme. Abhängig vom Bodentyp ergab sich für die behandelten Böden generell eine höhere Wasserspeicherkapazität verglichen mit unbehandelten Böden. Damit zeigte sich eine optimierbare Nutzung geringer Wassermengen in Gebieten mit geringen Niederschlägen und hohem Degradierungsrisiko.

Ethnologische Untersuchungen im Drâa-Tal lassen eine zunehmende Verknappung der natürlichen Ressourcen und sich immer weiter verringernde Möglichkeiten der lokalen Bevölkerung diese Ressourcen sinnvoll zu nutzen, erkennen. Neben Umweltfaktoren ist es vor allem die rasche Zunahme des von äußeren Einflüssen bestimmten sozialen Wandels, der den Umgang mit den lokalen Gegebenheiten erschwert. Eine Konsequenz daraus ist immer kleiner werdende Haushalte, die oft in "besseren", modern ausgestatten Häusern leben, was zu einer Zunahme des häuslichen Wasserverbrauchs führt. Ein solches Muster ist nicht nur in städtischen Zentren wie Ouarzazate zu beobachten, sondern auch in ländlichen Gemeinden. Diese Entwicklung ist eng mit dem Phänomen der Arbeitsmigration verknüpft, die sich als ein wesentlicher Einflussfaktor auf lokale, in soziale Systeme eingebunde Verhandlungen über Zugang und Nutzung von Wasser erweist. Technologische Innovationen wie die massive Verwendung von Motorpumpen, die oft von Arbeitsmigranten finanziert werden, führen zu einer kaum kontrollierbaren Entnahme von Grundwasser, wodurch traditionelle Strukturen des Wasserbesitzes und der Wasserverteilung geschwächt werden. Die daraus resultierenden Umwälzungen bei der Einkommensverteilung ist ein weiterer Faktor bei der Veränderung ländlicher Sozialstrukturen.

Summary

The overall objective of the 1st phase of the IMPETUS West Africa project was to describe, to analyse, and to quantify the most important aspects of the hydrological cycle of two river catchments north and south of the Sahara, the wadi Drâa in southeast Morocco and the Ouémé in Benin. This was made possible due to the unique concentration of a high number of experts both from the natural and the socio-economic sciences within a single project. The broad knowledge gained thereby will be integrated in model approaches of the various disciplines involved and will serve as a solid basis for the assessment of future developments carried out in the 2nd project phase. The following most striking milestones were achieved throughout this 3-year study.

One of the hypotheses at the beginning of this project was that the areas north and south of the Sahara are possibly linked from a climatological point of view. This also motivated the choice of basins. We found strong evidence by identifying a tropical-extratropical interaction mechanism where the moisture sources for the associated precipitation in the Atlas Mountains are the West African tropics. Atmospheric modelling pointed to the important role of tropical SSTs and vegetation for the decadal-scale drought conditions observed in the West African Sahel during the 70s and 80s. Results from a small-scale model also hints at a substantial risk of precipitation decrease in the area if the vegetation cover is reduced by more than 50%. A stepwise multiple regression model using different predictors yielded considerable rainfall forecast skills for the area south of the Sahel that can be used to install an operational seasonal forecast system in Benin.

Based on intensive measurements within the Aguima super test site the hydrological process knowledge could be improved and used for model adaptation to the West African conditions (subhumid climate, savannah vegetation, tropical soils). Catchment properties and parameters concerning soil hydraulic properties and aquifer parameters were determined by field experiments. Furthermore the local soil map of the Aguima catchments was finalised. A significant correlation between erosion rates and cultivation practice of the local farmers was determined.

Analyses of long term inter-seasonal land use / land cover changes (LUCC) with the help of remote sensing showed that in the upper Ouémé valley the main causes for such changes are new colonisation of agricultural land, logging activities, and growth of settlements. Between 1986 and 2001 the agricultural land has more than doubled. Within the same period areas with dense forests were reduced by 40%. Regeneration of forests is possible if a sufficient number of seed productive trees at a minimum diameter of 45 cm are protected. A unique over 200-year long dendroclimatic proxy was developed and allows the reconstruction of precipitation regimes for pre-instrumental periods. With respect to food security the water use efficiency and biomass production of the main field crops was investigated. It was found that by adequate farming practice up to three times higher yields could be gained.

The insufficient availability of water in the rural areas of Benin shows up in the fact that about six hours per day and household are needed for collecting water due to long distances. During the dry season the water stress situation is increased as many of the water sources fall dry. Although water poverty is for 85% of the households the most obvious problem it is not a reason for migration. It is the scarcity of land in northwestern Benin and Togo that attracts migrants into the southern parts of the upper Ouémé resulting in population growth rates of up to 11% p.a. The undirected agricultural colonisation leaves intensification possibilities in resource management

unused, accelerates the deforestation process, and creates conflicts between the new settlers and the autochthonous population. A socio-economic modelling system was developed which allows calculating and assessing different development paths of resource use and food security in Benin. At a later stage it will serve as a decision support system for agricultural policy.

In Morocco a network of twelve climate stations was installed to measure, quantify and model water availability and soil degradation at selected sites along an altitude and aridity gradient, 350 km in length and 2500 m in height within the Drâa catchment. The transect stretches from the arid, middle parts of the catchment to the periodically snow-covered mountains of the High Atlas in the north. Characteristic rainfall patterns include short low-frequency and high-magnitude events in the south and more frequent, low-magnitude rain- and snowfall events in the mountainous north. As a result of sparse rain- and snowfall events, the main dam at Ouarzazate has experienced suboptimal filling rates and the irrigated regions are increasingly degraded due to extensive salinization. Soil erosion is problematic in almost all regions due to the sporadic nature of events, poor vegetation cover and the removal of protective topsoils. Snow-hydrological processes in the Atlas Mountains, especially accumulation and depletion of snow cover, were measured and subsequently modelled and validated. Little snow is delivered directly into the ground- or surface water system in winter since most snow is lost by sublimation as a result of typical subzero temperatures and high wind speeds. Satellite image analyses showed that snow cover is no longer continuous in winter and that it may repeatedly and entirely deplete between events.

A change detection study based on LANDSAT data didn't show a clear long-term trend for the southern Drâa oasis. Agricultural surface fluctuated strongly between "dry" and "wet" years. A certain extension of the arable land has been established in the last 30 years due to the increasing amount of diesel-pump irrigated fields outside the traditional oasis. Vegetation dynamics are being monitored in 35 permanent plots alongside the IMPETUS transect. Biomass increase is significant under non-grazing conditions in the Atlas, whereas the Saharan test sites showed a lesser response. Agricultural experiments with the application of super absorbers to the soil helped to establish perennial plants and showed a general increase of productivity. There was generally a higher water holding capacity of the treated soils as compared to pure soils, the extent being dependent on the soil type. The results indicate an optimized use of small water amounts in areas with low rainfall and high risk of degradation.

Anthropological studies in the Drâa valley indicate a growing scarcity of natural resources and limited options for the local population to effectively manage these resources. Apart from environmental constraints, the increasing speed of social change due to external forces is one of the major problems in coping with the local conditions. The tendency towards smaller households, often accompanied by residence in "better" equipped houses and an increasing domestic water demand is one result. A similar pattern can be found not only in urban centres like Ouarzazate, but also in rural settlements. This development is closely linked with labour-migration, which was identified as a major factor in the socially embedded negotiation about water use. Technological innovations like the massive introduction of motor pumps, often financed by labour migrants, led to a barely controllable abstraction of groundwater and weakened traditional structures of water distribution and water ownership. The resulting modification of income distribution is one factor that will alter rural social structures.

I. Introduction

Fresh water is an essential component of life on Earth. It plays a vital role in the maintenance of the natural environment of the world and its continuous availability is indispensable for virtually every human activity. Shortage of fresh water is expected to be the dominant water problem of the forthcoming century and one that, along with water quality, may well jeopardise all other efforts to secure sustainable development, and even in some cases lead to social and political instability. Fresh water has already become critically scarce in many regions. The global mean water withdrawal per capita has shown a significant decrease during recent decades; there are now 22 countries that have renewable fresh water resources under 1000 m^3 per capita per year, a value commonly accepted as a benchmark for fresh water scarcity. It is forecast that for the first quarter of the 21st Century about one-quarter of the world population will suffer from severe water scarcity. Some estimates suggest that already the amount of fresh water available for each person in Africa is only about a quarter of that in 1950 ([1]Obasi, 1999), and that fresh water supply could become problematic especially in West Africa, where about 30 years of drought have been observed. Although the climates of West Africa are still relatively poorly known and understood, it is recognised that North West and tropical West Africa have experienced the most pronounced inter-decadal variability of climate in the world during the 20th Century ([2]Ward et al., 1999). The possibility of human-induced climate change adds additional serious aspects to the challenging water-related problems already encountered in many parts of the world.

Motivation

The available fresh water is controlled by the hydrological cycle. Climate, in particular the spatial and temporal distribution of precipitation and evaporation, plays a significant role in the hydrological cycle, and climate data are therefore of the utmost importance in the analysis of ground and surface water supply for domestic and industrial users, irrigation, hydropower generation and ecosystems. Dealing effectively with the hydrological cycle and its impacts demands not only a strong co-operation between different disciplines within the natural sciences (e.g. hydrology, meteorology, botany, agriculture, geology, remote sensing), but also consideration of socio-economic and medical issues; all disciplines involved have to interact in a complex and co-ordinated manner. Hence, in order to solve possible future problems with regard to fresh water supply, a clearly interdisciplinary approach is necessary. This is done in the present initiative for West Africa and it is the purpose of this project to offer concrete ways of translating into action scientific results through scientifically based strategies. This approach will provide a reliable basis for political measures and international agreements. In the first three-year phase the focus is set on the identification and analysis of influencing factors regarding different aspects of the water budget. Based on this, in the second three-year phase methods will be developed to predict changes during the coming decades. In the final two years the collected insights of all the disci-

[1] Obasi, G.O.P., 1999: Hydrology and water resources: a global challenge for WMO. Lecture at the 14th Conference on Hydrology - 79th Annual Meeting of the American Meteorological Society. Dallas, Texas, USA, 16pp.

[2] Ward, M.N., P.-J. Lamb, D.H. Portis, M. El Hamly Rachid Sebbari, 1998: Climate variability in Northern Africa: Understanding droughts in the Sahel and the Magreb. To appear as chapter 6 in: Beyond El Niño - Decadal variability in the climate system, Ed. A. Navarra, Springer-Verlag.

plines will be coupled in order to assess management options and to install operational tools for the decision-making process (so called "Decision Support Systems").

Choice of catchments

West Africa was chosen because (i) it has experienced the most pronounced inter-decadal variability of climate in the world during the 20th Century, (ii) relations to the climates of Europe might exist via complex atmosphere-ocean interactions, and (iii) the regions north and south of the Sahara might be linked via atmospheric teleconnection processes with regard to precipitation anomalies; first results presented below give evidence for the existence of such a link by atmospheric moisture transports out of the West Sahel zone across the Sahara towards the Atlas mountains.

Since the 1970s both subtropical Northwest Africa and tropical West Africa have experienced a general rainfall decline, which have probably been related (cf. Figs. I-1a and 1b). For this reason it is of advantage to consider both areas north and south of the Sahara desert in a combined approach, realised by means of a transect between the Atlas mountains and the Gulf of Guinea (Fig. I-2). This transect contains two reasonably sized river catchments (< 100.000 km^2) which are representative in the following sense: the Drâa catchment in the south east of Morocco is typical of a gradient from humid/sub-humid subtropical mountains to their arid foothills; the Ouémé basin in Benin is typical of an alternating sub-humid climate ("Guineo-Soudanien") of the outer tropics embedded within a transect from the Sahelian to the Guinean Coast climate.

The feasibility of the presented initiative has been guaranteed by the good availability of data of both the natural and the human sciences and by politically stable conditions in the respective countries.

Past and present situation

Moroccan precipitation is strongly related to the large-scale atmospheric circulation over the subtropical and extratropical North Atlantic and the Mediterranean Sea, with the bulk of precipitation occurring in winter (November - March). Since the late 1970s, Morocco has experienced a number of extremely dry winter seasons (cf. Fig. I-1a), the causes of which are not fully understood. Against this background, the development of sustainable water resource management is even more a necessity. The considered wadi Drâa possesses two main tributaries, the wadi Dades and the wadi Ouarzazate that drain the south-eastern and the south-western parts of the Atlas and confluence near the city of Ouarzazate thereby forming the wadi Drâa. At the site of confluence construction of the Mansour Ed Dahbi dam (60 m height) was completed in 1972 with an original storage capacity of 560 million m^3. Due to strong sedimentation a capacity of only 440 million m^3 remains today. Approximately 250 million m^3 of stored water is released in normal years for irrigation purposes. Release is done periodically in several waves called ‘lâchers’ which consist of an average discharge of 25 m^3/sec during approx. 3 weeks. The first lâcher is usually planned for August and an ideal number of 7 such releases from the dam take place per hydrological year. The actual number of lâchers carried out, however, strongly depends on the temporal evolution of the filling situation. Once a critical margin of 50 million m^3 is reached irrigation is no longer possible. The main irrigation structures downstream of the Mansour Ed Dahbi dam consist of five smaller dams and a complex network of traditional and modern canals. The irrigated perimeter covers a total area of approximately 26.500 ha.

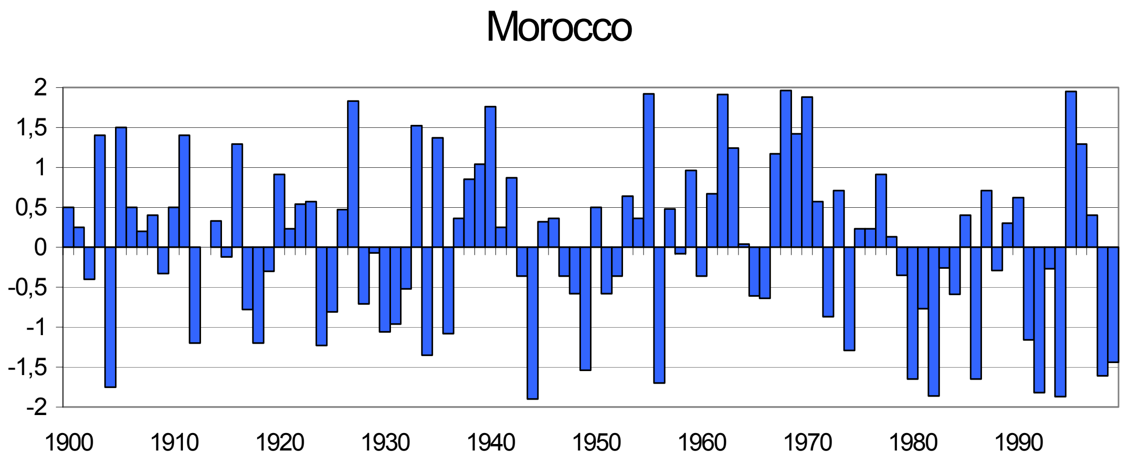

Fig. I-1a: Annual precipitation variability in Morocco throughout the 20th Century.

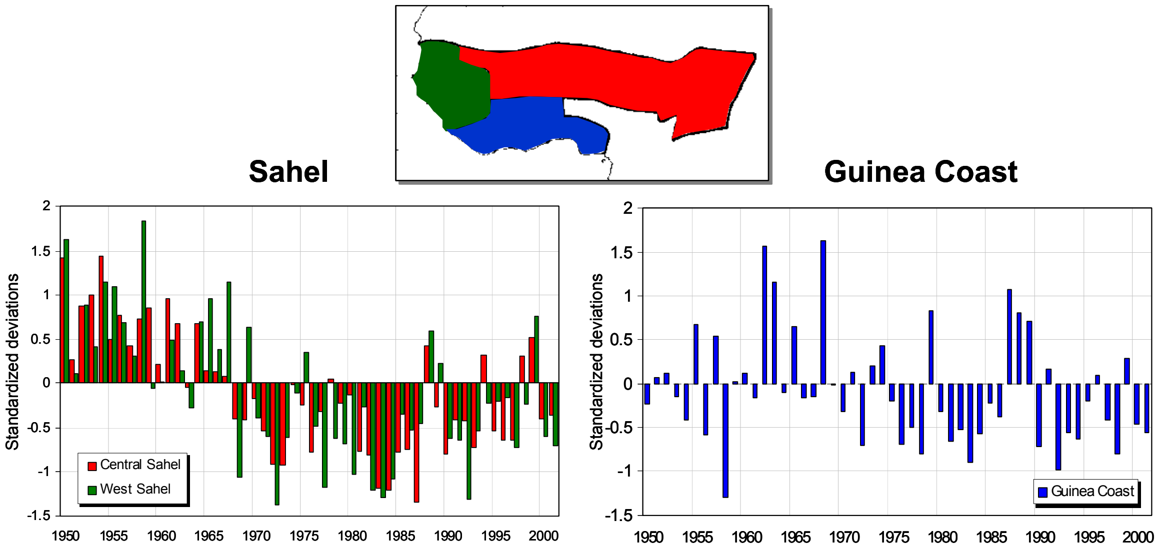

Fig. I-1b: Precipitation variability in West Africa for the period June - September 1950-2002.

Since the snow melt in spring contributes significantly to the annual discharge of the main storage lake tributaries, diagnosing the spatial distribution of accumulated snow water equivalent in the elevated areas of the catchment is particularly desirable. An effective and sustainable management of water in the Drâa valley is essential to enable the competing users (water power generation, irrigation, domestic consumption) to have adequate supplies, and to prevent social tensions related to water resources. Figure I-3a shows the dramatic low levels of the reservoir at the end of the rainy seasons of the mid 1970s, mid 1980s, and of the very recent years.

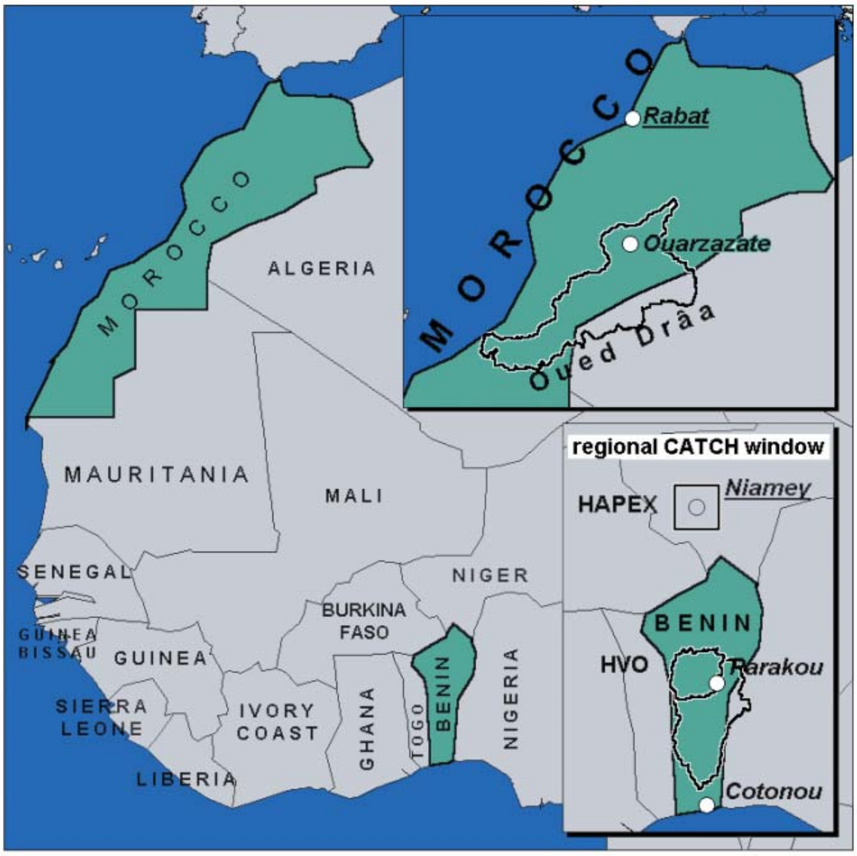

Fig. I-2: The two catchments of consideration. The DRÂA catchment in Morocco and the OUÉMÉ catchment in Benin are boldly bordered. A sub-catchment of approx. 100x100 km west of Parakou (Haute Vallée de l'Ouémé: HVO) has been chosen as an area of focused investigations.

Since the early 1970s tropical West Africa has suffered from a prolonged drought that reached its first climax in the first half of the eighties (cf. Fig. I-1b). The average rainfall deficit over 1971-1990 was of the order of 180 mm/year compared with the interval 1951-1970. All climatic zones, from the semi-arid Sahel and the subhumid Sudanese zone down to the humid Gulf of Guinea, have been affected. The prolonged West African drought has already brought about a profound deterioration in the economic and social development of the West African countries. As a consequence river discharges in West Africa have decreased by about 40-60% in recent decades, causing shortages in river water available for domestic and agricultural purposes. For instance Fig. I-3a shows the decrease in run-off of the Ouémé at Bétérou, which reflects the integral for the southern part of the upper Ouémé catchment. This has led to extensive migrations in the past. During the rain-rich fifties, water power stations were built in the Guinea coast zone to supply a substantial amount of energy to Ivory Coast, Ghana, Togo, Benin and Nigeria.

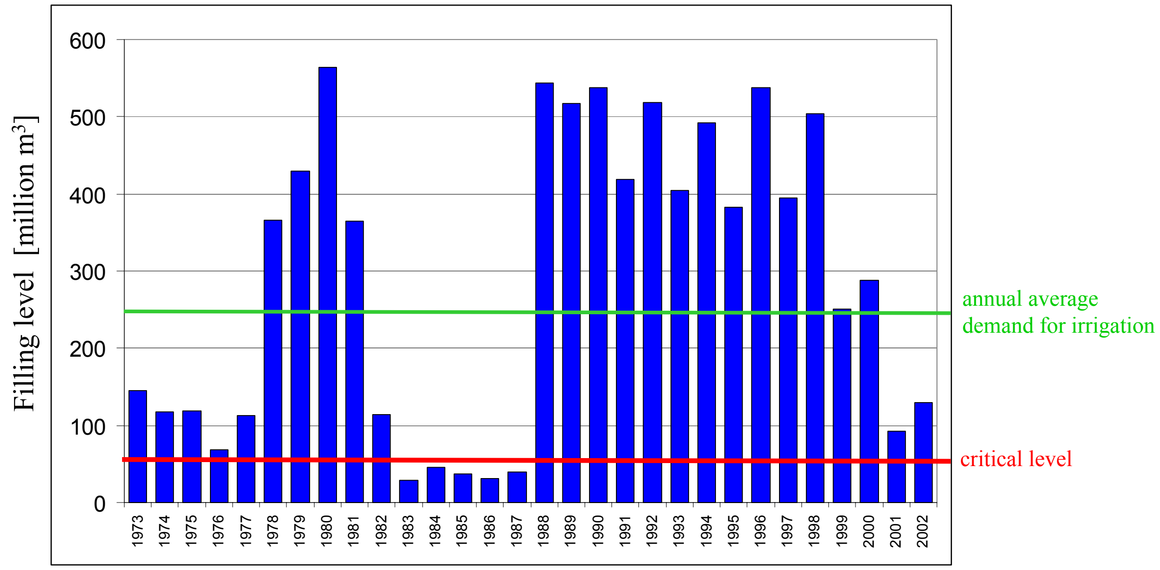

Fig. I-3a: 1st April-filling levels of the "Mansour Ed Dahbi" reservoir near Ouarzazate, Morocco (1973-2002).

Apart from the decreasing availability of fresh water per capita both in Morocco and in Benin the current situation north and south of the Sahara is also characterized by increasing population (population growth rate more than 3% per year), increasing degradation of the natural vegetation due to overgrazing (Morocco), demands in fire wood, and shifting cultivation (Benin). As a consequence soils quickly erode in Morocco (to a lesser degree also in Benin) and salt contents rise due to intensive irrigation practices. In combination the aforementioned factors are likely to accelerate the degradation and desertification processes for the coming decades.

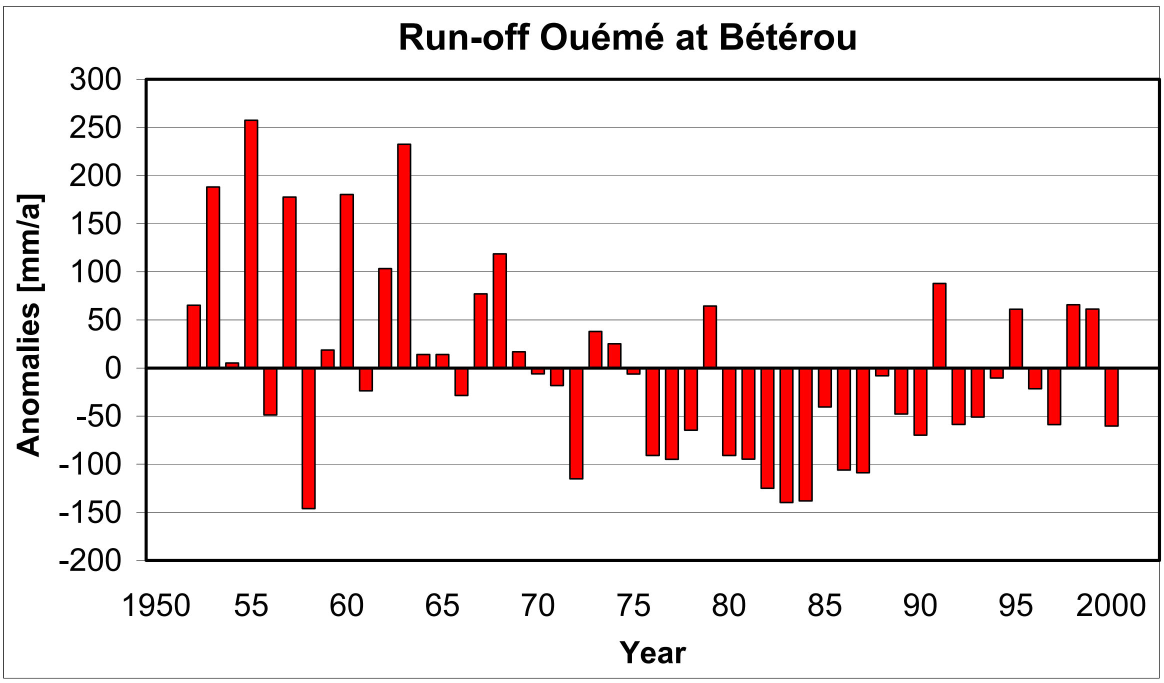

Fig. I-3b: Annual run-off anomalies of the Ouémé river at Bétérou for the period 1952 through 2000. Units are in mm/year, thereby taking into account the size of the upstream catchment area.

Methodology

Due to the importance of the hydrological cycle regarding the availability of fresh water, its different components and their interactions (cf. Fig. I-4) are identified in its complexity and quantified in the course of this project: the atmospheric variability, the continental hydrosphere, and the land surface processes from the natural science perspective. However, focal point of the investigations are human activities related to fresh water, e.g. economic behaviour, migration, construction of wells, water related rights and conflicts, etc.

In an integrated approach a sequence of existing models for the individual components have been adapted in the first project phase in order to describe the relationships and dependencies within the hydrological cycle in its present state. Basic research was only carried out if existing competence proved to be insufficient. These adapted models will then be coupled in the subsequent phase with the aim of developing and computing likely scenarios of change for the coming decades. This will also serve as a basis for assessment of management options and the installation of operational tools for decision makers during the third phase of the project.

A measurement network of essential parameters has been set up in data sparse areas in order to fill gaps in the existing national databases and networks. In the Drâa catchment 4 water-level gauges and 11 climate stations were installed along a representative north-south height gradient from the High Atlas to the pre-Saharan desert (cf. subproject C2, Fig. C2-1) thereby representing also the transition from the Mediterranean forest species to the semi-desert species. The selection of test sites also covers the most important grand units of the natural landscape (e.g. High Atlas mountains, basins of the Atlas foothills, pre-cambrian mountains of the Jbel Sarrho, paleozoic ridges south of the Anti Atlas, basins of the pre-Sahara, etc.). One additional mobile climate station is located within the oasis near Zagora in the southeast of the catchment.

For the Ouémé catchment we concentrated on the upper Ouémé valley where the existing national and IRD hydrometeorological networks have been enforced with focus on a super test site 'Aguima' near Doguè in central Benin (cf. subproject C2, Fig. C2-2).

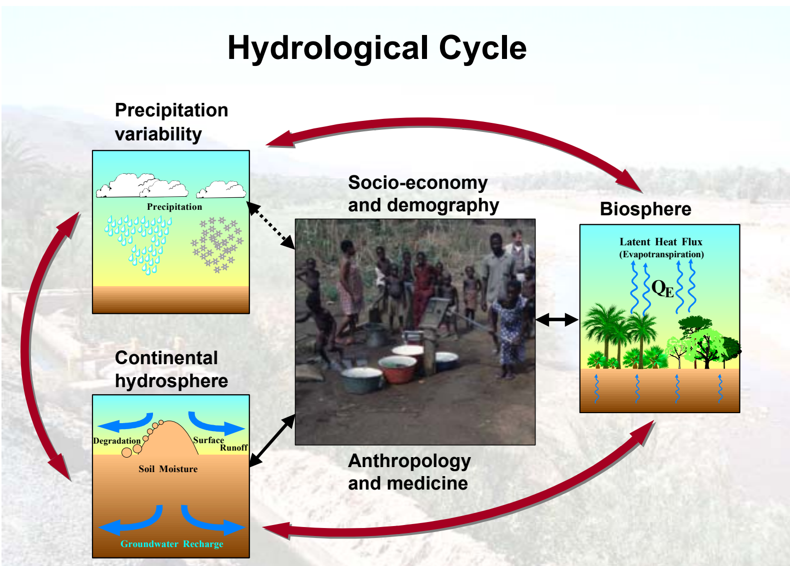

Fig. I-4: Main components of the hydrological cycle and interactions considered in IMPETUS.

II. IMPETUS Publications

Adanguidi, J. und M'barek, R., 2003: Analyse des côuts de production agricole au Bénin (forthcoming)

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III. Presentation of the Subprojects

Part A

The hydrological cycle of the Ouémé catchment and socio-economic implications

Subproject A1

Diagnostics and modelling of the spatial rainfall variability on intraseasonal to decadal time scales

Participants	Discipline
Prof. Dr. P. Speth (Coordinator) Institute of Geophysics and Meteorology, University of Cologne	Meteorology: Climate Diagnostics
Prof. Dr. A. Hense Institute of Meteorology, University of Bonn	Meteorology: Climate Dynamics
Prof. Dr. M. Kerschgens Institute of Geophysics and Meteorology, University of Cologne	Meteorology: Small-scale Modelling
Prof. Dr. C. Simmer Institute of Meteorology, University of Bonn	Meteorology: Modelling / Remote Sensing

Summary

The major focus of the subproject A1 within the first three-year phase of IMPETUS was the diagnosis and modelling of the atmospheric branch of the hydrological cycle in Benin and surrounding areas. On the modelling side, a nested hierarchical model chain consisting of the Global Circulation Model, ECHAM, the continental-scale model, REMO, the regional model, LM, and the local model, FOOT3DK, was set up and validated for tropical West Africa. Applications of the model chain or its individual components comprised climate change scenarios, an evaluation of seasonal rainfall prediction potential, sensitivity studies with respect to large-scale (e.g. sea-surface temperatures, SSTs) and continental-scale (e.g. soil moisture) forcings of rainfall, synoptic case studies of individual rainfall events, as well as rainfall sensitivity to land surface changes on time scales of individual precipitation episodes. The diagnostic studies provided various rainfall statistics for model validation and to all other subprojects, deduced both from raingauge data and satellite remote sensing techniques. Furthermore, the interactions between synoptic wave disturbances and squall-type rainfall events over Benin were studied, as well as the sources and advection paths of water vapour that rained out over the Haute Vallée de l'Ouémé (HVO). A focus year of the latter studies, including investigations with respect to the types of rainfall in Benin, is the rainy season 2002, during which a successful radiosonde campaign was conducted and enhanced surface observations were collected.

It was found that slowly varying global-scale variations in tropical SSTs were the major influencing mechanism that explains up to 50% of the annual rainfall variability along the West African Guinea Coast in the 20th Century. Incorporating a simple dynamical vegetation model in ECHAM4 improves the simulation of the observed decadal rainfall fluctuations in the West African Sahel. On the other hand, soil moisture is not an appropriate precursor of rainfall in the ECHAM4 model from monthly to annual time scales. On the contrary, a stepwise multiple regression model using SSTs, sea-level pressure and simulated precipitation by global models as

predictors yielded considerable forecast skill for the area south of the Sahel that can be used to install an operational seasonal forecast system in Benin. With respect to the types of rainfall it was found that night-time squall line systems are one of the major rainfall-producing weather events in the HVO study region. While for Benin as a whole, only about 27% of these squall systems could be related to a synoptic forcing by African Easterly Waves (AEWs) during the 1998 and 1999 rainy seasons, this percentage increased to 35–40% during the rainiest months, August and September. The ability of the AEWs to trigger squall systems seems to depend on the near-surface moisture content and water vapour convergence that in turn varies with air mass origin and advection path length over the continent.

The LM was set up and validated for two regions in West Africa. Moreover, the interface to the smaller-scale FOOT3DK model was built and tested. Several case studies, mainly during the radiosonde field campaign of the rainy season 2002, were conducted to study (a) the impact of initial fields (e.g, moisture) on the simulation, (b) any systematic deviations in the model behaviour, and (c) the dynamical behaviour of convective rainfall systems. Idealised ensemble studies and complex modelling of real precipitation events were preformed using the FOOT3DK model. The idealised ensemble studies exhibit a dominant influence of initial soil water content and an enhanced dependence of precipitation on vegetation when soil water availability is reduced. For wet soils, the influence of parameters that determine the intensity of near-surface turbulence is dominant. For the complex simulations of real cases, FOOT3DK was nested into the LM. These studies confirm that the parameters identified by the idealised ensemble studies induce notable rainfall reductions in realistic settings. As a whole, the results hint at a substantial risk of precipitation decrease if the land surface is unfavourably changed.

The principal objectives of the meteorological subproject A1 consisted of the diagnosis of the atmospheric branch of the water budget over sub-Saharan West Africa (with a regional focus on the Haute Vallée de l'Ouémé (HVO)) and the determination of the types of rainfall and their interactions with the large- and synoptic-scale flow, as well as the underlying smaller-scale surface characteristics. In the later context, the sensitivity of individual precipitation events to changes in the soil water content and vegetation was assessed. These objectives were pursued by a twofold strategy based upon diagnostic and model studies. In workpackage A1-1, the observational database and some related statistics are presented together with a satellite-based rainfall monitoring system to overcome the lack of ground-based rainfall observations. In the chapter on workpackage A1-2 the impact of Atlantic sea-surface temperatures (SSTs) on sub-Sahelian rainfall is described and – based on these results – the prospects for seasonal forecasting are evaluated. Another topic will deal with the interactions of synoptic wave disturbances and squall lines. In workpackage A1-3 results of idealised and complex case and sensitivity studies using the LM and the smaller-scale FOOT3DK model are discussed.

The following results were achieved in the above mentioned three workpackages in detail:

Workpackage A1-1: Classification and diagnosis of the variability of precipitation events

One major objective was to collect, quality-check, and archive rainfall and other relevant meteorological data and to provide project members with various requested statistics and to aid them with respect to their interpretation. A second pivotal goal pertained to the remote sensing of rainfall. An attractive rainfall monitoring system for Benin, Morocco and surrounding areas based on passive microwave radiometer measurements was developed.

Rainfall database and related statistics

The daily rainfall dataset for Benin starting in 1921 and consisting of about 69 stations was quality-checked and updated to 2002. Various statistics were generated, many of them on requests from the subprojects A2 through to A5. Some of the more salient statistics will be presented here. Figure A1-1 (a) displays the annual standardized rainfall anomaly indices and the respective 11-y running means for the southern (6–9°N, Guinea Coast) and northern parts (9–12.5°N, Soudanian zone) of Benin. The time series reveal a strong decadal variability in the 20th Century and the fact that the recent three years (2000-2002) were anomalously dry all over the country. As a consequence, the decadal trend again returned to below-normal values (Fig. A1-1 (a), red curves). After the removal of erroneous data, the diurnal probabilities of rainfall were calculated from the digitised pluviograph records of the six synoptic weather stations in Benin (Source: IRD France) and are shown in Fig. A1-1 (b). From the mean diurnal cycle of rainfall and the

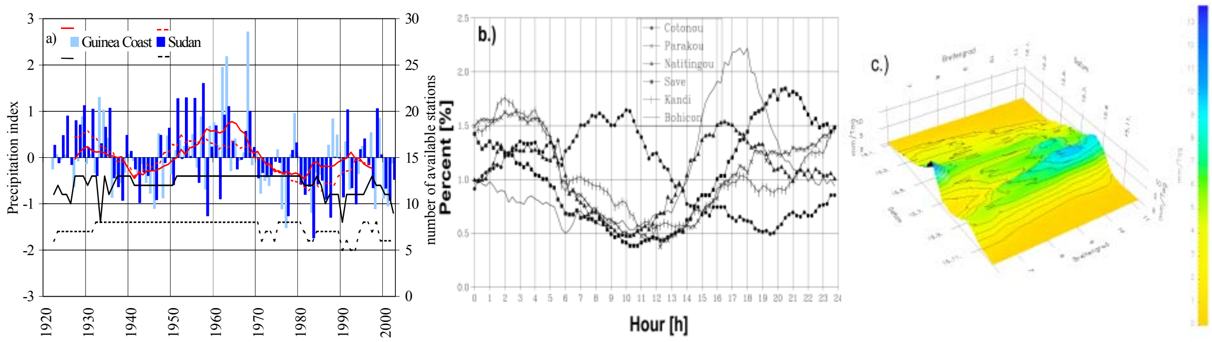

Fig. A1-1: (a) Annual standardized precipitation [no units] indices for stations at or close to the Guinea Coast (6–9°N) and the Soudan climatic zone (9–12.5°N) of Benin. The base period is 1922-2001.(b) 30-y (1969-1998) average diurnal cycle of rainfall. Shown are the long-term mean percentages [%] of daily rainfall that occur in 15-minute intervals at the six Beninese synoptic stations. (c) Three-dimensional time-latitude diagram of 15-day running mean rainfall intensities in mm day^{-1}.

seasonal cycle (Fig. A1-1 (c)) conclusions with respect to the rainfall climate and the type of the rainfall-generating events can be drawn. For instance, the morning peak at Cotonou indicates the frequent occurrence of night-time convective showers over the Gulf of Benin that start to propagate inland in the early morning hours in association with the developing sea breeze convergence line. The station in the Upper-Ouémé valley, Parakou, has a broad peak after midnight indicating the arrival of squall lines from the east (see workpackage A1-2). Finally, Figure A1-1 (c) shows a time-latitude diagram of mean (1931-1990) rainfall intensities, thus allowing to assess the inland progression of rains during the rainy season. Note the abrupt inland shift of rains in mid-June after the termination of the first and more intense of the two rainy seasons at the Guinea

Coast. This occurs in addition to the classical notion of a continuous inland incursion of the monsoonal rains, resulting in a tri-modal rainfall distribution around 8°N. The abrupt inland shift of monsoon rains has recently been emphasized by several authors (e.g. Le Barbé et al., 2002).

Remote sensing of rainfall

The first three years were devoted to further development and adaptation of algorithms employing active and passive microwave radiometer measurements from the Tropical Rainfall Measuring Mission (TRMM). The TRMM satellite carries the first spaceborne precipitation radar (PR) and on the same platform a microwave radiometer (TMI) is available. Thus, co-located radiometric and radar measurements from TRMM provided an outstanding data source covering the tropical and subtropical latitudes over various climatological regimes.

The estimation of rainfall over land surfaces is an ongoing challenge because neither at VIS/IR wavelengths nor at microwave wavelengths do raindrops provide significant contributions to the total signal to allow a direct estimation of rain rate. Principally, cloud top temperature and reflectivity is related to space-time averages of surface rainfall in VIS/IR methods. The loose physical connection between these quantities prohibits an instantaneous rainfall estimate. At microwaves, surface emissivity is high and spatially variable which increases the uncertainty of the atmospheric contribution estimate compared to estimates over ocean surfaces. The main information over land surfaces comes from scattering by precipitating ice particles. However, since the beginning of remote sensing both wavelength regions were exploited (Petty, 1995) and recent accuracy assessments indicate average errors of at best 50-100% with strong dependence on season and region as well as dataset resolution (Smith et al., 1998). Thus, algorithm improvements may only be achieved if local surface conditions are accounted for and if the signal to rain rate relationship is based on data which is more representative of global rainfall system variability.

In the following, rainfall intensity is always treated in terms of rain liquid water content (LWC in gm^{-3}) to avoid uncertainties imposed by the somewhat uncertain drop size distributions and the dependence of rainfall rate calculations on fall speed parameterisation. Additionally, both scattering ($\propto D^6$) and emission ($\propto D^3$) are closer related to liquid water and ice volume densities (where D denotes the particle diameter).

The rain detection part of the IMPETUS algorithm whose fundamentals are based on a methodology developed by Conner and Petty, 1998, consists of a two-stage approach to distinguish precipitation signatures from other effects: (1) Contributions from slowly varying parameters (surface type and state) are isolated by comparing observed brightness temperatures to those obtained from previous orbits only containing rain-free observations. (2) Effects of more dynamic parameters, i.e. surface temperature and moisture, are reduced by successive subtraction from the observations by means of principal component analysis. For this purpose, the general signatures of both temperature and moisture variations are deduced from radiative transfer simulations. The technique is applied to TMI observations and compared to co-located measurements of PR over Benin employing the technique described in Bauer et al. ,2002. To quantitatively estimate the rain water content, Heidke skill scores as a function of rain water content and bright-ness temperature range are used to efficiently calibrate the near surface rainfall intensities with a polynomial fit where the coefficients depend on location and time. The final rainfall product is provided in TMI scan coordinates with a spatial resolution of 18 km x 30 km.

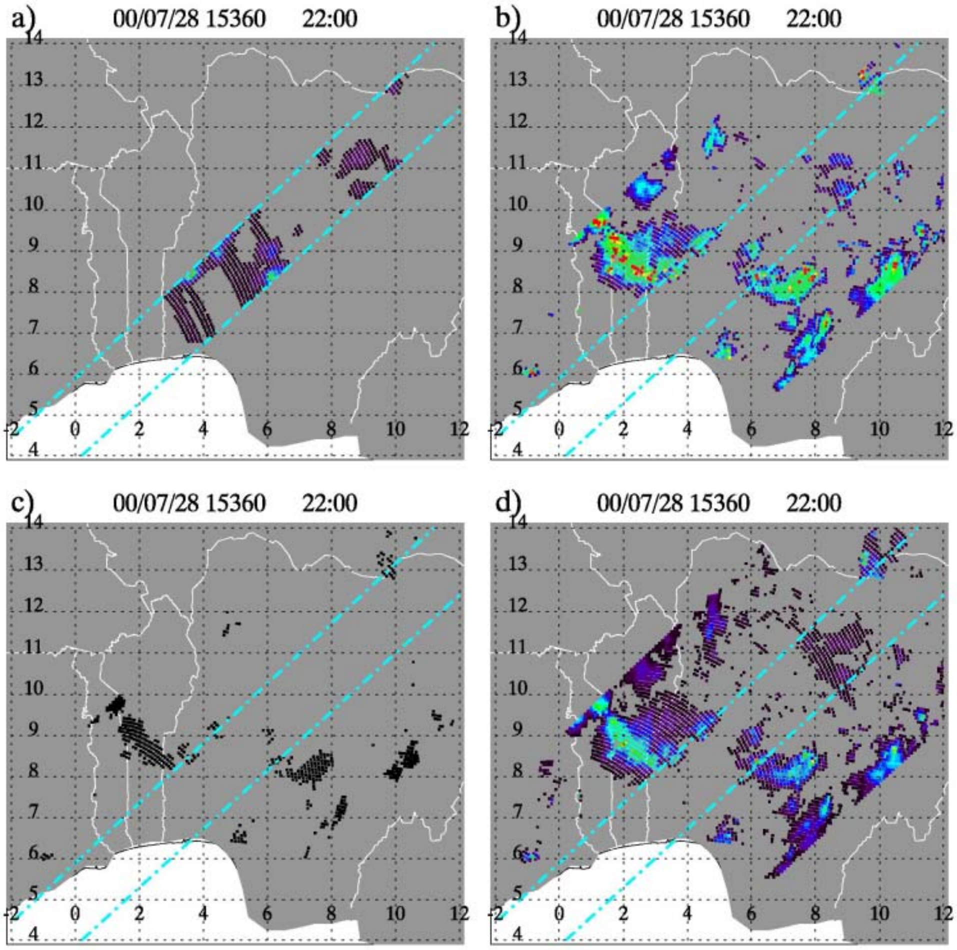

Fig. A1-2: Distributions of retrieved rain water content for orbit 15360 on 28. July 2000 over Benin and Nigeria from (a) PR estimates averaged to TMI reference resolution, (b) 2A12 V.5 algorithm, (c) pixels where the Ferraro et al. (1998) scattering index indicates rain, and (d) calibrated estimates from the IMPETUS algorithm.

Figure A1-2 presents a typical example of the results obtained by using the polynomial fits to calibrate the Precipitation Index (PI) into rain water contents. The case represents the passage of a meso-scale convective cluster over southern parts of northwest Africa on 28th July 2000. The measurement was taken in the decaying stage of most of the convective cells around 22 UTC. A couple of cases were analysed to demonstrate the differences between the new algorithm and the NASA standard algorithm for the TMI (2A12) as well as to show the performance versus the calibration source product 2A25 (standard rainfall estimate from the National Space Development Agency of Japan (NASDA)) generated from PR data. Comparing the 2A12 with the 2A25 product (Figs. A1-2 (a) and (b)), it is obvious that 2A12 doesn't detect rain water contents lower than 0.2 gm^{-3} which lead to a significant smaller rain area. The calibrated PI (Fig. A1-2 (d)) represents the PR swath data relatively well, e.g. between 8°E and 10°E and 10°-12°N. However, it is also not able to detect the very small rain water contents in the south western part of this scene although some errors can also be attributed to the 2A25 product. The Ferraro scattering index represents only the convective cores and is not able to detect any LWC lower than 0.3 gm^{-3}

(Fig. A1-2 (c)). Compared to 2A12 the calibrated PI shows a very similar structure at medium and high rain intensities but it exhibits a large negative bias in the convective cores which is introduced by the use of the PR as the calibration source.

Figure A1-3 shows scatter plots for the orbit considered in Fig A1-2. In Fig. A1-3 (a) the scatter between 2A12 and the calibrated PI is increasing with decreasing rain water content. Other cases not shown here reveal that the spatial correlation between 2A12 and PI is relatively high (r > 0.7) for rain water contents larger than 0.1 gm^{-3} but the negative bias for the PI was found in any case considered. This bias is also obvious in Fig A1-3 (c) showing the comparison between 2A12 and 2A25 where also the scatter is considerable larger than between 2A12 and the PI. The comparison of PI to its calibration source in Fig A1-3 (b) and (d) shows an overestimation of the PI at rain water contents lower than 0.03 gm^{-3} which is a common feature of all investigated cases. For

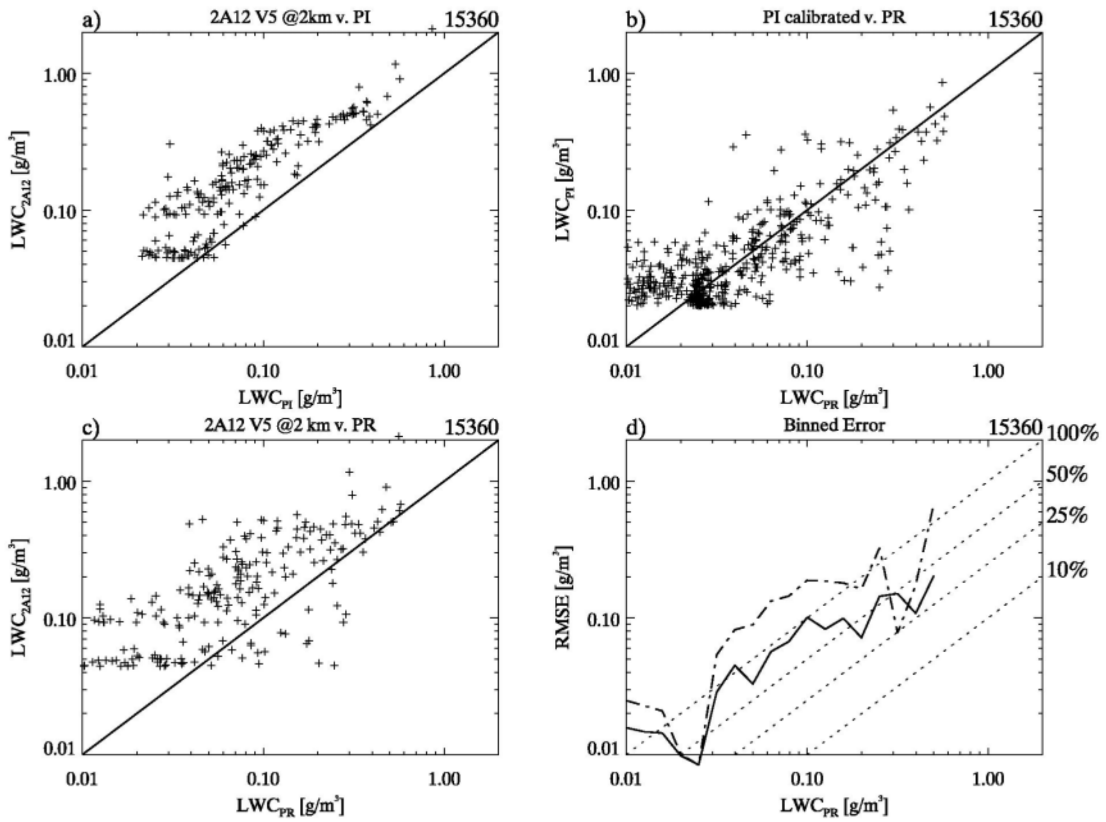

Fig. A1-3: Scatter plots of (a) calibrated PI estimates versus 2A12 V.5 estimates, (b) calibrated PI estimates versus averaged PR estimates, (c) 2A12 V.5 versus averaged PR estimates, and (d) remaining standard deviation between calibrated PI (solid) and 2A12 (dashed) and averaged PR pixels for the same case as in Fig. A1-2.

greater rain water contents there is no bias as expected from the calibration procedure but still a large scatter. The large scatter around values of 0.1 gm^{-3} is potentially caused by the large area chosen to build the Heidke skill score diagrams for the calibration. Together with the time average over 10 days variability is suppressed finally causing the scatter in the comparison. A second dynamical calibration like in the PATER ocean algorithm (Bauer et al., 2001) could be envisaged but is not necessarily expected to improve the calibration very much. The remaining rms error between 2A25 and the PI is still around 100% at rain water contents below 0.1 gm^{-3} and decreasing to 25-50% above 0.1 gm^{-3} represents an error lower than that of the 2A12 (shown by the dashed curve in Fig. A1-3) which shows higher rms-errors at almost all rainfall bins. A more detailed error analysis should analyse the resulting probability density functions of the different products and their errors. Also a stratification of errors in terms of different meteorological regimes with the help of rain gauge and radar data in Benin will help to characterise the errors better. Further improvements of the technique can be expected from the consideration of rain and cloud classification as well as the additional use of microphysical properties of clouds derived from measurements of the SEVIRI instrument onboard of the Meteosat Second Generation satellite.

Workpackage A1-2: Large- and synoptic-scale forcings of rainfall

The first major goal of this workpackage consisted of the identification and quantification of the larger scale driving forces of rainfall (events) over West Africa. A regional focus was laid on Benin and neighbouring countries. With respect to the large-scale forcing mechanisms, it has been suggested by several authors that rainfall fluctuations over tropical West Africa are predominantly induced by global SSTs, but are reinforced by feedbacks with the continental-scale land hydrology (e.g. Nicholson, 2001). On the synoptic scale, this workpackage aimed at quantifying the role of the synoptic African Easterly Waves (AEWs) in forcing and maintaining a major rainfall-producing weather systems in northern Benin, the so-called squall lines (SLs). The second main goal was the determination of the water vapour source regions, the corresponding atmospheric transport paths and the patterns of moisture convergence over Benin and its vicinity. An upper-air sounding campaign was successfully performed during the rainy season 2002 to improve the regional analyses of relevant upper-air meteorological fields. Due to its postponement from the rainy season 2001 to 2002, several of the planned diagnostics are still ongoing at the time of writing and will be presented in more detail in the annual reports of the 2nd phase.

Nonetheless, a first example of the data obtained during the radiosonde campaign is given in Fig. A1-4. Figure A-4 (a) displays the vertical wind (barb) profiles from 00 UTC 11 Sept. – 12 UTC 26 Sept. 2002, a period with the strongest seasonal activity of AEWs in 2002. The latter is seen from the coloured meridional wind component by the change from northerly (greenish colours) to southerly winds (reddish colours). Moreover, wind shifts mark the passage of rainfall systems on the 15, 18 and 25 September. The coloured relative humidity field (Fig. A1-4 (b)) reveals that these events were associated with a moistening of the mid- and upper-troposphere. The latter subsequently dried out in the 48-72-h period after the rainfall events. The drying in the mid-troposphere set the precondition for the development of strong squall line systems.

The relationship between AEWs and SLs have been investigated over West Africa for the two six-month periods May–October 1998 and 1999. Results have been published in Fink and Reiner, 2003. In all, 81 AEWs have been tracked using analyses from the European Centre for Medium-Range Weather Forecasts (ECMWF) and 344 SLs have been identified by localizing their leading edges mainly from passive microwave rain rate retrievals. It is found that the area west

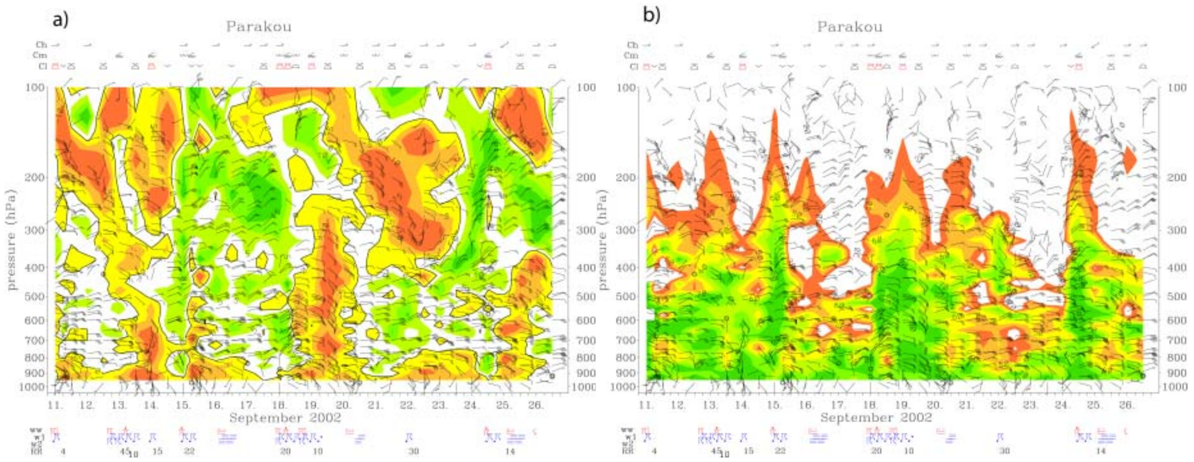

Fig. A1-4: Time-height plots of 12-hourly wind barbs (plus 4 extra soundings) and meridional wind (relative humidity) in panels (a)((b)). The 6-hourly significant weather reports and the 24-hour accumulated rainfall measured at 06 UTC are indicated below the panels. Above the panels the 6-hourly low (Cl), mid-level (Cm) and upper-level (Ch) cloud observations are displayed.

of the AEW trough is a favourable location for SL generation over the entire tropical West Africa. In the Sahel, a secondary peak around the region of maximum AEW-related southerlies is observed. In these wave phases, 42% of all 344 SLs were identified and defined as „AEW-forced". According to this definition, the contribution of AEWs to SL generation increases from 20% around 15°E to 68% at the West African coast (15°W), and is larger for the Sahel than for the Guinea Coast/Soudanian region. Furthermore, the impact of AEWs on SL genesis is greater at the height of the Sahelian rainy season (July–September) than in the remaining early and late monsoon months. In Benin, 27% of the SLs were forced by AEWs in 1998 and 1999, but this fraction rose to 40% (35%) in August (September) in North Benin, the rainiest months in this part of the country. Reiner, 2003, investigated the potential causes of "dry" AEWs, i.e. AEWs that never forced a SLs during their life cycle over West Africa. Evidence is given in his work that such dry synoptic disturbances are characterized by a lower-than-normal low-level moisture content at radiosonde stations along 12°N. The latter can partly be explained by the low-level air mass origins: in the drier situations, air parcels coming from the Gulf of Guinea either travelled a longer distance over the continent or originated from the east, i.e. the continental interior. Further results of trajectory analyses with respect to air mass origin and advection towards the HVO is given in the IMPETUS Annual Report 2002. Finally, it should be mentioned that the study on the relationship of AEWs and SLs helped to understand the process chain involved in tropical-extratropical interaction events during which substantial rains are observed south of the Atlas Mountains in the study region of project B. The moisture source was found to be associated with rainfall clusters over tropical West Africa. This mechanisms has been described in Knippertz et al., 2003, and Fink and Knippertz, 2003, and is also detailed in subproject B1 of this report.

It has been suggested by several authors that rainfall fluctuations over tropical West Africa are predominantly induced by SST anomalies and reinforced by feedbacks with the land surface (e.g. Nicholson, 2001). Meanwhile, several climate model experiments were realized in ensemble modes which were forced by observed global SST anomalies as lower boundary condition. The idea is that such model experiments closely reproduce the variability of climate features which are affected by SST anomalies at a given time scale. Fig. A1-5 reveals that this is true for sub-Sahelian precipitation as a measure of the West African monsoon dynamics (top panel, left hand side): SST-driven model runs with ECHAM4 and HADAM2 simulate the remarkable drying tendency between the 1960s and 1990s, although the amplitude is somewhat underestimated compared with the CRU observational dataset (New et al., 2000). In recent years, observed rainfall is partly recovering and future coupled climate change simulations predict an increase of annual rainfall over Benin and adjacent countries into the 21st Century (top panel, right hand side). As most climate model experiments are provided as ensemble members, being subject to identical forcing but varied initial conditions, it is possible to quantify the forcing contribution to total rainfall variability by analysis of variance. During the 20th Century, SST clearly is the dominant player, accounting for 50% of the variance on average. SST-driven simulations suggest that the role of increasing greenhouse gases (GHGs) is getting significant from the 1970s onward. Coupled climate models project a further rise of the GHG impact into the future. It was found that the mechanism, which translates the global radiative forcing to changing precipitation, is the tropical Atlantic SST field (Paeth and Hense, 2003a). Warmer SST is associated with enhanced latent heat fluxes to the atmosphere and humid air advection into the southernmost part of West Africa. Thus, SST and GHGs have a crucial influence on present and future rainfall variations.

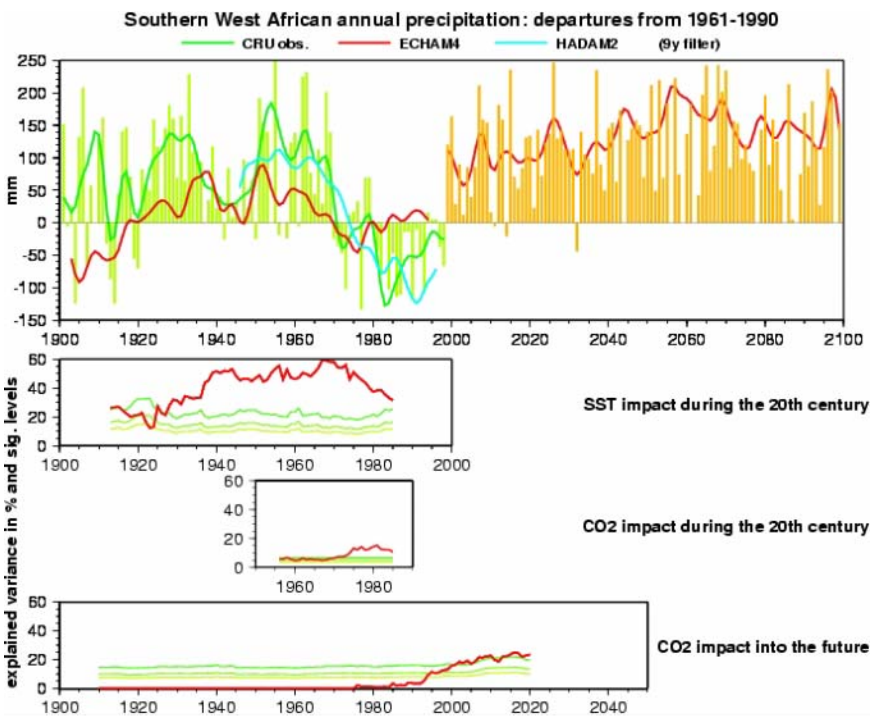

Fig. A1-5: Time series of observed and simulated Guinean Coast-Sudan rainfall from SST- and CO_2-driven climate models (top panel) and contribution of the external forcings to total rainfall variability (mid and bottom panels) during the 20th and 21st Centuries.

The result of increasing rainfall into the future is somewhat counterintuitive given the recently observed drought tendency which was suggested to be tied to land cover changes and exploiting land use (Nicholson, 2001). These processes are not taken into account in the model experiments mentioned above. Therefore, the basic question is how anthropogenic land cover changes and radiative forcing may interact with each other, a matter of further investigation. During the first IMPETUS phase it was found that incorporating a dynamical vegetation model in ECHAM4 considerably improves the simulation of Sahelian rainfall with respect to the amplitude of variations and the meridional shifting of the intertropical convergence zone (Schnitzler et al., 2001). On the other hand, soil moisture is not an appropriate precursor of rainfall in the ECHAM4 model, at least at the monthly, seasonal and annual time scales. The synoptic-scale role of soil moisture in a regional climate model will be subject to future studies.

The impact of SST at the synoptic scale was examined by means of the mesoscale climate model REMO (Hagedorn et al., 2000) which was set up over West Africa in a 0.5° resolution. This model was found to provide a useful and realistic description of West African climate, including the complex dynamics of the African Easterly Jet (AEJ) and African Easterly Waves (AEWs) (Paeth et al., 2003). Sensitivity studies with idealized SST variations in the tropical Atlantic and Indian Oceans reveal a statistically significant impact of SST changes on sub-Sahelian rainfall,

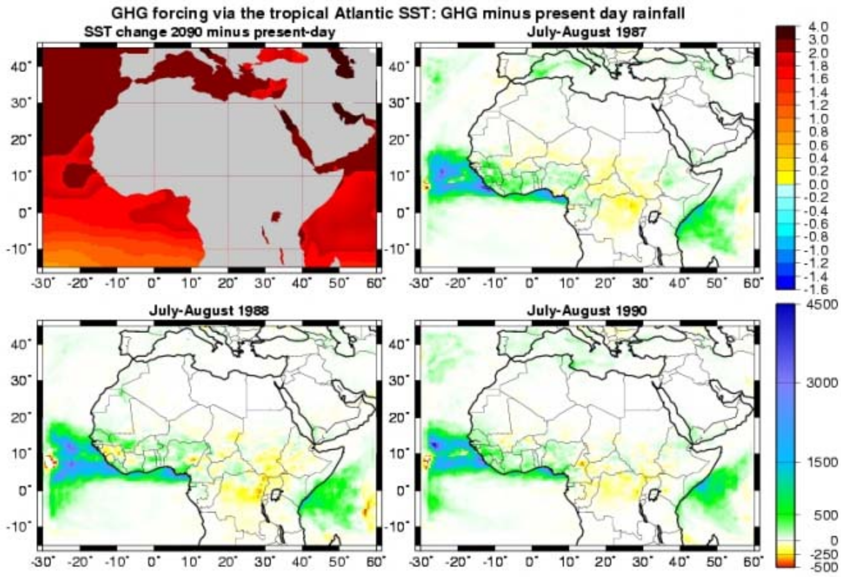

Fig. A1-6: REMO sensitivity studies with warmer tropical and subtropical SST (top left panel) as predicted for the year 2090, rainfall differences 2090 conditions minus present-day (remaining panels).

amounting to 50% over the coastal region. The change in rainfall associated with a more realistic warming up of the tropical and subtropical oceans is displayed in Fig. A1-6. The changed oceanic boundary field (top left panel) is derived from a coupled climate change simulation and represents the 2090 condition under an enhanced greenhouse effect. Imposing these SST anomalies on the present-day field leads to the rainfall changes shown in the remaining panels for the July-August period in different years: Rainfall is increasing by about 4000 mm over the oceanic convergence zone off the western Guinea Coast and still by about 250 mm over coastal sub-Sahelian West Africa, including Benin. On the other hand, rainfall amount is decreasing over the Sahel by out 200 mm. Thus, warmer SST under enhanced radiative forcing appears to intensify the meridional north-south gradient in freshwater availability, implying large-scale migration processes when persisting over longer periods. Applying the linear theory of tropical thermodynamics, it has been found that the response of REMO to tropical oceanic heating largely corresponds to the Kelvin and Rossby wave responses, as suggested by Vizy and Cook, 2001. Thus, the physical mechanism on the ground seems to be partly linear.

The important role of SST in sub-Sahelian rainfall fluctuations holds the prospect of seasonal forecast. A stepwise multiple regression model with cross validation has been developed, based on observed seasonal sub-Sahelian rainfall as predictand and global as well as regional SST, sea level pressure (SLP) and precipitation simulated by global climate models as predictors (Paeth and Hense, 2003b). This simple ground-based statistical model accounts for up to 50% of total interannual variability (Fig. A1-7). Given the distinct autocorrelation of low latitude SST, this relationship can be used to install an operational seasonal forecast system in Benin.

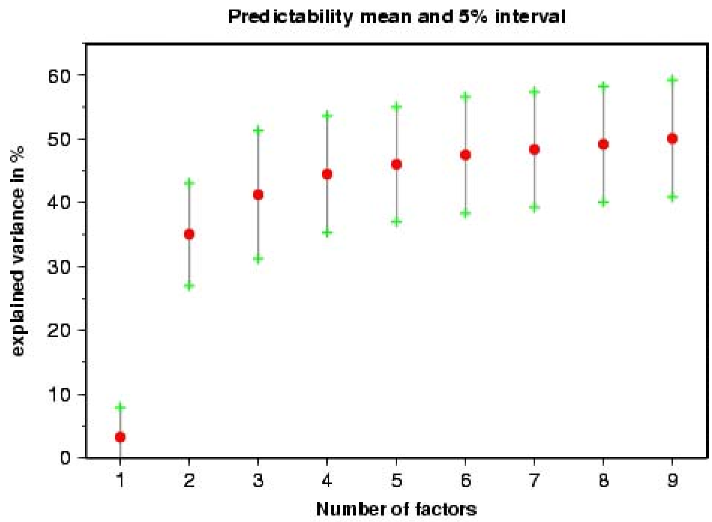

Fig. A1-7: Explained variance by an increasing number of predictors, derived from SST, SLP and simulated precipitation, relative to total interannual rainfall variability over sub-Sahelian West Africa.

Workpackage A1-3: Meso-scale modelling of rainfall systems and their interaction with the large-scale flow and the land-surface characteristics

The LM (Local Model) was set up for two regions in West Africa: A larger one between 30°W and 60°E on a 0.25° grid which covers the whole of North and Central Africa between 15°S and 45°N. This region was chosen to enable simulations of the synoptic-scale AEJ/AEW-regime; another intention was to look at tropical-extratropical interactions, mainly by means of moisture transports. The smaller region covers the Guinea Coast area around Benin on 0.0625° (ca. 7 km) grid. On this smaller grid, single convective cloud clusters can be resolved.

For a couple of test cases in the year 2000, initial data were acquired from DWD (German Weather Service). They covered different classes of convection. With the test cases, the interface LM-FOOT3DK was built and tested. In principle, the test cases showed that the LM simulates elements of West African weather correctly. However, a closer look revealed discrepancies in location and strength of rainfall events. Although the grid scale of 7 km is relatively small compared to grid sizes of global models, for which the convection parameterisation originally were designed, the main features of the rainfall systems could be represented only with the use of convection parameterisation. Rainfall amounts and spatially distribution were qualitatively correct, but for further validation, the observations were not sufficient.

Due to differences between modelled and observed convective rainfall events, a series of 18 case studies for summer 2002 were conducted. The intention was to look for any systematic deviations in the model behaviour. During the 2002 field campaign of IMPETUS, observation and classification of important rainfall events of the case studies, improved by additional radiosondes in Parakou, allowed a more detailed comparison of model output and observations as in former studies. It turned out that the moisture analysis especially in tropical regions was spurious, mainly because over land areas no satellite observations of humidity are available for assimilation into the analysis. The sparse network of upper-air stations over West Africa is not sufficient to provide reliable initial moisture field for short and medium range predictions. For dynamical parameters, even the comparison of initial fields and observations is still not possible.

Because initial atmospheric moisture fields are much less important than, e.g. the soil model behaviour for the future seasonal predictions (hindcasts) or scenario runs planned in IMPETUS, no efforts were undertaken to improve the results of the case studies by assimilating satellite data.

Another essential feature of the model predictions is the dynamical behaviour of convective rainfall systems: in some cases, they moved north-eastward, upstream to the mid-tropospheric flow. Satellite observations showed similar departures of cloud fields only in cases where the cold thunderstorm outflow triggered new convective cells, but other than in the model runs, size and strength of eastward moving convective cells were quite small compared to the commonly westward shifted cells. Additionally, dynamics of AEWs seemed to be difficult to assess from predictions of only some days. Therefore, model studies with idealized boundary and initial conditions revealed some important aspects of AEW dynamics.

Interactions between the land surface and precipitation systems

As a first step towards an evaluation of tolerable regional land use changes with respect to rainfall availability in the HVO, investigations in workpackage A1-3 focused on rainfall sensitivity to land surface changes on time scales of individual precipitation episodes. For this purpose, a twofold strategy of sensitivity studies with the model FOOT3DK (Flow Over Orographically Structured Terrain, 3-dimensional, Köln Version) was employed. The strategy consists of a combination between idealised ensemble simulations with a column version of the model and complex modelling of real precipitation events. It allows to consider the regional applicability of simplified approaches, as well as to improve the understanding of the mechanisms that affect precipitation in complex realistic settings.

For the complex simulations, FOOT3DK is nested into LM forcing fields and into itself on horizontal resolutions of 9 km and 3 km. Complex modelling of a real precipitation event between

28th and 30th July 2000 confirms that parameters identified by the idealised ensemble studies induce notable rainfall reductions in realistic settings. An example is given in Fig. A1-8 for an experiment on a 35 x 35 mesh grid with 9 km resolution. The sensitivity simulation refers to a hypothetical reduction of vegetation by 50% and of initial soil water by 66% within randomly chosen areas that amount to half of the simulation domain. It is compared with a reference simulation that is based on undisturbed surface conditions (Fig. A1-8, left). The resulting rainfall anomaly pattern (Fig. A1-8 right) exhibits a predominant decrease with local patches of enhanced precipitation. This distribution of rainfall differences cannot exclusively be explained by pattern of hypothetical land use changes. It is the interplay of convection cells with both land surface processes and larger-scale atmospheric dynamics that eventually determines the rainfall anomaly pattern. Additional experiments show that rainfall anomaly patterns induced by land surface variations stay basically robust when parameterizations and/or resolution are varied while absolute rainfall amounts are moderately affected (not shown).

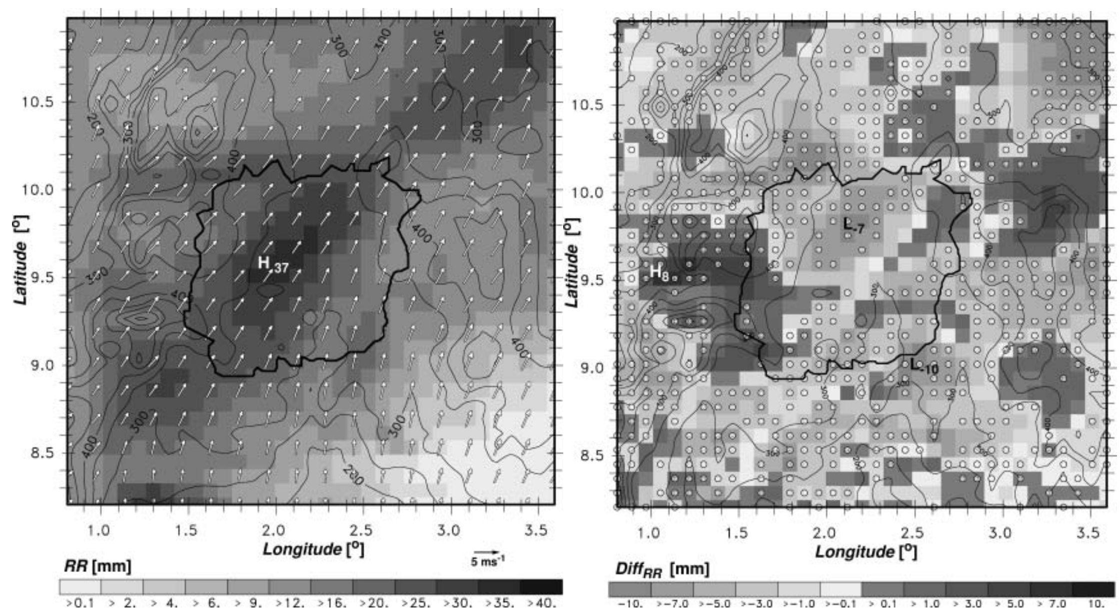

Fig. A1-8: Left: Accumulated precipitation and temporally averaged near-surface wind from July 28, 06 UTC to July 30, 06 UTC, 2000 simulated by FOOT3DK for an undisturbed surface. Right: Differences in resulting rainfall for the same event if adverse properties for rainfall (reduction of vegetation, soil water, roughness; increase of albedo) are introduced at the grid points that are marked by dots.

Consecutively, the response of rainfall to

a) a successive increase of the surface fraction with adverse conditions for the development of precipitation systems and
b) a successive reduction of surface vegetation and soil water at randomly distributed areas that cover half of the simulation domain

was tested. For this purpose, two series of each nine complex sensitivity studies were carried out for the same event and on the same grid as shown in Fig. A1-8. The response can be de-lineated in compact form by comparing number density distributions of rainfall differences between the reference run and the respective sensitivity experiment. Distributions reflect the sample of all grid points in the domain (cf. Fig. A1-9). This response consists of a nearly monotonous decrease in rainfall on average over the whole sub-catchment and an enhanced tendency to extreme rainfall reduction in some parts of the area for both series. While the response in series b) is remarkably systematic, series a) exhibits partly chaotic response. The methodology established hence enables the assessment of both systematic behaviour and uncertainties in the response of precipitation systems to land surface changes. As a whole, the results hint at a substantial risk of precipitation decrease if the land surface is unfavourably changed.

Sensitivity analysis with FOOT3DK will be incorporated into a statistical–dynamical approach based on a classification of characteristic regimes that account for the rainfall in the HVO. This methodology will enable a regional assessment of rainfall reduction risks by future land use changes.

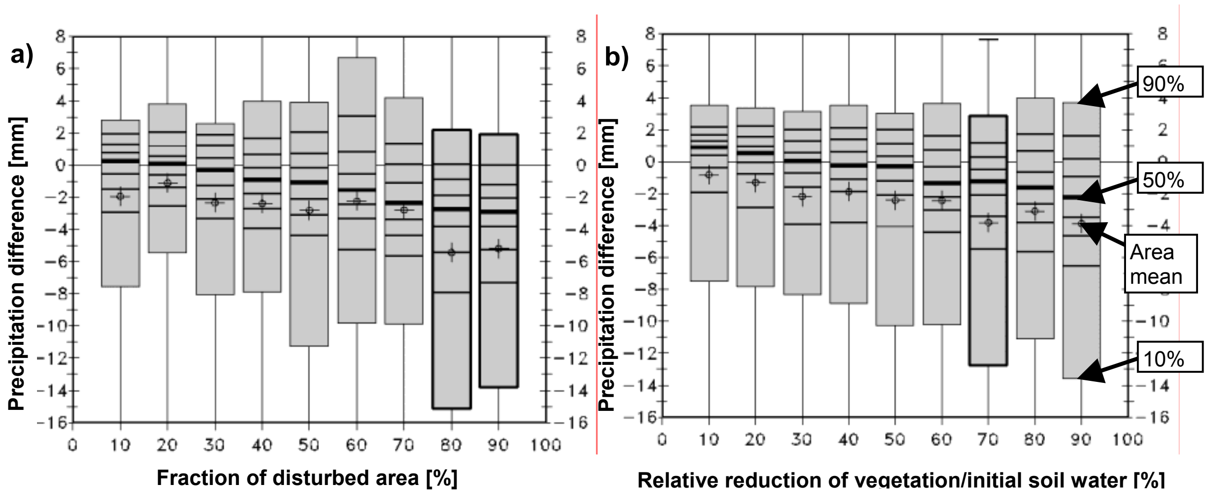

Fig. A1-9: Number density distributions of rainfall differences for two series of sensitivity experiments. Rainfall differences are based on a comparison between a reference run for the 28–30 July 2000 rainfall event and 9 sensitivity experiments for each series after 48 hours. Distributions are sampled from all grid points of the simulation domain. Each box refers to one simulation, representing the deciles of the domain that exhibits differences below the corresponding value on the y-axis from 10% to 90%. Medians: bold horizontal lines. Arithmetic area means: cross-circles. Left: response to successive increase of disturbed area fraction. Right: response to successive decrease in vegetation and initial soil water for randomly distributed areas that cover 50% of the domain.

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Subproject A2

Soil water dynamics, surface runoff, groundwater recharge and soil degradation on local to regional scale

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Summary

Main objective of the subproject A2 in the first project phase of IMPETUS was to describe, to analyse, and to quantify the land phase of the hydrological cycle and to integrate this knowledge into hydrological model approaches applied at local and regional scales. These models will be used in the second project phase as modelling tools for the scenario analysis. The nested approach of the hydrological subproject is based on intensive measurement campaigns and permanently installed instruments within the super test site Aguima (30 km^2) which is situated within the upper Ouémé valley. The permanent instruments (climate, soil water status, discharge) have been installed during the field campaign April/May 2001, and data have been gathered up to now showing only small gaps due to technical problems. These data are the basis for model application and validation on the local scale.

Based on intensive measurements the hydrological process knowledge could be improved and used for a model adaptation to the West African conditions (subhumid climate, savannah vegetation, tropical soils). Catchment properties and parameters concerning soil hydraulic properties and aquifer parameters were determined by field experiments. Furthermore the local soil map of the Aguima catchments has been finalised and has already been applied for local model applications in the super test site. Soil degradation and soil erosion rates could be determined by an installation of erosion plots. A significant correlation between erosion rates and cultivation practice of the local farmers was determined.

Hydrological model applications have been performed based on data gathered by IMPETUS on the local scale and derived from available standard datasets on the regional scale. Different model approaches have been applied successfully, the process based models TOPLATS and HILLFLOW on the local scale and the conceptual UHP model on the regional scale. Dependent on the scale and on the data available the models TOPLATS, HILLFLOW and UHP can be used for scenario analysis during the second project phase of IMPETUS. A comprehensive uncertainty analysis of the models has been performed to quantify possible errors and to assess the model performance to predict the catchment water fluxes. For a final validation of the process based TOPLATS model on the regional scale further data are required (regional digital eleva-

tion model, regional map of soil physical properties) which will be generated in the first year of the 2nd phase of IMPETUS.

The main task of the hydrological subproject in Benin during the first project phase was the identification and quantification of the dominant hydrological processes in the subhumid tree savannah in central Benin. From former projects in adjacent zones such as the Sahel (e.g. Hapex-Sahel-project) main processes and methodologies are known. But most of these investigations concern semi-arid catchments, and a transfer to subhumid conditions is not feasible. Therefore measurements at the local scale were necessary. As future predictions in the second project phase will be made on the regional scale on which detailed measurements cannot be performed, regionalisation approaches are required to transfer the knowledge from local to regional scale. From the problems and tasks described above the main objectives of the first phase were

- to analyse, understand, and quantify the hydrological processes in the subhumid tree savannah of central Benin,
- to apply, adapt, and validate hydrological models on local and regional scales to provide tools for the scenario analysis during the following project phase,
- to analyse the soil degradation process and the anthropogenic influence on soil degradation,
- to quantify selected hydrological processes and storages (surface water, ground water) and
- to combine all relevant results of the different sub-disciplines to a common understanding of the hydrological cycle.

To achieve these common objectives of the hydrological subproject of IMPETUS-Benin, subproject A2 was structured into four workpackages (WP): the analysis of the local hydrological processes (WP A2-1), the development and application of a regional hydrological model (WP A2-2), the analysis of soil degradation and soil erosion by water as well as the influence of human activities on soil degradation (WP A2-3), and the analysis of groundwater and groundwater recharge (WP A2-4).

The following results have been achieved in the different workpackages:

Workpackage A2-1: Investigation of the soil and surface hydrology of a small catchment

The aim of this workpackage was the investigation of the dominant hydrological processes in a representative local catchment in the study area of the upper Ouémé valley. The analysis was based on detailed field investigations concerning soil and surface hydrology of the super test site (Aguima catchment, permanent instrumentation (cf. subproject C2, Fig. C2.2) and the simulation of the hydrological processes using two different process based hydrological models.

Soil hydrology – soil moisture

To determine the spatial variability of the surface soil moisture on a small scale the nested sampling approach (Oliver & Webster, 1986) was applied in the upper Aguima catchment (natural vegetation) and in the upper Niaou (cultivated land) with measuring distances ranging from 30 cm to 100 m. The investigation revealed that in both land cover systems the small scale variability was very high. For woodland 70% of the variability was achieved in 3 m measuring distance, while for cultivated land the 70% were already achieved in 0.3 m distance. Despite this very high small-scale variability a spatial pattern of surface soil moisture, with highest soil moisture on the foot of the hillslope (*frz.: bas-fonds*) and lowest soil moisture on Plinthosol, was identifiable on hillslopes for the period of the high rainy season (August – October), where soil moisture was measured on transects with a mobile TDR-probe from March to November 2002. During the dry season and at the beginning of the rainy season no spatial pattern was observed along the hillslope. To analyse the soil water dynamic of different soil horizons of the dominant soil type Lixisol and different land cover types (sparse woodland, dense tree savannah, maize and cotton) four plots were equipped with four TDR-probes and four tensiometers in the depth of 0-20, 30-50, 80-100 and 120-140 cm. These data were also used for model validation.

Soil hydrology - Saturated conductivity and its relevance for the runoff generation processes

In order to examine the influence of landuse on soil surface permeability infiltration experiments using hood, double and single ring infiltrometers were carried out on different land cover types (agricultural and natural). To determine the saturated conductivity (k_s) of different soil types and different soil horizons core cylinders were extracted from 50 profiles, and saturated conductivity was measured using the constant head method based on Darcy's law. For the same soil profiles also other soil physical properties needed for model parameterisation were determined (unsaturated conductivity, saturated soil moisture, bulk density, soil water retention curve).

The infiltration experiments revealed that the permeability of the soil surface is strongly dependent on land cover. While for the different types of natural vegetation (sparse woodland, dense tree savannah, grass savannah) only small differences between the mean saturated conductivities were observed (cf. IMPETUS Annual Report, 2002), a significant difference between natural vegetation and cultivated land was measured. The main influencing factor for the saturated conductivity is the macroporosity of the soil which strongly depends on the soil biologic activity. An unpaired two-tailed *Student-t-test* proved the significant difference of the mean k_s-values measured by infiltration experiments on natural vegetation and on agricultural areas.

While the conductivity of the upper soil layer is mainly dependent on land use, the saturated conductivity of deeper soil horizons is more related to soil type and texture of the horizon. The soil types occurring on hillslopes (Lixisol and Plinthosol) show moderate conductivities (50-80 cm/d) for B-Horizonts and higher values for the Btc-Horizont (110 cm/d) which is characterized by a texture of loamy sand and a high amount of plintitic gravel. An apparent decrease of k_s was determined for the saprolithic horizon occurring in Lixisols from 60 cm depth with a more loamy texture. In deeper horizons macropores were also observed and caused an increase of measured k_s of single soil samples up to 160 cm/d. Concerning the predominant flowpaths within the soils on the hillslope, the decrease of k_s, which was determined on Lixisols (saprolithic horizon) and the impermeability of the plinthitic crust of Plinthosols forces lateral flow processes on the hillslope.

Water balance and runoff generation

To quantify the water balance of different sized sub-catchments of the Aguima catchment five water level gauges were installed at the (sub-)catchment outlets. Two gauges delimitate two small sub-basins with different land cover (upper Aguima: natural woodland/ tree savannah, 3.2 km²; upper Niaou: agricultural land use, 3.5 km²) in order to analyse the influence of land use on the water cycle. The gauges of these sub-basins were additionally equipped with automatic electric conductivity probes for the rainy season 2002 to get information about the ratio of groundwater and surface water of the streamflow.

The water balance of the year 2001 (cf. IMPETUS Annual Report, 2001) which was a dry year (about 800 mm rainfall) showed a huge difference of the discharge amount of the upper Niaou (139 mm) and the upper Aguima (23 mm) which could mainly attributed to the difference in land use. Because of lower infiltration rates on cultivated land, infiltration excess overland flow occurs on fields during rainfall with high intensity. In catchments with natural vegetation infiltration excess is very rare and surface runoff occurs mainly as saturated overland flow when the soil is saturated in September and October. For the year 2002 with 954 mm precipitation the difference in water balance between the two sub-catchments was less significant (115 mm upper Aguima, 160 mm upper Niaou). This could be mainly ascribed to the higher amount of saturated overland flow in the upper Aguima catchment, caused by a higher frequency of rainfall events in September and October in 2002. At the beginning of the discharge period in August, where soil is not yet saturated, discharge peaks of the upper Niaou were significantly higher than of the upper Aguima which was caused by infiltration excess runoff on the fields. In September and October only small differences in discharge amount and peaks of the two catchments were observed. The calculation of the amount of surface runoff of two events, based on electric conductivity measurements, has proved this observation. For the event 24.08.02 only 0.3 mm surface runoff was calculated for the upper Aguima, while 1.4 mm for the upper Niaou. For the event on 14th Sept, 2002, where the soil was almost saturated because of several antecedent rainfall events, nearly the same amount of surface runoff was determined for both catchments (2.6 mm upper Aguima, 2.5 mm upper Niaou) (see Fig. A2-1).

Hydrologic modelling on local scale

On local scale two different model concepts were applied to evaluate the suitability of these concepts for a hydrological process analysis and regional model application in the research area. The TOPLATS model (Famiglietti & Wood, 1994) is a grid-based spatially distributed model which combines the simulation of spatially distributed, single SVATS with the lateral TOPMODEL concept. The validation of the simulation results revealed that the water balance and the discharge were well reproduced by the model (Fig. A2-2). Additionally the surface runoff simulated by the TOPLATS model was validated by comparing the model results with measured surface runoff data from erosion plots (WP A2-3). The agreement of the simulated (58 mm) and the observed (50 mm) for the year 2002 was fairly good. Finally also the simulated soil moisture was compared to measured values gathered by the automatic soil water stations. A good agreement was observed.

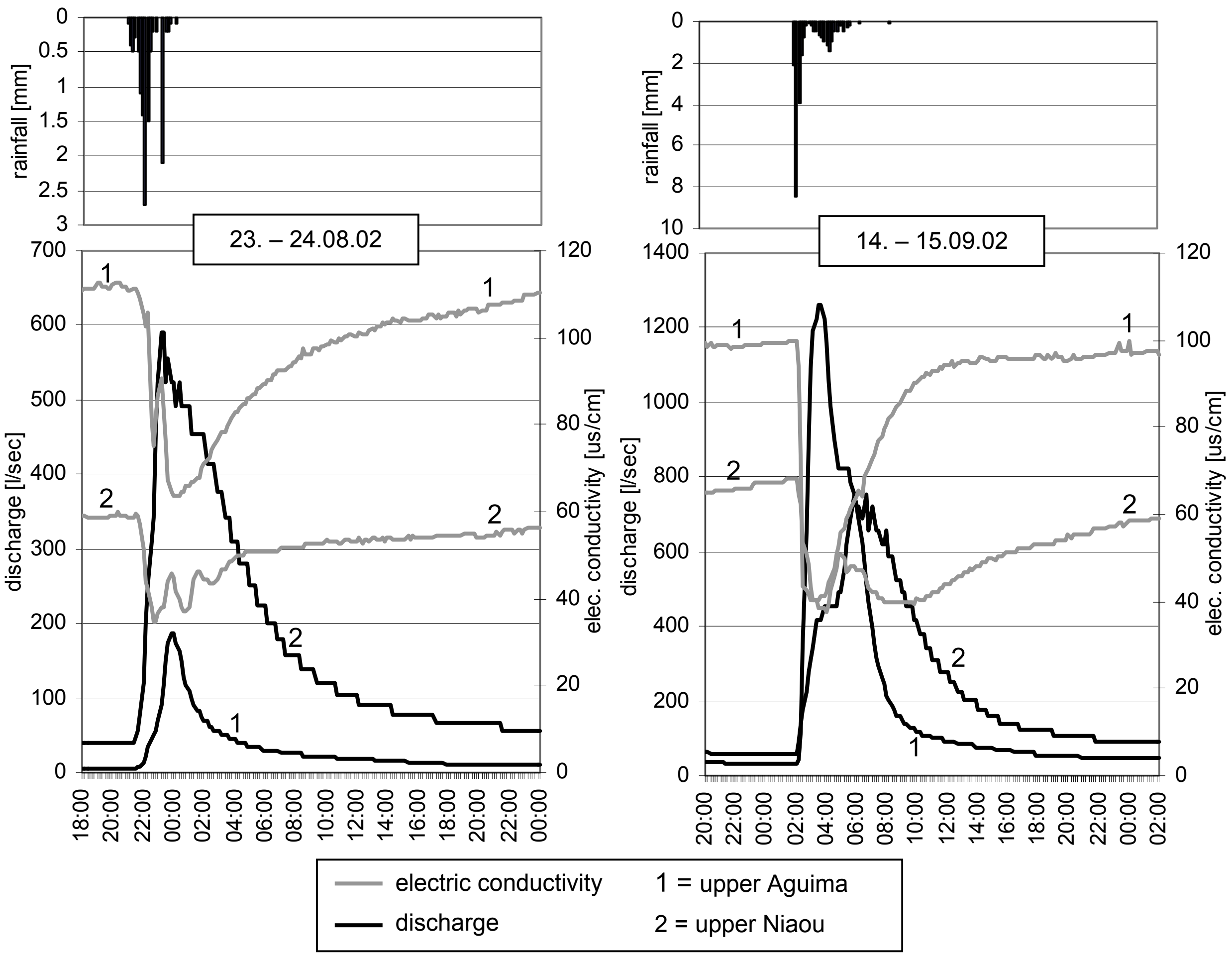

Fig. A2-1: Comparison of measured discharge and electric conductivity of the upper Niaou and the upper Aguima catchment for two events (23rd / 24th August 2002 and 14th / 15th Sept. 2002).

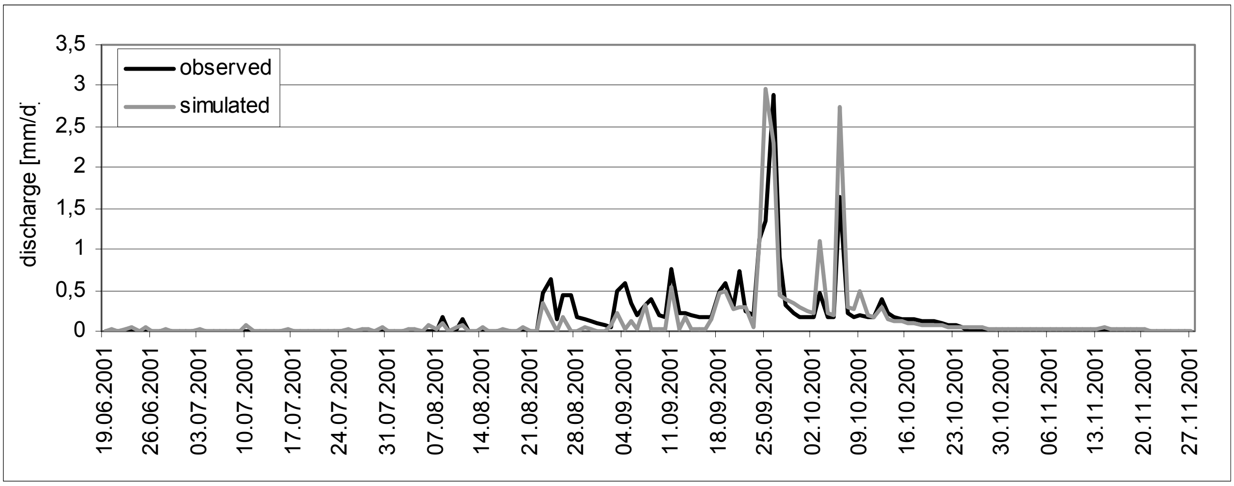

Fig. A2-2: Comparison of simulated (TOPLATS model) and observed discharge of the Aguima catchment (super test site) for the year 2001.

As second model concept the hillslope based hillflow2d model (Bronstert, 1994) was tested for the upper Aguima. The advantage of this model is the detailed vertical discretisation of the soil profile which enables the user to analyse the soil water dynamic of different soil horizons. The simulation results showed a good correspondence for the simulated and measured mean soil water behaviour measured with TDR-probes in different depths.

The local measurements in the super test site showed the importance to consider the spatial variability of the soil water dynamics when quantifying the local water budget. Two different process-based models now are available on the local scale for scenario analyses considering the spatial variability of the predominant catchment properties. In the second project phase the knowledge about the processes and the models themselves - validated at the local scale - have to be upscaled for predicting changes at the lower mesoscale. Therefore regionalisation strategies are required.

Workpackage A2-2: The regional hydrological model

Main objectives of the workpackage A2-2 in the first phase were the selection, adaptation, and validation of a suitable model concept to reproduce the hydrological processes at the regional scale in the upper Ouémé valley. Different model concepts were compared to decide which concept is the most appropriate for the regional scale water flux simulations and which one can be used for the scenario analyses planned for the 2nd phase of IMPETUS.

As a second task the completion of a regional spatial dataset based on standard datasets of soils, topography and geology was performed for the Térou catchment to build up a Hydro-GIS to be used for regional hydrological model applications.

Two model concepts for regional hydrological modelling in the Térou basin (3133 km^2, a subcatchment of the upper Ouémé valley) were compared, a process and physics based model and a conceptual model. The process based TOPLATS model (Famiglietti & Wood, 1994) requires a number of spatially distributed model parameters (using a grid size of 100*100 m) and therefore needs detailed input data on soils, vegetation and topography. The conceptual and lumped UHP model (Bormann & Diekkrüger, 2003) consists of four storages generating the different flow components on the subcatchment level. The catchment water fluxes are calculated by superposition of the subcatchment water fluxes. As the process description of this model is simple the data requirements are significantly smaller. Model parameters have to be determined only on the subcatchment level. Both models were applied to standard datasets of the Térou catchment and driven by climate and rainfall datasets of the French CATCH project. The quality of the simulations was compared by standard quality measures (longterm water balance, model efficiency, coefficient of determination) and by the investigation of different sources of uncertainties incorporated in the model application process. Main focus was set on the uncertainties caused by input data and model parameters.

A Hydro-GIS was established by digitising spatial maps of soils (1:200.000) and geology (1:600.000) for the Térou catchment. A digital elevation model was built by digitising the contour lines of the topographic map 1:200.000 and converting them into a raster based terrain model.

The TOPLATS model was applied and validated successfully at the super test site scale (see WP A2-1). For the application at the regional scale (Térou, upper Ouéme basin) further datasets are required containing information on soil physical properties and spatial distribution on rainfall intensities. A comparison of the TOPLATS model to a conceptual approach showed that based on the data available on the regional scale a model validation is not feasible (Bormann & Diekkrüger, 2003). Main reason is the high sensitivity of soil physical model parameters on the one hand and their limited spatial availability on the other hand. Thus a validation of TOPLATS at the regional scale will be done when these datasets are available (2^{nd} phase of IMPETUS).

Due to the described limited data availability at the regional scale a simplified model concept was applied (UHP model) which does not require spatially distributed data on soil physical properties and rainfall intensities and which is robust with regard to data uncertainties. The model, similar to the HBV-model (Bergström, 1995), was calibrated using a 7 year dataset of hydrometeorological data (1993-1999). For the validation period (2000-2002) further data are required from the CATCH project, especially for the year 2000. From April 2001 onwards own IMPETUS data are available. So the model validation at the moment is limited to the results of the uncertainty analysis. The 7-year water balance is simulated exactly (25.2 m^3/s mean observed discharge compared to 25.1 m^3/s mean simulated discharge) with a model efficiency of 0.76. The seasonality as well as the slow runoff component (base flow) are simulated very well (cf. Fig. A2-3).

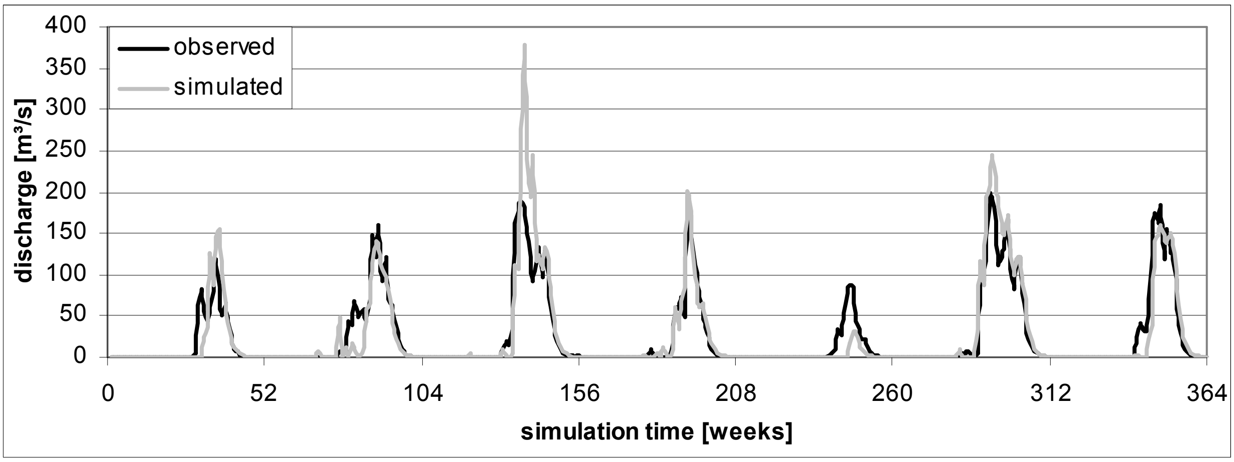

Fig. A2-3: Observed discharge versus simulated discharge (using the UHP model) at the gauge Térou-Wanou (3133 km^2) for the 1993-1999 period.

The uncertainty analysis focused on the uncertainty of model parameters using the Latin Hypercube method (McKay et al., 1979) and on the comparison of the effect of decreasing knowledge about catchment precipitation (decreasing number of rainfall stations considered). Taking into account the data of more rainfall gauges and therefore better information on spatial rainfall variability led to an expected increase in the model efficiency (from 0.77 using 4 gauges to 0.91 using 6 rainfall gauges). Applying the Latin Hypercube method the model parameter uncertainty (described by a statistical distribution of the model parameter) could be transformed into a reliability measure of the simulated hydrograph. An uncertainty confidence interval (e.g. 80%, 90%) was calculated. If the observed hydrograph lies within the uncertainty band, then the model can be assumed to be useful as a predictive tool. In the case of the Térou catchment the uncertainty band was narrow for most of the simulated years and the observed hydrograph was lying mostly within the 80% confidence interval (cf. IMPETUS Annual Report, 2002).

To investigate the suitability of the conceptual model approach for scenario and management applications, first simple scenario examples were calculated. Concerning the temporal distribution of a change in annual rainfall as well as concerning changes in vegetation cover and soil thickness a high sensitivity was detected. This points out the need to define scenarios of a possible future development based on the local and regional knowledge about changing properties and boundary conditions.

The Hydro-GIS for the Térou catchment was completed at the end of the first phase. All data sources available (soil map, geological map) were digitised and integrated into the Hydro-GIS. A digital elevation model (DEM) was built from the digitised contour lines of the topographic map 1:200.000. The DEM is needed to derive the catchment boundaries, the drainage network and the topographic wetness index. Adding the vegetation classification of the subproject A3 to the Hydro-GIS, all information layers needed for regional hydrological model application are included. The usability of the dataset is limited due to the fact that the information available is not sufficient to derive all model parameters, especially soil physical model parameters. Thus some data and parameters uncertainties persist.

From the work of the first phase two different models which can be used as modelling tools for the scenario analysis are available. The spatially distributed TOPLATS approach was validated at the super test site scale, but until now it is not applicable at the regional scale due to data deficiencies. When the regional map of soil properties is finished, the applicability of TOPLATS at the regional scale will be tested. In addition to TOPLATS the UHP model was introduced and adapted for the purpose of calculating longterm water balances. It is a simple and robust model to calculate water balances at the regional scale, not considering spatial patterns and changes in patterns their dynamics on the water cycle but being able to consider changing boundary conditions (precipitation, evapotranspiration, water demand) and changing catchment land surface properties.

The Hydro-GIS datasets need to be completed for the entire regional-scale upper Ouémé catchment. The vegetation classification (subproject A3) is available as well as the digital elevation model derived from the topographic maps of the scale 1:200.000 (generated by the former Soviet Union). The regional soil map is available but has to be improved with regard to information about physical and chemical soil properties which will be examined in the forthcoming project period by workpackage A2-3. Finally the digitising of the geological maps for the whole upper Ouémé catchment will be available within the next months. At the end of the first year of the second project phase the Hydro-GIS will be finished for the target region upper Ouémé.

Workpackage A2-3: Anthropogenic soil degradation due to water erosion in the upper Ouémé valley/Benin - soil loss on pediplain relief under semi-humid tropical summer rain climate

During the last two decades an increasing settlement activity has been registered within the target area of the IMPETUS project. Accordingly, agricultural use of the soils has extended and intensified and it can be assumed that there is an increasing impact on the soil degradation process. Thus the objective of this study was to analyse the current situation of soils and soil degradation, including the collection of precise data on the spatial distribution of soil types and soil properties. Using theses field data the existing soil map 1:200.000 was improved for the local scale super test site. Furthermore the objective was to collect information about soil erodibility and to assess the influence of different crops and cultivation practises on the soil erosion by water.

Profiles and drillings of soils in the super test site (Aguima, 30 km^2) were analysed and described according to the Guidelines for Soil Description (FAO, 1990). Soil samples were taken and analysed according to the Procedures for Soil Analyses (Van Reeuwijk, 2002) to obtain detailed information on soil properties and their distribution. For the classification the following systems were used: *Classification des Sols* (Aubert, 1965), *World Reference Base* (FAO-ISSS-ISRIC, 1998) and *Keys to Soil Taxonomy* (USDA, 1998). The assessment of the chemical soil properties was made according to Landon, 1984.

Runoff plots (16 m^2) and sediment traps were installed in the savannah and on cultivated land with different crops (cotton, yam, maize) and different tillage systems (rows, mounds) to quantify the soil loss rates. Erosion pins were installed within the fields to investigate the soil movement on the micro scale. For comparison purposes soil analyses and erosion measurements by traps were also performed in Awanla and Serou (35 km to the west and 5 km to the east of Djougou), two other villages in the upper Ouémé region.

The potential soil loss was estimated according to the Universal Soil Loss Equation (Wischmeier & Smith, 1978). To assess the rainfall erosivity, precipitation data gathered by the CATCH project and IMPETUS subproject A1 were analysed.

<u>Soil Units</u>

The super test site is located in an undulating pediplain relief. Due to the genesis of the landscape, the soils show a discontinuity. The autochthonous bedrock (granites, gneisses) and its weathered residues are covered by allochthonous layers, pediment gravel and a fine grained substrate (Rohdenburg, 1969; Fölster, 1969). Soils formed on the slopes are *Sols ferrugineux tropicaux lessivés modal* (Orthidystri-Epi- or Endoskeletic Acrisols/Haplic Lixisols or Typic Kandiustults/Typic Kandiustalfs), the dominant soil unit of semi-humid regions (soil map, Fig. A2-4). *Sols ferrugineux tropicaux lessivés indurés* (Hyperalbi-Petric Plinthosols/Plinthic Petraquepts) developed at lower parts of the slopes. The soils of inland valleys are classified as *Sols hydromorphes minéraux ou peu humifères à pseudogley à nappe perchée* (Humic Gleysols/Typic Epiaquepts). In riverbeds *Sols peu évolués non climatiques d'apport alluvial modal* (Arenic Fluvisols/Typic Ustifluvents) are distributed. In Awanla and Sérou similar soil units are found.

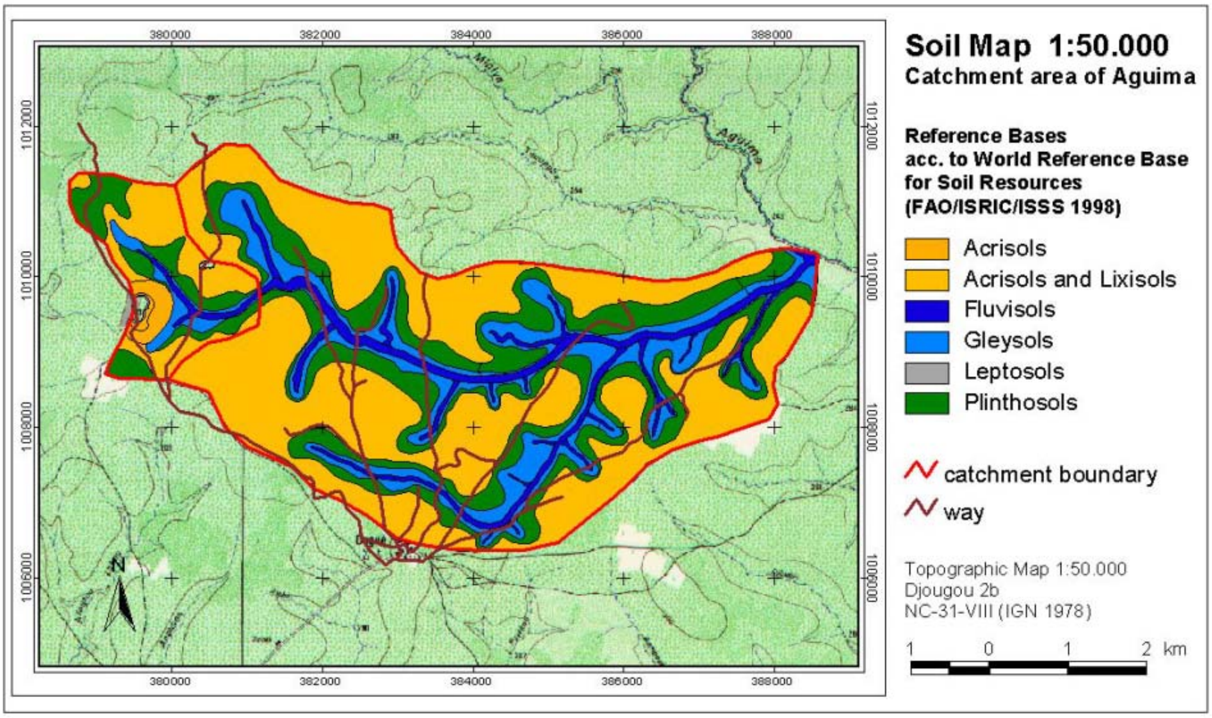

Fig. A2-4: Soil map of the super test site Aguima.

The maximum rooting depth of the soil units on the slopes is shallow to moderate (30-100 cm) because of substrates with very high bulk densities such as saprolite or ferricrete. Due to the sandy top layer and the small thickness of the solum, the available field capacity in the root zone is low to moderate (50-140 l/m^2). The soil reaction is moderate acid to neutral (pH_{H_2O} 5,5-7), only termites' nests are alkaline. The soils have a moderate base saturation (BSP) (20-60%) and a low to moderate cation exchange capacity (CEC_c) (15-25 $cmol_c*kg^{-1}$) due to the high amount of kaolinite (about 80%). Only the horizons at the surface show higher amounts of organic matter and therefore higher BSP and CEC_c. The contents of the main plant nutrients nitrogen (< 0,1%), potassium (< 0,2 $cmol_c*kg^{-1}$) and phosphate (< 15 ppm) are also low. For the two test sites in the northern part of the upper Ouéme basin (Awanla, Sérou) almost all concentrations of nutrients and contents of organic matter are slightly lower. This result fits well to the assumption that a more intensive agricultural use of the soils in the northern part of the catchment has enforced the leaching of the solutes.

Soil Degradation

Measurements of the current soil loss by runoff plots indicate a significant influence of different growing systems (KW-test, $p < 0,01$) and crops (KW-test, $p < 0,05$) on soil loss (Fig. A2-5). The highest loss was found on cotton fields cultivated in rows parallel to the hill slope. In comparison, there was less erosion in fields with yam planted on mounds and crops on rows parallel to contour lines (e.g. 4.3 $t*ha^{-1}*a^{-1}$ soil loss under maize). In the savannah soil erosion also occurs, but to a significantly lower extent. In Sérou and Awanla the measurements show comparable results, only soil loss in Awanla was slightly higher due to steeper slopes. Measurements with erosion pins on differently prepared soil surfaces show similar results. In summary soil loss in agriculturally used fields was always higher (mean 40 $t*ha^{-1}*a^{-1}$) than in the savannah (mean 3.9

t*ha^{-1}*a^{-1}). Assuming these conditions for the future, erosion would lead to a decrease of the thickness of the top soil layer and thus decrease rooting depth and field capacity. Drillings near the super test site already show this reduction of hillwash thickness (up to 13 cm, n = 7) on farm land clearly visible in the higher content of gravel and the colouring of the top horizon.

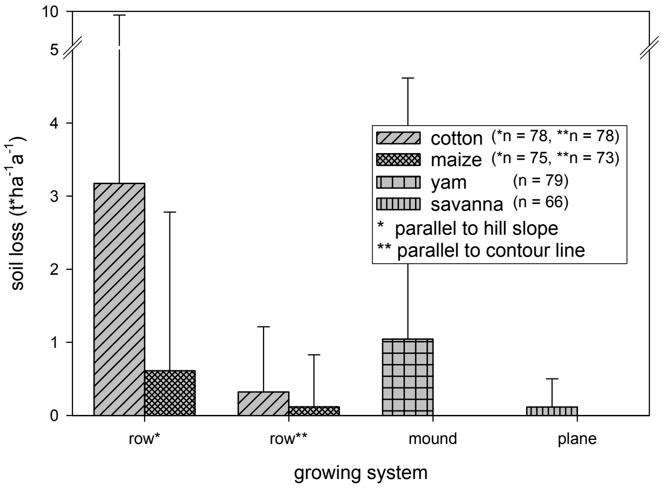

Fig. A2-5: Mean soil loss rates depending on land use and cultivation practices (2002, Aguima).

Analyses of grain size distribution reveal that surface substrata of Acrisols consists of sandy loam or loamy sand, but in about 90% of the analysed eroded sediments (n = 83) the clay content is about twice as high. It is also noticeable the that eroded material contains higher quantities of organic carbon and nitrogen (up to twice as high in Doguè, 3-4 times higher in Sérou, Awanla) than the A-horizon of the soils. These results point out that chemical degradation also occurs. The comparison of chemical parameters of savannah soils and agricultural fields also show this leaching under human cultivation. For example the amount of humus and thus the CEC_c in the upper horizon of agricultural fields (n = 7) is significantly lower than in savannah soils (n = 17).

The mean rain erosivity (R-factor of the Universal Soil Loss Equation) in the test site of about 893 N*h^{-1} (1998-2002) is comparable to former investigations close to the IMPETUS research area (Van Campen, 1978). The variability between 677 N*h^{-1} (minimum in 2000) and 1152N*h^{-1} (maximum in 1998) is within the limits defined by Roose, 1977, for this latitudes in West Africa. Also the erodibility (K-factor of the USLE) of Acrisols (0.21 - 0.29 (t*h)*(N^{-1}*ha^{-1}) and finally the calculated soil loss (20 – 27 t*ha^{-1}*a^{-1}) is comparable to those for *Soils ferrugineux tropicaux lessivés* estimated by Van Diepen, 1980. But a comparison of the field measurements to the estimated results remains difficult. For a detailed comparison further research over a longer period would be needed.

For the 2nd phase of IMPETUS the knowledge about the soil genesis at the local scale has to be transferred to the regional scale to improve the regional soil map 1:200.000 of the upper Ouémé valley. Combining the available regional soil map, the vegetation classification of subproject A3, a digital elevation model, and some soil sampling along typical catenas a regional map of physical and chemical soil properties will be generated.

For the prediction of soil erosion in the future soil erosion models are required. Different concepts will be tested in the 2nd phase of IMPETUS to hindcast historical soil erosion rates and to be used for prediction purposes under changing environmental conditions (climate, vegetation degradation, soil cultivation, etc.). The results of the measurement campaigns are useful to parameterise and to validate the models (e.g. rUSLE, SWAT). Using the rUSLE equation simple scenario calculations can be performed, investigating the effects which changing factors (‘environmental change’) have on the predicted soil loss.

Workpackage A2-4: Groundwater and groundwater recharge in the Ouémé catchment

Groundwater dynamics and groundwater recharge are of significant importance within the hydrological cycle. In order to understand the utilisation potential of the groundwater resources in the Ouémé catchment research during the first project phase was focused on the development of a conceptual model of the groundwater related processes, on a detailed description of the aquifer system including both water quality and quantity, and on the investigation of the transport processes within the vadose zone. Research was carried out at the local catchment scale (instrumentation map of the Aguima super test site (cf. subproject C2, Fig. C2.2).

Basic requirements for a hydrogeological evaluation of the basement aquifer are well-grounded knowledge in both the general geological setting and the structural pattern of the area under investigation. Therefore detailed geological mapping accompanied by thorough literature survey was performed. Additional information on the different lithological units was derived by mineralogical and geochemical analyses of rock and soil samples.

Hydrochemical analyses and environmental labelling with ^{18}O, ^{2}H and ^{3}H of groundwater, soil water, and surface water samples taken during the dry and wet season allow a hydrogeological classification as well as an evaluation of the origin of the various water types.

For the understanding of the flow system hydrodynamic measurements such as local and regional piezometric mapping and pumping tests as well as tracer experiments were performed. Furthermore the recharge mode in the vadose zone was examined by a monitoring network of TDR measuring tubes and suction cups (super test site, cf. subproject C2, Fig. C2.2). Monitoring was performed by weekly measurement with a mobile TDR tube access probe and frequent sampling.

Hydrogeological setting

As part of the African Precambrian shield the aquifer in the area under investigation is built up by granitoid and gneissic migmatites, characterised by a NNW-SSE (fractures) and NNE-SSW striking (faults, dikes) structural pattern. This pattern is decisive for the regional groundwater flow. The first regional water table contour map (Fig. A2-6) has to be improved by further regional data acquisition. The fractured basement aquifer is characterised by a transition towards a quasi-porous aquifer in its overlaying weathering zone. This vadose zone is structured and consists of a saprolithic weathering zone above the migmatitic basement followed by a lateritic strengthened horizon which is overlaid by a (mostly) high permeable sandy topsoil (Fig. A2-7). The saprolithic weathering zone has a mean thickness of about 12 m and is only partly saturated due to differences in the water table between dry and wet season (Fig. A2-7). Pumping tests during the wet season 2002 proved the reaction of the vadose zone as a leaky (semi-confined) quasi-porous aquifer with the lateritic strengthened zone as a low permeable upper boundary. The transmissivity (T) is in the range of 0.7 to $2.0*10^{-6}m^2/s$.

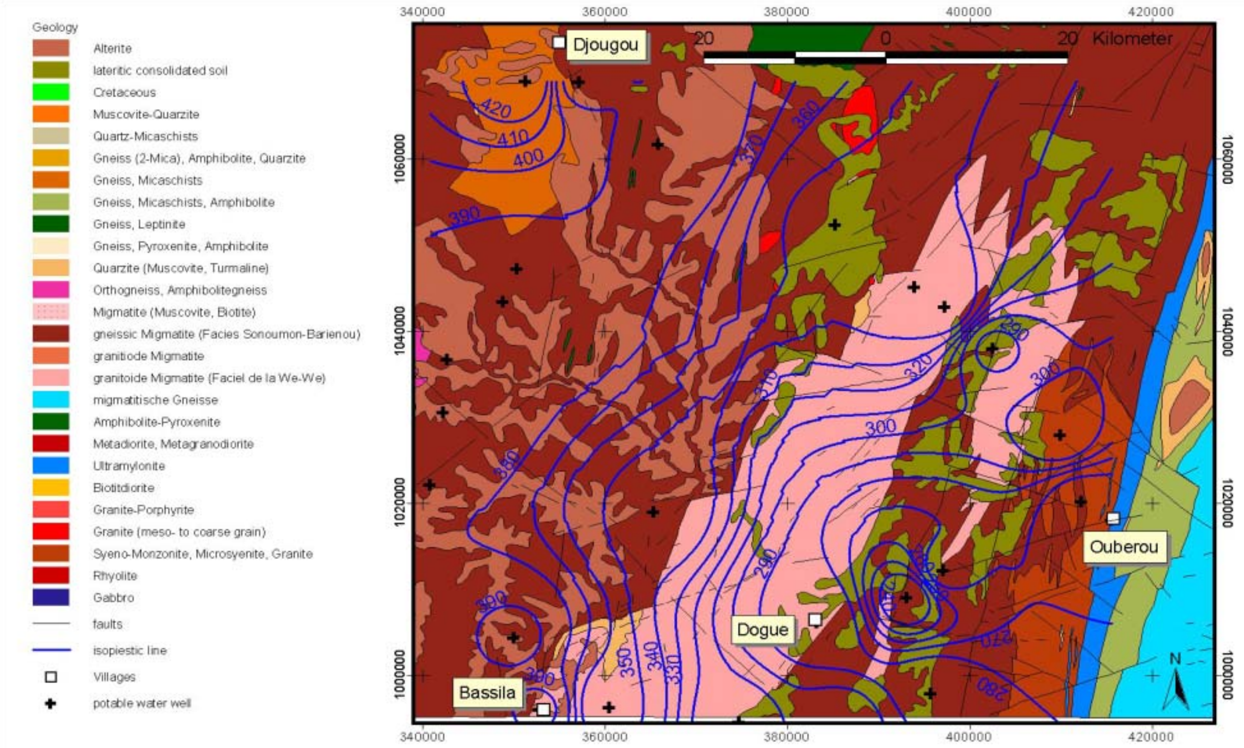

Fig. A2-6: Regional geological map of the study area with contours of the observed groundwater depth of the year 2002 (dry season).

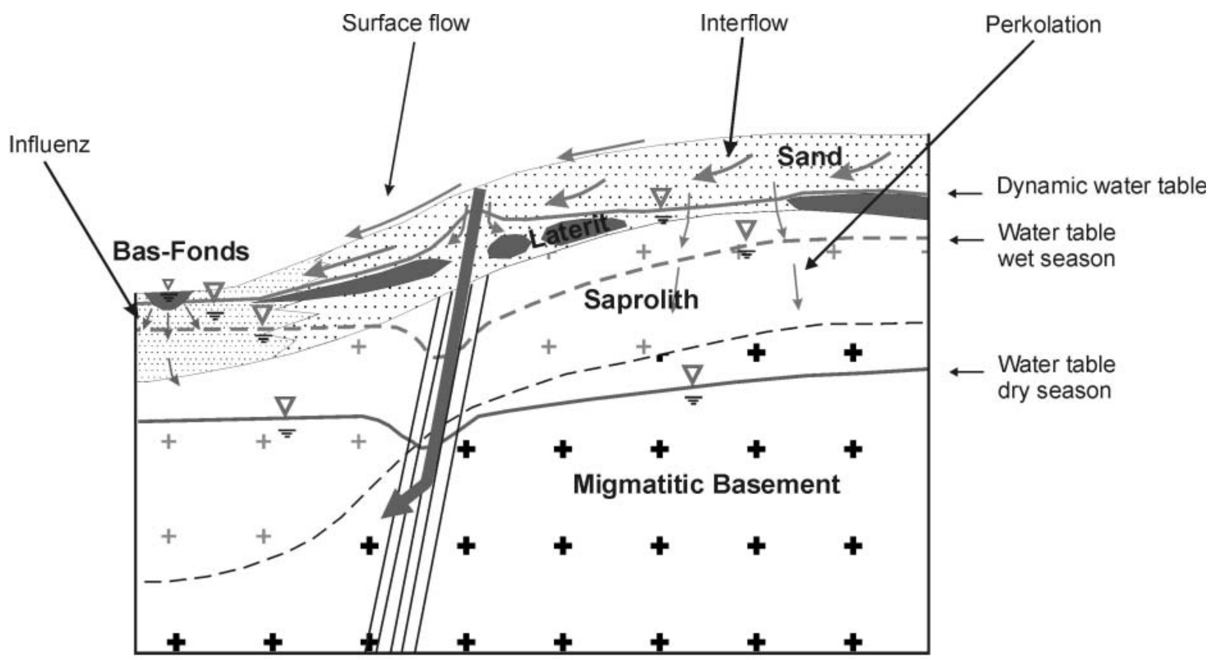

Fig. A2-7: Conceptual hydrogeological model for the basement aquifer including the vadose zone in the Aguima catchment.

Recharge mode

The development of the soil water content in the vadose zone can clearly be distinguished with respect to geology and lithology. Both a clear dependence of the soil moisture content on the substrate as well as a strong influence of low permeable horizons on the percolating water is evident. The lateritic strengthened horizons act as aquitards, where percolation of the infiltrating precipitation water is deviated. While this part of the percolate contributes to the surface water (interflow), another part is able to pass the nearly impermeable lateritic horizons through preferential flow-paths and thus contributes to the groundwater recharge. This local groundwater recharge only can take place in periods with high soil water contents (mid-August to mid-October at the super test site Aguima). It can be assumed that due to significant deviations between groundwater and soil water chemistry, major recharge of the groundwater at the super test site derives from inflow from regional recharge areas outside the local scale catchment. The ^{18}O-content of groundwater provides some evidence for recharge by evaporated water. The analysis of samples taken from ground and surface water (tracer tests, isotopic samples) is still ongoing.

Regionalisation of the results of the first phase includes the upscaling of the local hydrogeologic results from the super test site Aguima to the entire upper Ouémé valley. The Aguima conceptual hydrogeological model will be used as the nucleus for a 3D numeric groundwater flow (transport) model for the whole catchment. Regional anisotropy effects in the hydrogeologic characteristics of both basement aquifer and its vadose zone have to be examined by selected further field investigations. After the calibration for steady state conditions the 3D numeric groundwater model will run in transient conditions. This allows the prediction of the changes in the groundwater resources under various environmental change scenarios.

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Subproject A3

Functional relationships between spatio-temporal vegetation dynamics and water cycle

Participants	Discipline
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Summary

The investigation of the functional relation between the spatio-temporal vegetation dynamics and water cycle was the main focus of the IMPETUS Work-package A3. Therefore a comprehensive classification of the actual land use / land cover in a spatial resolution of 30 m was performed. This classification was backed by detailed investigation on representative test plots for the different vegetation units with an assessment of the key vegetation parameters. The inner seasonal vegetation dynamics were analysed with remote sensing data and through detailed studies within the test plots. It turned out that more than 60% of the area of investigation are affected by fires. The impact of the fires with regard to the nutrients, biomass, and CO_2-cycle was examined. Analyses of long term inter-seasonal land use / land cover changes (LUCC) showed the dramatic dimension of the changes. The area of farm land doubled between 1986 and 2001 and 40% of the dense forests disappeared. The impact of logging on the ecosystem, ecosystem stability and micro climate was investigated with different botanical and eco-physiological methods. Based on the outcomes of that research a sustainable management system for the forests can be developed further on. To understand the LUCC process the spatial pattern of changed land use / land cover was linked with additional socio-economic data, especially detailed census data. This analysis can lead to a model approach describing land use / land cover change.

With respect to food security the water use efficiency and biomass production of the main field crops was investigated. Therefore extended field experiments with more than 100 test plots were carried out. The yields gained with recent farmer practice were compared with yields from fields with different manuring. By adequate practice up to three times higher yields can be gained. This is an important result for sustainable land management.

An essential contribution to the climate history of the study region was achieved by tree ring analyses.

The following results have been achieved in the different workpackages:

Workpackage A3-1: Assessment and modelling of land use / land cover and their changes with remote sensing

Land use / land cover is one key parameter within the hydrological cycle. Up to now available datasets of the land use / land cover for the area of investigation (e.g. from the IGBP) are not very detailed and accurate. Therefore a main focus of the IMPETUS workpackage A3-1 was the precise assessment of the land use / land cover as well as the description of the vegetation dynamics on different temporal and spatial scales.

<u>Land use / land cover classification</u>

It was a goal to derive an up-to-date land use / land cover classification in a resolution of 30 m from LANDSAT 7 ETM+. The classification scheme was set up in a close co-operation with the botanists and from discussions with the meteorologists. Classifying the land use / land cover in the test area is a difficult task due to the very high vegetation dynamics arising from the alternation of wet and dry seasons. Additionally there are strong atmospheric influences (e.g. moisture, dust). To overcome these problems an advanced processing chain for classification was developed. First the remote sensing scenes were radiometrically and geometrically corrected. The land use / land cover classification itself was performed by a combination of supervised and knowledge based multi-temporal classification approaches (Thamm & Schöttger, 2001). Beside the spectral properties of the vegetation units their characteristic changes due to the change of dry and wet season were used to distinguish the different vegetation units. This lead to a comprehensive classification of the LUCC in a resolution of 30 m for the years 2000 and 2001. The LUC classification for the "historical" LANDSAT TM scenes of 1991 and 1986 was performed as well. Another step was the derivation of land use / land cover classification from SPOT VEGETATION data in a resolution of 1 km.

All the classification results were composed in maps and digital form and distributed to the other IMPETUS workpackages to use it as input for their models.

To back the classification and for a quality assessment of the classification results comprehensive information about the ground truth was gathered in various field campaigns and compiled in a spatial related database with more than 3000 datasets. Additional information like spot measurements of leaf area index (LAI) or phenological properties are attached in that database as well. The so gained "ground truth" can be included as a regional dataset in other international accessible databases like the Africover (http://www.africover.org/).

<u>Vegetation dynamics</u>

Within the area of investigation high vegetation dynamics can be observed. On the one hand there is the inner-seasonal vegetation due to the change of wet and dry seasons and on the other hand there is a long term change of the vegetation due to human activities (e.g. degradation) or changes in the hydrological cycle. The investigation of the inner-seasonal dynamics was performed in different spatial scales. In a high spatial resolution (30 m) multi-temporal LANDSAT scenes of the catchment where analysed between for the years 1999 to 2002. In a higher temporal resolution 10-day NDVI data of the European satellite SPOT VEGETATION with a resolution of 1 km where investigated for the period 1998-2002.

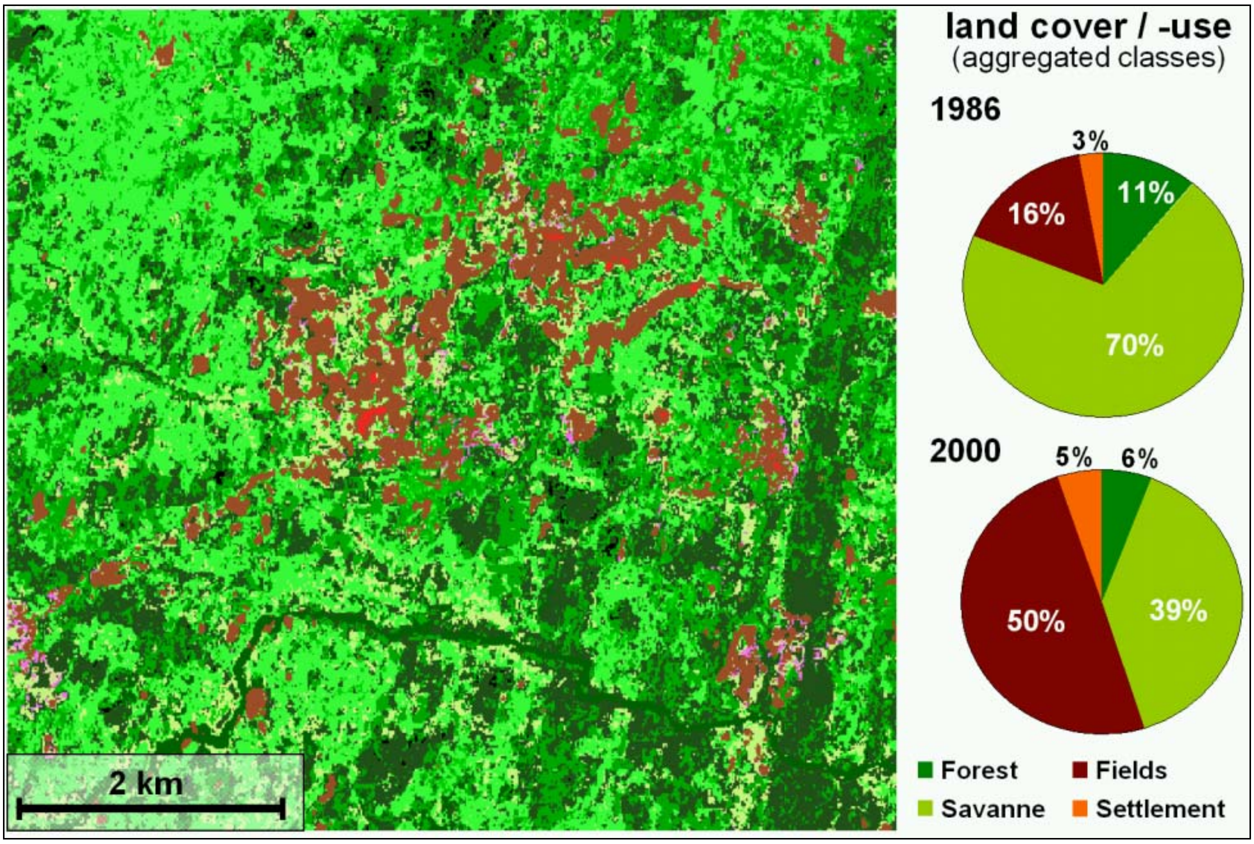

Fig: A3-1: Subset of the detailed land use / land cover classification (with 14 classes) around Kpawa for the year 2000 (left) . Percentages of land use / land cover (aggregated classes) for the whole catchment of the upper Ouémé for the years 1986 and 2000 (right).

One essential outcome of this work was fact that more then 64 % of the area is subject to fire within the dry season 2000. This has dramatic consequences on the nutrient cycle, the CO2 output, and on the regeneration potential of the vegetation. In co-operation with agronomy and botany a quantitative assessment of burned biomass and fire temperature was achieved. This is an important step towards the modelling of carbon budget and biomass production.

Analyses of the long-term inter-annual vegetation dynamics between 1986 and 2002 showed dramatic changes in the land use / land cover for the area of the upper Ouémé (Fig. A3-1). The detection of the land use / land cover changes (LUCC) was done using advanced techniques like change vector and principal component analyses. Hereby the methods were adapted and improved to suit the situations of the Guinean-Sudanian vegetation zones (Thamm et al., 2002). It turned out that there are three main causes for the LUCC in the area of investigation 1) new colonisation of agricultural land, 2) logging activities and 3) growth of settlements. Between 1986 and 2001 the agricultural land has more than doubled. Within the same period areas with dense forests were reduced form 11% to 6%. The speed of the LUCC has non-linearly increased in the last two years.

To create scenarios for future development it is important to understand the driving processes which lead to the LUCC. In this context there was a close co-operation with the other work-packages of IMPETUS to link the spatial patterns of the land use / land cover changes with additional information. For example together with the botanists (work-package A3-2) the effects of the logging activities and the fragmentation of the forests where investigated more in detail. A part of this results where presented at the annual meeting of the American Association of Geographer (AAGI) in Los Angeles (Menz & Thamm, 2002).

Intensive discussions with the colleagues for anthropology and economy (subproject A4) leads to an identification of the actors and gives the rational of the LUCC for parts of the upper Ouémé catchment. For example based on the detailed census data gathered by subproject A4 the speed and the pattern of the LUCC could be linked with this data (e.g. number of people, age structure, origin, system of agriculture, etc.). To meet the demands of the remote sensing the census was intensified. According to a subsample procedure more than 400 households were questioned. This comprehensive dataset is an important precondition for the regionalisation and calibaration of a LUCC model and herewith for the calculation of different scenarios of the land use / land cover under different boundary conditions.

An important question with regard to landscape management is the impact assessment of infrastructure measures like roads. Therefore the spatio-temporal changes of the land use / land cover along new-built roads were critically analysed in relation to census data.

Evaluation of land conservation, forest conservation, and fire management measures

For the protection of the environment and food security, numerous development agencies undertook projects to protect forests, to reduce soil erosion and to incorporate an appropriate fire management. However, it is difficult to evaluate the success of these measures. Traditionally the success is evaluated by field campaigns, but this method is expensive, time consuming and cannot cover the whole area of intervention. Remote sensing offers a good alternative as it observes wide areas at the same time. In this context a new project was started in co-operation with the GTZ to investigate the possibilities and limitations of an evaluation of the land conservation measures with remote sensing. It turned out that for the evaluation of fire management and forest conservation measures remote sensing is a suitable, efficient and comparatively cost-saving tool. Presently limitations are caused by insufficient spatial and/or spectral resolution of the remote sensing data (Thamm et al., 2003).

Other activities

In the course of the first project phase, the remote sensing research group conducted training courses for our Beninese partners (CENATEL and the University of Abomey-Calavi) in modern remote sensing and GIS including the exchange of data and discussion of new methods. With the GTZ there is a close co-operation with regard to measures for forest conservation and land management. Good contacts exist to the AGRHYMET institute in Niamey, Niger, for gathering and interpreting the remote sensing data in a high temporal resolution. Together with the DLR an experiment to evaluate the newly developed satellite for fire detection (BIRD) was conducted

(Oertel et. al., 2003). There is also a close co-operation with the Bank-of-Africa-financed PAMPF project which tries to manage three forest reserves in Benin.

Workpackage A3-2: Analysis and modelling of spatio-temporal vegetation dynamics in the upper Ouémé valley in dependence of climatic and anthropogenic factors

Vegetation changes are one key factor within the hydrological cycle. In the study region we found dramatic changes in vegetation cover in the past years. The aim of the subproject A3-2 is to describe and analyse the vegetation cover, its variability and ruling mechanisms from the botanical point of view.

Two main anthropogenic impacts on near-nature systems can be found in the study region: selective logging and grazing. Both became increasingly severe in recent years. Selective logging of timber wood takes place since 1950 (PAMF, 1996). Until about 1990 mainly two tree species, *Afzelia africana* and *Khaya senegalensis*, were logged (PAMF, 1996). For both species only trees with very large diameter classes (bigger than 1m diameter at breast height (DBH)) were felled. During the 90s logging pressure became more intense first by logging of additional trees, *Isoberlinia doka* and *Pterocarpus erinaceus*, and second by logging smaller diameter classes.

In general, logging is illegal and therefore completely uncontrolled. Another pressure on the natural forest are herdsmen (Peul), migrating mainly from the northwest, populate the zone not only in times of transhumance but also by permanent settlements. This process started in 2000. This leads to an increased grazing intensity in the study region. A third important human impact on the vegetation is burning which takes place for hundreds of years and affects annually nearly the whole study region (PAMF, 1996).

In the first phase the studies were concentrated on sampling key parameters of near-nature systems in the test area and on quantifying the impact of logging.

Based on the results of the first field campaign dominant vegetation types were classified. Based on this work the test sites of the hydrologists (subproject A2) were selected. They were also used for ground truth for analysis of remote sensing data. Since 2001 the research work was focused on the population biology of five representative tree species (cf. Tab. A3.2) which are of ecosystematic importance or logging interest. In permanent plots supplementary data on soil properties, microclimate and the temporal / spatial appearance of fire were collected.

Our spatially explicit rule-based modelling approach, first developed in 2001, was carefully worked out. For the next phase we plan to combine a grid-based model for the landscape with an individual-based model for trees. The aim of the model is to gain insight into ecosystem functions and to calculate scenarios as a basis for the development of management tools. All filed work mentioned above was carried out in strong correspondence to our modelling approach.

Analysis of the present performance of vegetation dynamics in the Aguima catchment near Doguè

Sampling of vegetation data took place on 72 permanent plots in the six dominant vegetation types (Savane herbeuse, Savane arborée, Savane boisée, Forêt claire à *Isoberlinia doka*, Forêt claire à *Anogeissus leiocarpus* and Forêt claire à *Uapaca togoensis*) and on gaps caused by felling of trees. The permanent plots have a size of 30 x 30 m. In these plots data on species composition and cover were collected each year. All tree individuals with a DBH over 1cm were measured (height, crown height and diameter), mapped individually and marked with a placket. In the centre of each 30 x 30 m plots a subplot of 5 x 15 m was established to sample tree seedlings and saplings (DBH < 1 cm). This measurements took place at the end of the dry season and at the end of the rain season. To gain knowledge about the germination rate, an “in situ” seed experiment was performed in 2001 for our focus species (cf. Tab. A3.2, except *Uapaca togoensis*).

To discover the factors which determine vegetation the most important abiotic parameters were analysed. Soil properties were taken in September 2001 in cooperation with subproject A2. Date of fire and fire temperature were recorded in the dry season of 2002 and 2003. This information is very valuable to be tested with regard to correlations with detailed data on ground biomass (grasses, herbs and litter). Microclimatic measurements were carried out for air temperature and humidity (mini-data-logger, September 2001 to December 2002) and for solar radiation (hemispherical photos taken in March 2002 and October 2002). Data assessment took place in all 72 study sites with the exception of several mini-data-logger.

Some results for the six dominant vegetation types of our study region are shown in Tab. A3.1. The ecological gradient within these vegetation types is clearly indicated by an increase of woody biomass, resulting differences in light conditions and grass biomass. Soil conditions differ between the vegetation types, too, but are less clearly separated for the vegetation types.

Tab. A3.1: Mean values of different parameters for the six vegetation types. Letters indicate significant differences between the vegetation types (ANOVA, Tukey-Posthoc Test).

Parameter	Savane herbeuse		Savane arborée		Savane boisée		Forêt claire Anogeissus		Forêt claire Isoberlinia		Forêt claire Uapaca	
Woody Biomass [t/ha]	13	d	35	dc	57	bc	97	a	84	ab	76	ab
Gras Biomass 2001 [t/ha]	8,48	a	4,37	b	2,77	bc	0,8	c	1,73	bc	1,52	c
Soil depth [cm]	114,8	a	83,3	ab	85,8	ab	100,0	ab	66,4	b	73,3	ab
pH	4,8	c	5,7	ab	5,4	bc	5,7	ab	6,3	a	5,7	ab
Global radiation Factor [%]	0,929	a	0,819	ab	0,682	bc	0,677	bc	0,526	c	0,498	c
Temperature Fire 2001 [°C]	506	a	381	ab	304	ab	236	b	292	ab	314	ab

Impact of selective logging on regeneration potential of tree species in the Aguima catchment near Doguè

Apart form the collection of population biological data in the permanent plots as described above, gathering of additional data on tree felling in the whole area of the Aguima catchment (10 km² in size) was the focus of the activities. Logged trees on the test site were mapped with a hand held GPS. Logging year, DBH of the felled tree, and the number of explored timber were estimated for each tree and a GIS was built up.

Afzelia africana and *Khaya senegalensis*, which have been logged for more than 50 years (PAMF, 1996), are almost extinct. Presently, *Isoberlinia doka* is the most used tree species (cf. Tab. A3.2). Compared to the biomass of *Isoberlinia* in the original stand, illegal logging led to an export of more than 20% of the biomass of *Isoberlinia* during the last three years. 90% of these logged trees rest in the forest and only 10% were taken out of the system. A more efficient management of exploited logged trees could simply lead to a higher benefit and reduce logging intensity. Analysis of the seed production revealed that all species start relevant seed production at a minimum diameter of 45 cm DBH. Especially trees of this diameter class are highly attractive for logging activity. At present the number of large reproductive trees declines dramatically in the area which leads to a dramatic decline in seed production.

Tab. A3-2: Woody biomass (original stand), biomass of logged trees (last five years) and biomass of used timber (last five years) for six different tree species.

Species	Forest builder	Logged since	Woody biomass Forêt claire [t/ha]	Biomass logged trees [t/ha]	Biomass used timber [t/ha]	Biomass individuals DBH >45 cm all vegetation types
Afzelia africana	–	ca. 1950	0,2	0,0	0,0	0,0
Khaya senegalensis	–	ca. 1950	0,5	1,0	0,2	0,0
Isoberlinia doka	X	ca. 1990	50,6	11,8	1,5	4,3
Pterocarpus erinaceus	X	ca. 1990	9,4	1,2	0,1	4,4
Anogeissus leiocarpus	X	–	6,6	0,0	0,0	3,0
Uapaca togoensis	X	–	1,8	0,1	0,0	0,0

Concerning the regeneration potential analysis of the seed experiments, natural germination and density of saplings showed that neither the germination nor the survival rate of any of the five investigated species (cf. Tab. A3.2, except *Uapaca togoensis*) differ for the six studied vegetation types. This might indicate that regeneration is possible in any of the studied environments and that the main factor enabling regeneration is seed production.

Tree ring analysis of six tree species

In spring 2002 about 200 cores and 10 stem discs of *Isoberlinia doka, Afzelia africana, Pterocarpus erinaceus, Khaya senegalensis, Anogeissus leiocarpus* and *Daniella oliveri* were taken and analysed by standard dendrochronological techniques to examine the periodicity of the growth zone structures in the wood. For all tree species – except *Khaya senegalensis* – it was possible to construct ring-width chronologies by statistical and visual cross-dating. Indexed chronologies of every tree species correlate significantly with the annual precipitation in the Ouémé catchment area which proofs the existence of annual tree rings. More than 46% of the rainfall variability at the study site can be explained by the mean chronology (Fig. A3-2a). The over 200-year long dendroclimatic proxy – the first developed for the innertropics in Africa – allows the reconstruction of the precipitation pattern for pre-instrumental periods. A weigthed running mean (low-pass filter) indicates an increasing aridity during the last two centuries (Fig. A3-2b). Especially *Afzelia africana* and *Daniellia oliveri* are recommended for further dendroclimatic analyses due to the distinctiveness of the annual tree rings, their high ages of more than 300 years and their relatively strong climate-growth relation.

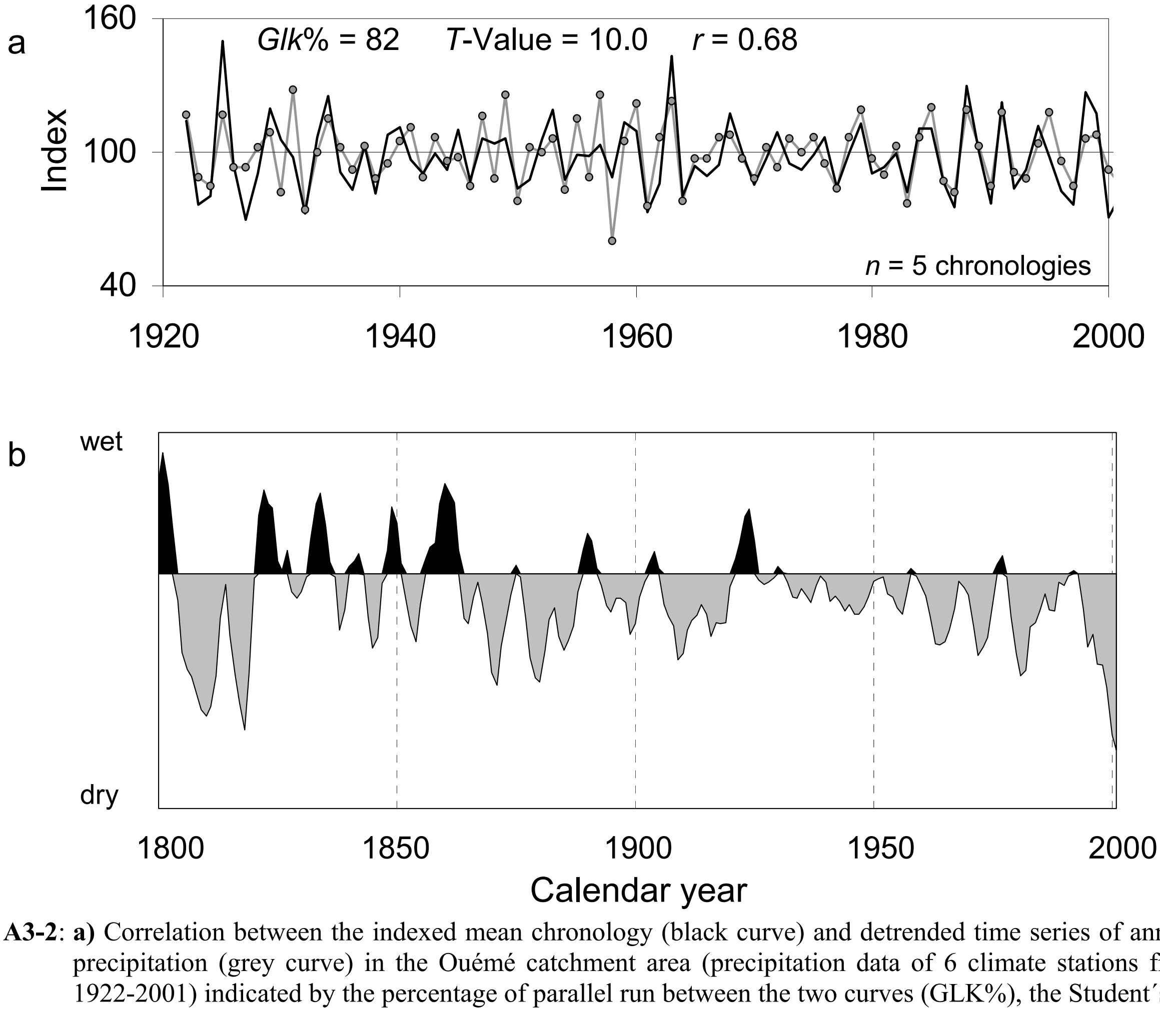

Fig. A3-2: **a)** Correlation between the indexed mean chronology (black curve) and detrended time series of annual precipitation (grey curve) in the Ouémé catchment area (precipitation data of 6 climate stations from 1922-2001) indicated by the percentage of parallel run between the two curves (GLK%), the Student´s T-Value and the correlation coefficient r. **b)** Low pass filter (11-year running mean weigthed with a Hamming window) exploring wet (black) and dry (grey) periods of the last two centuries.

The existence of annual tree rings allows the construction of cumulative diameter growth curves for timber species by ring-width measurements. The combination of the mean diameter growth curve with non-linear regression analysis of the DBH-height relation enables the estimation of volume growth and – considering the specific wood density – the accumulation of wood biomass over the whole life-span of a tree. These models can be used to estimate minimum logging diameters (defined as the DBH at the culmination of the annual current volume increment) and cutting cycles for timber species (mean passage time through 10 cm DBH-classes) and thus are valuable instruments for forest management based on sustainability. For *Isoberlinia doka* the minimum logging diameter is 48 cm which is in good accordance with the results of the seed production studies. The cutting cycle revealed by the growth model for *Isoberlinia doka* is detected with 20 years.

Workpackage A3-3: Assessment of the transpiration of plants and possibilities of a manipulation

Land use changes will cause changes of evapotranspiration which is dominated by plant transpiration. Plant transpiration is driven by the water vapour deficit of the air and dependent on soil water availability, plant species or cultivars, development state, and canopy structure. Plant nutrition is an additional factor affecting water use efficiency (WUE) by means of plant physiology. Regional estimates of evapotranspiration may result from the combination of land use maps with estimates of specific Kc (ETa / ETpot) values for different land use classes. The aim of this workpackage was to quantify actual evapotranspiration of agricultural crops and to study the effect of organic matter and mineral fertilizer on water use efficiency of maize, yams, groundnut, sorghum, and cotton. Water use efficiency was determined by the ratio between the yield or above-ground biomass and the actual evapotranspiration (ETa). ETa was measured by the aerodynamic method (eddy-covariance) during a measurement campaign on a maize field in 2002, and estimated using gravimetric humidimetry and tensiometry methods. Transpiration was measured using porometry, sap flow, and leaf surface conductance.

Field experiments were established in the year 2000 on three sites (Doguè, Wèwè and Bétérou) on 150 fields, using complete random blocks with four treatments and eleven replicates distributed in these sites. Treatments were: farmer's practice (FP0); 10 T ha^{-1} of mulch (OrgF); 75 kg ha^{-1} N, 40 kg ha^{-1} P2O5, 24 kg ha^{-1} K2O (MinF) and 10 T ha^{-1} of mulch with 75 kg ha^{-1} N, 40 kg ha^{-1} P2O5, 24 kg ha^{-1} K2O (MinF + OrgF).

For maize, higher yield and WUE (grain, cob and straw) were obtained with T2 and T3. Statistical analysis showed a significance difference between treatments for grain and its WUE (T0 and T3), for straw and its WUE (T0 and T2; T0 and T3), proving that water use efficiency is highly affected by mineral fertilizer and the combining of mineral fertilizer and mulch (Fig. A3-3a). Yield increases were also found for the other crops, although results were not always significant (Fig. A3-3b, Tab. A3.3). Increases were smaller for cotton as farmer's practice (FP0) usually already includes mineral fertilizer. Groundnut as a leguminous crop is also not much affected by additional fertilization and yield increases of yam are probably smaller due to the fact that it is usually the first crop after fallow.

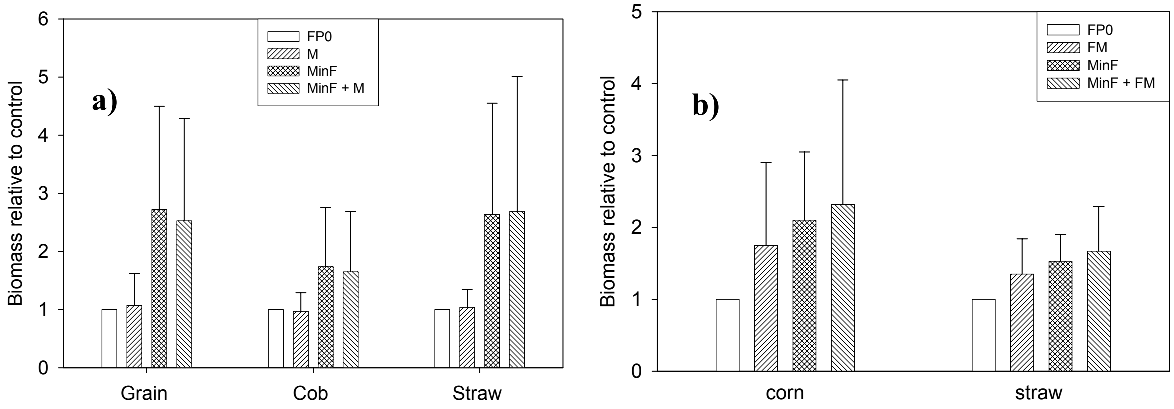

Fig. A3-3: Biomass of field experiments, normalized to FP0 (farmer's practice) treatment. **a)** maize, organic fertilizer mulch, **b)** sorghum, organic fertilizer farmyard manure. The four treatments are as follows: FP0 - farmer's practice, OrgF – organic fertilizer (either M: mulch or FM: farmyard manure), MinF – mineral fertilizer, MinF + OrgF – combined mineral and organic fertilizer (either M or FM).

Tab. A3.3: Biomass of sorghum field experiments, 2001, normalized to FP0 (farmer's practice) treatment. Only mostly used biomass compartments are displayed.

	Maize	Sorghum	Cotton	Groundnut	Yam
Compartment analyzed	grain	panicle	grain + lint	grain	tuber
Farmers's practice (FP0)	1,0	1,0	1,0	1,0	1,0
Farmyard manure (FM)	1,2 ± 0,4	1,7 ± 1,1	1,3 ± 0,4	1,1 ± 0,2	1,1 ± 0,3
Mulch (M)	1,1 ± 0,6	1,2 ± 0,3	0,9 ± 0,3	1,0 ± 0,3	1,3 ± 0,5
Mineral fertilizer (Min F)	2,9 ± 2,1	1,6 ± 0,4	1,2 ± 0,3	1,0 ± 0,3	1,5 ± 0,5
Min F+M	3,1 ± 2,1	1,5 ± 0,5	1,2 ± 0,4	1,2 ± 0,4	1,5 ± 0,8
Min F + FM	3,0 ± 2,2	2,3 ± 1,7	1,3 ± 0,2	1,0 ± 0,3	1,2 ± 0,2

It was recognized that there is considerable potential to increase harvests by optimizing the rate of fertilization. Organic fertilizers, which are less costly, are known to have the potential for increasing harvests, simultaneously conserving soil water. In the course of a prolonged duration, carry-over effects of organic fertilization are to be expected. It also became clear that the harvest index (used vs. overall biomass) is often very low as in the case of sorghum (Fig. A3-4) where obviously birds consumed large parts of the corn. At present, no defensive strategies seem to be applied. In addition, there might be significant harvest improvements using other cultivars with higher water use efficiency and/or a better timing of growth. Seed priming (pre-germination of seeds using a nutrient solution) would be another option to overcome problems with erratic rainfall at the beginning of the vegetation period. Thus, there are several management options which might be evaluated within the IMPETUS project while socio-economic problems might be overcome by the interdisciplinarity of the project.

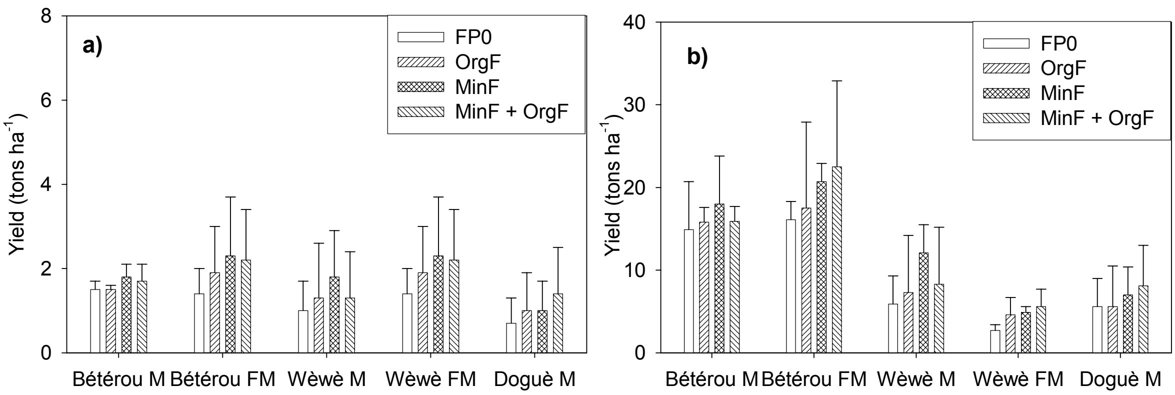

Fig A3-4: Biomass of sorghum field experiments, 2001. a): corn; b): straw. Bétérou, Wèwè, and Doguè are the experimental sites.

Mass spectrometric analyses of the plant samples are still on-going. The results should give an indication if different water use efficiencies can be detected between the different fertilizer treatments.

Monthly potential evapotranspiration as calculated using the Penman formula on a daily basis showed a water deficit compared to rainfall between October 2001 and July 2002, with the exception of April (Fig. A3-5). Measurements of actual evapotranspiration over a maize field using eddy-covariance (Fig. A3-6) showed constant Kc values of 0.6 . The calculated transpiration of Cashew trees on the basis of sap flow measurements was 0.3 * ETpot during the dry season. Cashew trees are introduced in the fields during crop rotation and over the range of about five years become dominating on many fields in the region. The measurements of actual evapotranspiration are going to be continued, especially focusing on the changes caused by land use, comparing native forests, agricultural crops, and secondary trees as Cashew. Using the Kc values for different crops, and combining with the data of vegetation cover, regional evapotranspiration is to be addressed making use of GIS applications.

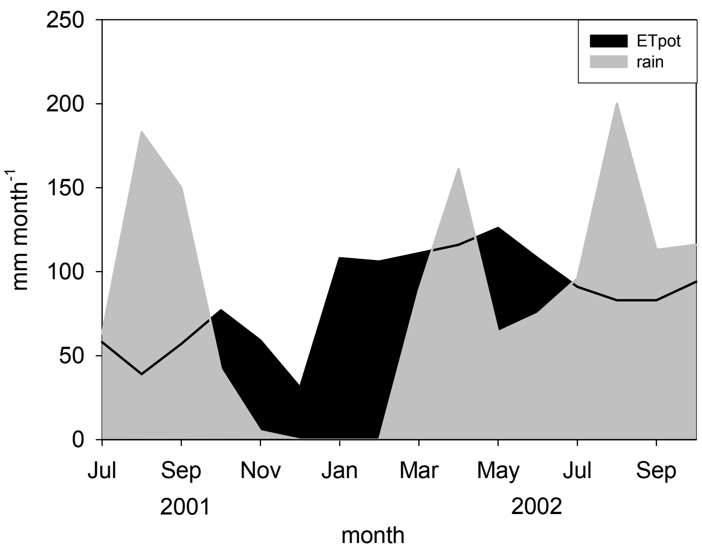

Fig A3-5: Potential evapotranspiration and rainfall at Doguè during a 16-month period.

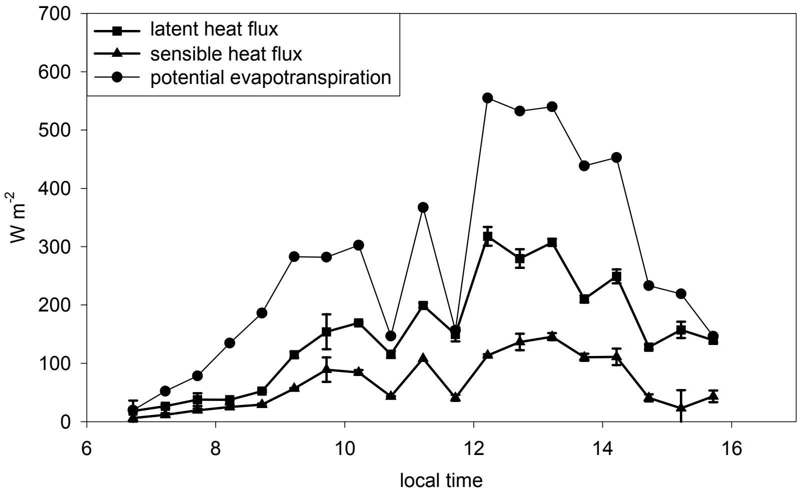

Fig. A3-6: Latent heat flux (= actual evapotranspiration) and sensible heat flux, determined by eddy-covariance measurements over a maize field in 20th August 2002, compared to potential evapotranspiration as calculated from weather station data by Penman's formula .

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Subproject A4

Socio-demographic development and migration against the background of resource scarcity

Participants	Discipline
Prof. Dr. W. Schug (Coordinator) Institute for Agricultural Policy, Market Research and Economic Sociology, University of Bonn	Water availability and demand
Prof. Dr. W. Henrichsmeyer Institute for Agricultural Policy, Market Research and Economic Sociology, University of Bonn	Policy information systems
Prof. Dr. M. Janssens Department of Horticulture, University of Bonn	Farming and land use systems

Summary

The socio-economic part within the IMPETUS-Project analyses interdependencies between resource availability and socio-economic development in Benin. The results of various research activities of natural and social sciences are integrated in a modelling system, in order to calculate development scenarios of resource utilisation and food security in Benin for the next two decades.

In the first project period data concerning water supply, migration and economic parameters were collected in field surveys, in co-operation with other disciplines and stakeholders on site, investigating the upper Ouémé-catchment in particular.

The first step in investigating the water supply situation in Benin was to conduct a water demand and water availability analysis. The insufficient availability of water resources shows up in the fact that approximately 6 hours per day and household are needed for collecting water. In one of the villages (Kaki-Koka) where the water stress situation is even more serious, the time analysis of the dry season resulted in 10 hours a day per household for the water collection. The survey of water consumption found out that about 18,85 l/day in the rural area and 23,65 l/day in the urban area were consumed per person. At the end correlations between the water consumption and socio-economic and socio-demographic parameters are to be determined.

An important issue is the analysis of migration within rural areas and undirected agricultural-colonisation processes. The current population displacement resulted in a very high average population growth of about 4.9% per year between 1992 and 2002. In the southern Catchment along the road between Oubérou and Bassila population growth goes up to 11% per year since 1997. These processes have a strong impact on the regional resource management and the socio-economic change in the upper Ouémé catchment.

The set of development interventions is examined on a regional scale under the conditions of migration and the shortening of natural resources. Due to the neglect of the intervention fields *agricultural production and land management, it is argued that the current strategies of development agencies cannot contribute enough to emerging land-related development problems.*

The study of carbon balance in different land use systems in the "Haute Vallée de l'Ouémé" allowed evaluation of the influence of deforestation on the carbon emission, which accelerates the climate change. The rain use management, that improves agricultural production, constitutes through the decrease of agricultural area extension an essential factor to reduce deforestation. In the two villages Dogué and Sérou it has been evaluated, that changes in the seasonal cycle of rainfall could lead to high rates of migration (5.5%), deforestation (2.6%), carbon release (77 t/ha and 3 t/inhabitant CO_2) and an increase of agricultural water use (from 1357 to 1756 and from 2562 to 3422 m^3/inhabitant-year in Dogué and Sérou, respectively).

A socio-economic modelling system (BenIMPACT) has been developed which consists of an Agricultural Sector Model, a Crop Water Requirements-calculator and a Basic Data System, linked to an internet based interactive mapping tool (BenMap) for result exploitation. BenIMPACT allows to calculate and assess different development paths of resource use and food security in Benin through the integration of extensive socio-economic and natural sciences based data, partly derived in other workpackages.

Low per capita income, a subsistence oriented agricultural sector dominating the economy, and high population growth, provoke scarcity and overexploitation of resources in several regions of Benin. Compared to other factors limiting development such as land and capital, water is not the most important one, but one of growing importance in a temporal, spatial, and economic dimension.

The main objective of the various research activities in this subproject is to analyse the interdependencies between resource availability and socio-economic as well as demographic development in selected places in Benin, focusing on the hydrological cycle. The project’s aim is both to point out damaging factors and to develop countervailing strategies, in order to provide concrete information on the management systems and policy measures, that are necessary to prevent an impending economic and ecological crisis in Benin.

Subproject A4 is divided in four workpackages being partly are structured themselves. In workpackage A4-1 the analysis of water availability (part 1) and demand (part 2) in the catchment of the *Haute Ouémé* from a socio-economic point of view is conducted. The demographic and development orientated studies are realised in workpackage A4-2 (part 1: Migration, settlement dynamics and resource use in the upper Ouémé catchment; part 2: Development Strategies in Central Benin under the conditions of migration and the shortening of natural resources). Focusing the agronomic and environmental aspects of the hydrological cycle is task of workpackage A4-3 (Farming and land use systems). As a framework for the above mentioned studies and other research activities within IMPETUS, workpackage A4-4 develops mathematical programming tools to model land use and food security against the background of resource scarcity and rainfall variation.

The following results have been achieved in the different workpackages:

Workpackage A4-1a: Analysis of water availability in the catchment of the *Haute Ouémé*

The main target of the analysis is to determine the reasons for the insufficient supply of safe and clean drinking water. The presently sufficient average quantity of 4.220 m^3 of fresh water per person and year in Benin indicates that the unsatisfactory access to safe drinking water must be caused by other factors than climatic and hydrologic conditions. This part of subproject A4-1 carries out an in-depth analysis of the existing water supply strategies and their acceptance in Benin. This allows to identify management problems, which cause deficits in safe drinking water supply.

Besides of collecting secondary statistic data available at the *Direction Hydraulique* and other institutions in Benin there have been carried out several field surveys to get necessary information on the development and management of drinking water supply. The first field survey was conducted by focus group discussions with target groups (women) in three different villages of the predefined catchment area. The results indicate that the main problem is the long distance and required time of collection water. Because of these preliminary findings a time analysis was conducted in the dry and rainy season in order to have comparable data on seasonal water problems. To find out, how the national strategy deals with this problem and if the national strategy is accepted by the population, a further survey is taking place. This survey is conducted on three different organisational levels. The first questionnaire deals with governmental policies. Here several experts of the *Direction Hydraulique* and the *Service Regional de l´ Hydraulique* in each department are interviewed. The second type of questionnaires takes place on a regional level, where Non-Governmental-Organisations and other involved actors in supplying drinking water are interviewed. The third type of questionnaire is done on a communal level. Here 30 villages of the catchment area are interviewed concerning their situation and their own strategies of managing the drinking water facilities. The results of all three different organisational levels will be analysed and compared to find out, if the different strategies of water supply complement one another.

The results of the focus group discussions in the three villages (*Dogué, Sérou, Kaki-Koka*) show that each village has several water sources. Only deep wells and pumps have water throughout the whole year. *Marigots* (holes, dug into the ground) are rather used for drinking water than other water sources. The main reason indicated by the participants is the taste of the water. In the rainy season the pumps were less frequently used than in the dry season. This shows, that the acceptance of the pump is not constantly high. The time analysis in *Kaki-Koka* shows, that in the dry season only 4 out of 9 water sources still carry water. Even though the waiting time at the pump takes several hours in the dry season, it is used most frequently, because there are not enough water carrying sources by that time of the year. Therefor, an important goal seems to be the installation of further water supply facilities and a stable and successful maintenance management, which can provide an appropriate drinking water quantity and quality all year around. The results of the survey at three different organisational levels are not yet available, since the interviews are still going on. After this first project period, which was conceived to identify management problems on all three organisational levels of water supply, it will be an important task of the next period to find out strategies, which help to solve the identified water management problems.

Workpackage A4-1b: Analysis of water demand in the catchment of the *Haute Ouémé*

Water demand has increased due to the growing population and higher standards of living leading to more competition and conflicts between the consumers. In the part of the analysis of water demand priority is given to the analysis of water consumption, as well as socio-economic and socio-demographic data in this investigation. The main target of the investigation of water demand is to find out correlations between influence-giving factors and the development of water consumption. Based on these realisations first recommendations for actions are to be given.

The study starts with an extensive literature search in order to find out those parts of water demand and influence-giving factors, which had already been investigated in Benin. The following studies were based on these evaluations in order to complete the secondary material regarding the question.

Preparing investigations in Benin, the target of finding possible starting points by means of questioning people in villages and cities. In this connection interviews with experts were led and achieved by participating observation. In the end of the second part, an investigation area was found where the following analyses took place.

With a structured questionnaire in 90 households in the dry season and 90 households in the rainy season, water consumption, income situation, the acceptance of water prices and water supply situation etc. were analysed (random sample). These data were analysed with the help of a statistic program (SBSS).

After this, a data collection was accomplished. A time analysis on a household basis in the dry and rainy season concerning the needed time for water collection.

The next field survey was conducted by focus group discussions with the target groups of the "sages" (Council of Elders) in a village and a city. These men were asked in order to find out the ten poorest and richest households of the investigation areas, as well as the basis criteria and characteristics for these definitions. Based on these results, an interdisciplinary research (with the subproject A5-2) was started in 40 households in four villages and one city, concerning water consumption per person in a household, water usage's, water resources, family structure, water access, socio-cultural affiliation etc. In the period from July 2001 to July 2002 assistants measured once per month the daily consumption. Besides of collecting secondary statistic data are administered and analysed with statistical programs.

The last main part of this analysis was a questionnaire with experts after the "Delphi method". In accordance with this scientific approach, 88 experts were asked to certain national topics (for example: GIP, irrigation, water consumption by industries, estimated water consumption for households, allocation of water between the sectors households, industry and agriculture). In three sequential rounds the same questions are placed to the experts. Starting from the second round the questionnaire contains the answers of all experts' opinions of the previous round. In the end, a group discussion among the experts could find explanations for the answers after "Delphi".

The results of the focus group discussions with the experts at the beginning of this study reveal 3 different conditions of water consumption: People, who are living in a village (Sérou) and people who are living in a city (Djougou) with and without access to water (tap).

The main result of the structured questionnaire in 90 households shows, that water poverty is for 85 % of the households the most obvious problem of the selected investigation area. Water poverty is for nearly 95 % of the interviewed persons not a reason for migration. As a solution strategy for the administration of scarce resources, a water prise was discussed. About 95 % of the asked would accept to pay, but only in the dry season.

After the preliminary results of the interdisciplinary research, the water consumption per capita was about 18,85 l/day for the people in the village and 23,65 l/day for the people in the city. There are many aspects which could influence the water consumption. The analysis is still going on and will be terminated in summer 2003.

Workpackage A4-2a: Migration, settlement dynamics and resource use in the upper Ouémé catchment

The objective of the research was a detailed socio-geographical analysis of patterns and motives of current migration processes in the upper catchment of the Ouémé river and their effects on the socio-political system, the settlement dynamics and the regional resource management. There were four main tasks in the field studies: Identifying the reasons for spatial mobility, the analysis of new social and political milieus, recording and interpretation of settlement dynamics, as well as the monitoring and analysis of the migration-dependent changes in land use and new land use patterns.

The quantitative and qualitative social data was gathered via a mixture of methods. On the household level a questionnaire was designed to get information about the areas of origin, ethnicity, education level, household size, migration step stones, motives etc. Data from open structured interviews and permanent participatory observation completed and sharpened the questionnaire results. To cover the spatial dimension and the ecological effects of population movements, GPS mapping of settlement dynamics, deforestation processes and changing land use patterns were linked with the findings of social science research, remote sensing data and GIS-modelling for analyses addressing the 'why' and 'how' of population-environment issues. About 430 questionnaires for the migrants, 300 for the autochthonous population and more than 70 interviews were interpreted.

Despite the well-known rural-urban migration streams, which could be observed also in Benin, much migration remains within rural areas. The current immigration process, primarily in the southern IMPETUS-research area, is an undirected agricultural colonisation, without any kind of intervention from the state. The regions of origin of the questioned migrants which settled down in this part of the catchment lie in the Northwest of Benin and the bordering regions in Togo which are relatively densely populated and at risk of land degradation. About 10.000 people have migrated into the southern catchment within the last five years and mainly in the two departments of Tchaourou and Bassila which cover the most affected southern part of the catchment.

The current population displacement resulted in a very high average population growth of about 4.9% per year between 1992 and 2002.

Many of the migrants didn't come directly form the Northwest. Rather than an unilinear one-way movement, migration here is essentially a series of exchanges between places within the catchment. Most migration studies over-emphasised the economic and demographic context that influence migration decisions. Land scarcity, of course, is an important push factor, but a focus on push-pull models can't explain the selective character of this frontier-migration, which is a highly dynamic social process, organised in kinship-networks.

The number of foreign farmers and animal owners already exceeds that of the autochthonous population, but the ecological and social consequences of the colonisation process is neglected by the state organisations and development agencies. The absence of formal institutions in the frontier region which could support and advise the new settlers, leave intensification possibilities in the resource management unused and accelerate the deforestation process caused by extensive production strategies. Like in the areas of origin, the traditional agrarian techniques of the immigrants leave largely tree-free landscapes susceptible to soil degradation, because the settlers in the southern catchment clear about 1500 hectares of the regional dry- and savannah forests per year for new yam fields. In the institutional vacuum of the frontier the new social and political structures must constantly be negotiated. This development is not free of conflicts, in which the actors compete for the political and economic control of the new settlements and the access to natural resources.

The described findings of migration processes provide a substantial input for the interdisciplinary modelling of the land cover change caused by in-migration which is undertaken together with the subproject A3. Population data was digitised and stored in a Geographic Information System. In a next step this information, together with new census data constitutes the foundation for a spatial differentiated modelling of the population dynamics within the catchment.

Workpackage A4-2b: Development strategies in central Benin under the conditions of migration and the shortening of natural resources

The two regional trends "in-migration" and "shortening of natural resources" contribute significantly to social differentiation in Central Benin. This process leads to the marginalisation of some social groups and growing conflict potentials through unequal patterns of access to natural resources. These problems are potential areas of intervention for development agencies. The main task of this analysis was to show how development agencies as well as the population perceive these problem complexes. The following objective was to find out whether strategies and actions were applied as a consequence of this perception in order to identify institutional weaknesses and best practices. These findings can be taken into account when planning future development work.

The analysis of secondary data was used for the description of regional development trends. The results concerning changing resource use patterns, power relations, access to development packages and their socio-economic effects on the local level were gathered with a set of semi-standardised questionnaires, participatory observation and mapping. For the institutional analysis this set of methods was completed through indirect observation tools and open expert interviews at the national level.

After the weakening of the state services after 1989 a number of programmes and projects were designed to close the service gaps. The main intervention sectors are education, health, microfinancing and infrastructure. At present there do not exist any surface-covering agricultural programs to promote sustainable land management. Because almost all NGOs and private sector organisations do highly depend on external financing through these programs and projects, they lack the budget and the will to participate in a foresighted development planning. It is not very surprising that all sorts of development agencies underestimate the effects of the ongoing social change caused by these regional trends. Most of them haven't got any resource concepts in order to measure the ecological effects of their interventions. Also missing are tools which help to better integrate migrants as target groups. The activities of the organisations are embedded in strong "development narratives", arguing that their current strategies are well designed to contribute to sustainable development in the region. For example, women were discovered as main target group for incoming generating activities such as transformation of agricultural products or petty trade, not taking into account the underlying problems of the extensive agricultural production systems and limited markets.

On the local level, the ongoing social differentiation was demonstrated by changing patterns of land use as well as access to development aid. It is mainly the village pressure groups that benefit from the existing development interventions. Also, in all research villages, the autochthonous farmers increased their land property up to 70 ha. While in villages with enough land to clear, the access for migrants was free and land use restrictions were not very strong, in those villages with relative land scarcity, the access was sometimes limited to subsistence level. Use restrictions worsened and taxation, raised by the village land owners, increased. Growing conflicts between different user groups as well as the emergence of a land market in semi-urban areas were observed. The only institutions that take the question of access and conflict related to land into consideration, are traditional leaders on the regional level and some bilateral donors, that begin to intervene in the field of community based resource management (CBNRM).

While a number of state-led agricultural programs have recently been started to promote the cultivation of more sustainable cash crops such as manioc and cashew, there are still no efforts made to introduce land management systems that include more intensive production systems. This fact, together with market-driven accumulation strategies of autochthonous farmers and large extern land owners, will lead to relative land scarcity in many villages of our research area. Marginalisation of non land-owning groups and a growing number of land conflicts between user groups are possible, unintended social effects. Therefore it is doubtful, whether CBNRM approaches, that are not embedded in state policies, are the right tool to resolve these problems. In a next step, these findings on land related development problems will further be illuminated through the examination of the accumulation and production strategies exercised by large land owners. All data will be stored in a regional GIS on ownership structures, types of agricultural production systems and conflict monitoring.

Workpackage A4-3: Farming and land use systems

Main goal of this workpackage was to analyse the influence of farming and land use systems on the carbon sequestration and food security in upper Ouémé catchment.

The carbon balance and food security were analysed through data collected principally on biomass production, which is the ultimate source of food supply and whose management influences the climatic changes through the release of carbon. In the upper Ouémé catchment, the villages of Dogué (320 km^2, 802 inhabitants) and Sérou (19 km^2, 450 inhabitants) were selected respectively, according to two criteria: villages with and without land to clear. Four land use systems have been determined in each village: forests, fallows, cashew plantations and seasonal crops areas.

Fig. A4-1: Crops calender in upper und middle Ouémé catchment

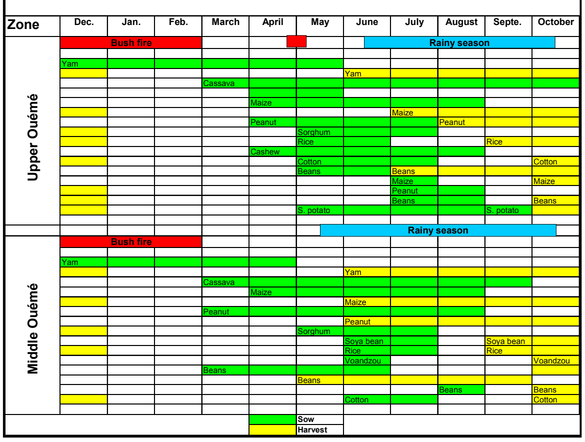


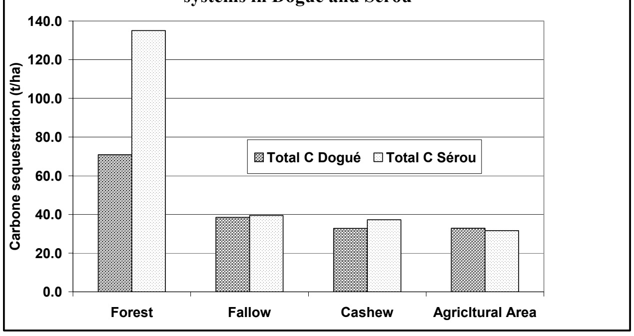
Fig. A4-2: Productivity and rain use efficiency in Dogué and Sérou

Crops groups	Productivity (10^6 Kcal./ha)		Rain use efficiency (Kcal./m3)	
Villages	Dogué	Sérou	Dogué	Sérou
Situation without seasonal rain variability				
Tubers	5,6	4,6	611	301
Cereals	5,3	2,8	662	318
Leguminous	1,4	1,2	362	247
Average	**4,1**	**2,9**	**545**	**289**
Situation with seasonal rain variability				
Tubers	5,6	4,6	611	301
Cereals	3,9	2,1	483	232
Leguminous	0,8	0,7	169	115
Average	**3,4**	**2,5**	**421**	**216**
Decrease (%)	**17**	**14**	**23**	**25**

Farming systems in the upper Ouémé catchment are mainly shifting cultivation. The crops are sown principally from May to August (Fig. A4-1) and the yam comes at the head of crop rotation: tuber (yam) - cereal - cotton or cereal - leguminous, cereal or cotton - cereal - fallow or cashew. Except yam, other food crops are intercroped and the number of intercroped crops increases with land scarcity. Farming systems are also still characterised by the growing of cashew plantations, which can provide a solution to deforestation.

On the assumptions that the rainy season ends in September instead of mid-October and that the quantity of rain and the farming systems thereby remain unchanged, the soil productivity and rainwater use efficiency will decrease respectively to 17 and 23% in Dogué, to 14 and 25% in Sérou (Fig. A4-2). Contrary to the tubers, which are planted well before the beginning of the rains in June, the cereals and the leguminous plants, which can be sown even late in July, could be more affected by an early end of the rainy season than other plants. Such an assumed change in the seasonal cycle of rainfall in Dogué and Sérou could lead to the peoples' migrations (5.5%), deforestation (2.6%), carbon release (77 t/ha and 3 t/inhabitant CO_2) and increase of agricultural water use (from 1357 to 1756 and from 2562 to 3422 m^3/inhabitant-year respectively in Dogué and Sérou).

Fig. A4-3: Carbone sequestration in different land use systems in Dogué and Sérou



Biomass burning and increase of agricultural areas are two principal factors that cause the release of carbon from the upper Ouémé catchment into the atmosphere. The carbon sequestration is higher in forest (70.9 - 135.0 t/ha) than in other land use system (Fig. A4-3). The difference between the forest system and the agricultural areas (38.0 - 103.4 t/ha) represents the carbon emission.

In summary, farmers in upper Ouémé catchment need efficient water use management to achieve their food security, otherwise they are obliged to extend their agricultural areas or to immigrate towards less occupied regions. Consequently the carbon release, which accelerate the climate change, will increase.

On the basis of soil and vegetation maps and of results obtained during the first phase, the activities will principally be carried out by making maps of: carbon dynamic, CO_2 emission, and of rain use efficiency in the upper Ouémé catchment.

Workpackage A4-4: Modelling of land use and food security against the background of resource scarcity and rainfall variation

Subproject A4-4 investigates the effects on land use, income and consumer's welfare, caused by changing climatic and socio-economic environments. It targets both to identify damaging factors and to develop countervailing strategies, establishing a decision support system for agricultural policy.

Collecting data in order to feed the modelling tools with input was a main task in the first project period. A large amount of statistical data has been digitised and stored in the basic data system. Missing information concerning production costs and labour force were collected in a large scaled field survey covering the whole country on district level. Time series of data were partially checked using statistical methods and tested with regression analysis so as to identify the most important factors influencing crop yield.

Mathematical programming is the methodological approach applied to build the quantitative modelling system. The subproject A4-4 created BenIMPACT (**Ben**in **I**ntegrated **M**odeling System for **P**olicy **A**nalysis, **C**limate and **T**echnology Change), a socio-economic decision support system for fresh water management, analysing interdependencies between resource availability, water use efficiency, socio-economic, and demographic development by integrating data and results from different IMPETUS-subprojects.

BenIMPACT consists of different modelling tools (see Fig. A4-4): a Basic Data System, an Agricultural Sector Model (ASM), a Crop Water Requirements calculator (CWR-calculator) and user-friendly reporting tools (e.g. BenMap).

Building up a model for simulation purposes requires a solid and comprehensive database. The basic data system joins a large number of secondary statistics and data collected in field research, and delivers the data input into the ASM.

The ASM covers the most important crops on a regional level. It incorporates aggregate primal-dual programming models, while maximising agricultural profits and minimising transport costs.

The demand system is globally well-behaved and allows to point out the impacts of changing income.

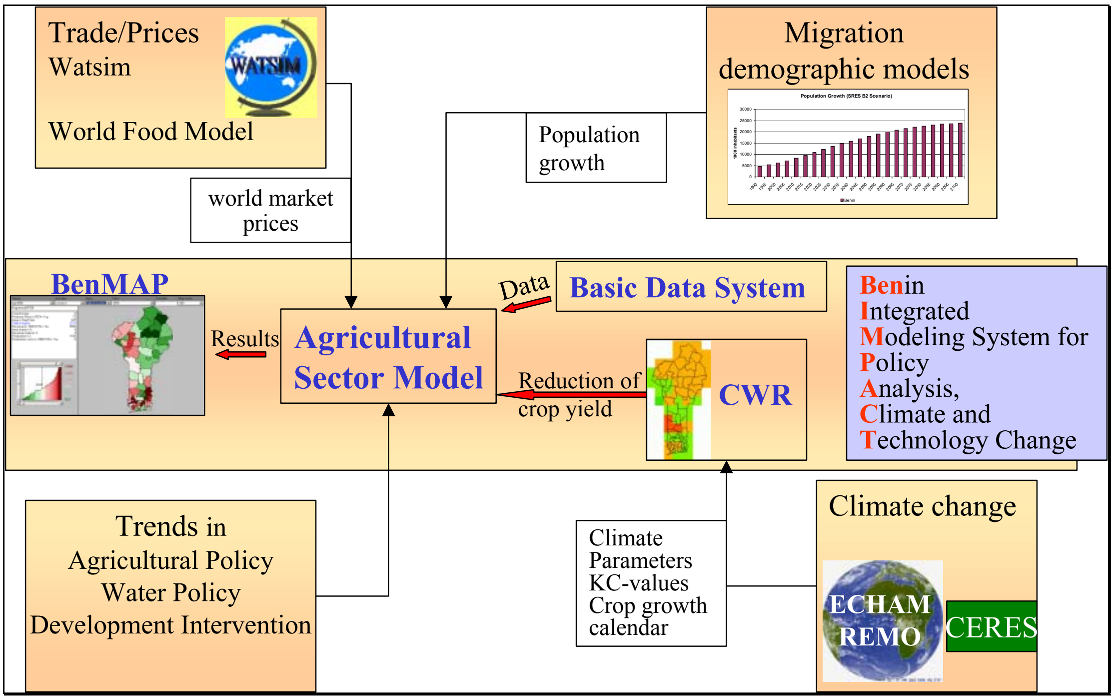


Fig. A4-4: Modelling system BenIMPACT and exogenous inputs.

The CWR-calculator defines effective rainfall and reference evapotranspiration per crop and region, depending on climate, crop management and crop varieties, based on a large set of regional climatic and engineering data provided by other teams in IMEPTUS. The CWR-calculator employs mainly the mechanisms of CROPWAT, an internationally acknowledged standard in this field.

The results of simulations with the ASM are visualised in the interactive “Benin Mapping Tool” (BenMap), based on a Java Applet, so that results can be accessed by stakeholders via Internet. An easy-to-use interface allows to exploit all data in the Basic Data System.

Preliminary results indicate, that Benin will face severe problems, mainly due to increasing population, limited availability of fertile soils, and regional and temporal water scarcity. Socio-economic scenarios for the year 2020 will be calculated, as soon as the possible climate change and demographic growth scenarios are available.

Crucial challenges for the next project period are the specification of the model and the intensification of co-operation, in order to establish the provided tools as decision support system in local institutions.

Expanding the research on animal production, detailed data on water balances, and alternative land use systems, as well as coupling economic, meteorological, hydrological and demographic models, will provide concrete information on the management systems and policy measures, that are necessary to prevent an impending economic and ecological crisis in Benin.

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Subproject A5

Risk and insecurity when resources are scarce: Ethnological and medical perspectives on the availability, quality, and management of water

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Summary

Poorness and scarcity of drinking water are the main characteristics in the major part of the West African Sahel and Sudan zones. According to the United Nations the daily income is less than 1$ (US) and nearly every second inhabitant lacks the access to clear and sufficient drinking water in this region. Social and health issues are predominantly affected by this situation.

Therefore the subproject A5 of the IMPETUS-initiative intended to face the water related problems in the Upper Basin of Ouémé River (Benin) from a socio-cultural and medical perspective. Based on modern risk theories three anthropological and two microbiological workpackages were created to perform a holistic analysis. Workpackage A5-1 concentrated on the macro-micro-level linkages of water-related policies. Using various inroads (property rights in water, fisheries, management of water-scarcity, etc) the study showed the weak institutionalisation of governmental institutions at the regional and local level. The ambiguity of institutions is obviously due to the high degree of ethnic heterogeneity, high rates of spatial mobility, and a conflict-prone socio-political environment pitching immigrants against locals. The second workpackage A5-2 focussed on the micro-level dynamics of households and individuals, both in quantitative as well as in qualitative terms. A detailed analysis of the almost bipolar organization of households forcefully pointed out the importance of gender as a key-variable for the understanding of the social and economic patterns. Gender-specific strategies pervaded resource use and economical choices, especially in the domains of land rights, water management, farming production, trade and monetary transactions. For example, market trade and household management were dominated by women, while men had better access to cash crop production and political decision making. Their monetary resources in annual balance sheets were higher, but unevenly distributed over the year.

The third workpackage A5-3 dealt in detail with health and disease management concepts at the local level. Empirical studies as well as systematic analysis of blood and stool samples were

done with a focus on water-borne diseases. Malaria, respiratory and gastrointestinal infections could be identified as leading diseases, highlighting hookworm infections as a predominate parasite. Interestingly the use of modern and traditional ways of treatment differed significantly. The (often inaccurate) self-administration of drugs and herbal remedies was favoured by two thirds of the local population, whereas only 7% relied on the indigenous medical specialists. The fourth and the fifth workpackage A5-4 and A5-5 focussed on the analysis of the microbiological drinking water quality in the catchment. As a prerequisite a stationary laboratory, a mobile unit and a special map with more than 900 watering locations (wells and surface water) had to be established in the countryside of Benin. Conventional and modern molecular techniques were used to detect, differentiate and quantify bacterial and viral (Enteroviruses, Norwalk-viruses and Hepatitis E-virus) pathogens. So far 150 samples have been taken and investigated. Nearly 50 % (74) were positive for bacterial indicators of faecal contamination, whereas only one positive result for Enteroviruses could be found in 72 samples. Interestingly usually rare subspecies of Salmonella enteridis spp. were isolated in 16 samples rising questions about their pathogenicity and virulence.

All these findings of the first project phase illustrate the various problems related to availability, quality and management of water in Benin. They represent not only the characteristic corner-stones of a complex conflict scenario, but also support the clear demand for a closer look at the interactions between the different factors and the development of intervention as well as prevention strategies.

The availability and quality of usable and drinkable water is crucial for the inhabitants of the West African Sahel and Sudan Zones. Both factors have an impact on settlement and mobility patterns as they influence directly agricultural productivity and health. Furthermore they determine local strategies of resource exploitation and represent an important factor for the epidemiology of the region. As a consequence of the increasing scarcity of water resources, the still growing population and the migration of larger population groups towards ecologically more advantageous areas there are conflicts in the wider region of West Africa concerning the use and distribution of local water sources. Conflict management therefore has become everyday practice and will probably intensify in the next years.

In Benin the problems caused by availability and quality of water are pronounced. The German Ministry for Development Cooperation (BMZ, 1999) has pointed out that the region exhibits a „high ecological instability“. The high rate of increase in population of approximately 3 % p.a. and the size of migration from the Sahelian north to the tropical south cause an tremendous pressure on natural resources. The health situation related to the water shortage, the restricted access to water resources and the low sanitary standards represent the principal problems. They correspond with the high rate of child mortality (< 5 years) of 140 per 1000 births and low life expectancy of 52 and 57 years for men and women respectively (BMZ, 1999).

Subproject A5 of the IMPETUS-initiative therefore intended to analyse the complex water problems in Benin from an interdisciplinary perspective involving anthropology as well as the medical disciplines virology and bacteriology. Five workpackages were created to face the questions related to the availability, quality, and management of scarce water resources in the upper basin of the Ouémé river:

- Workpackage A5-1: Water and water based resource management and local social and political arenas in the upper basin of Ouémé river.
- Workpackage A5-2: Water and household economy in the upper Ouémé basin.
- Workpackage A5-3: Water and health conditions: indigenous medicines in the upper Ouémé catchment.
- Workpackage A5-4: Water and infection: quality of drinking water and epidemiology of waterborne associated infectious diseases in the upper Ouémé-region.
- Workpackage A5-5: Water and viral contamination: proof of viral indicators in various drinking water sources in the upper Ouémé basin.

Their main objectives were the analysis of:

- the political economy of the current forms of water management in local and regional arenas in a context of scarcity, abundance and multiculturalism.
- social and economic strategies pursued by the members of local rural households.
- different perceptions and practices related to water-dependent diseases.
- the local epidemiological situation with respect to the microbiological quality of drinking water

The following results have been achieved in the different workpackages:

Workpackage A-5-1: Water and water based resource management and local, social, and political arenas in the upper basin of the Ouémé river

The objective of this work-package was an anthropological analysis of the political economy of the current forms of water management in local and regional arenas in a context of scarcity, abundance and multiculturalism. Five main topics were followed up: (1) the different forms of rights about water and water based resources (customary, formal and informal rights); (2) the relations between migrants and autochthones in regard to the access to water and water-based resources; (3) the relations between state and local community with regard to water-management; (4) the forms of conflict and conflict resolution processes pertaining to the control of water sources, and (5) the institutional aspects of water management from the national to the local level.

The study was based mainly on qualitative research methods: traditional anthropological approaches (surveys, participant observation, intensive fieldwork with different forms of interviews), the ECRIS approach, focus group discussions and ranking. It also combined local and regional level analysis. In order to cover the regional dimension of this research some transversal topics were identified as entrance to the field: water management in situations of water-scarcity and/or abundance, fishery, land rights, forms of integration, marginalisation and exclusion of migrants from the access and control of water resources, case studies about conflict and conflict resolution processes concerning water and water based resources including more than two administrative or customary levels. Intensive fieldwork was carried out in 10 villages as a way of comparing different typical situations and configurations. The following data were collected: around 550 interviews and 23 case-studies on institutional aspects and conflict and on conflict resolution processes. By cooperating with the University of Abomey Calavi (Cotonou) two students have achieved their “maîtrise” (Magister) in sociology and anthropology on different aspects of this topic.

Obviously the water policy in Benin at the national level is related to and perhaps determined by international discourses since the early 1980s. The state administration in charge of water affairs tries to extend these ideas through rural water supply policy, participative management of water points, etc. The great difficulty is the day to day interplay between public services and local community in the process of decision-making, realisation and control of water sources and the management of those sources. The control of water sources has a tremendous impact on the control of land in the Upper Ouémé region. Currently there is a great transformation of the customary basis of land rights: the former link between hunting rights and the control of land is replaced by the evocation of the control on water sources in these areas. Those people who have the right to authorise a fishery party in a specific part of a riverine system or who organise ceremonies related to water sources finally gain control over most of the surrounding land.

The management of water resources leads to the emergence of different forms of social transactions and negotiations of rights about water and other water based resources. Altough official legislation and customary law systems exist resolution processes and institutional responsabilities are difficult to prescribe when conflicts occur.

Women are predominately affected by the situation of increasing scarcity, as they have almost no control over water management. Water management is mainly a male domain. Many dynamics are at work in this field: there are processes of progressive changing appropriation rights of common water sources (particularly the rural pumps) to local big men and families as well as processes of exclusion and marginalisation of migrants by autochthonous villagers in many contexts of multiculturalism. The procurement of water takes more than half of the day-time for women in a period of about five months yearly (January to May). Water scarcity leads also to social tension in many villages: conflicts between women competing for water or men accusing women of adultery as a result of the time consuming search for water until late night.

Additionally many social constraints interfere with the use of local water sources, because wells and pumps often serve as places of social representation. Sometimes problems depend on the kind of the water source influencing decision-making processes: in villages where accusations of sorcery occur vulnerable villagers like young men refuse wells and prefer the pumps. They believe that this attitude helps to reduce the influence and power of witches who intend to keep occult political control over wells by practising sorcery.

How is it possible to manage water resources efficently in such a context of multiculturalism, water scarcity, great social conflicts, and processes of private appropriation of collective water sources? What kind of model of water management is feasible to integrate all these parameters at the local level? These are the challenges which have to be faced in the second phase of IMPETUS.

Workpackage A5-2: Water and household economy

Objective of workpackage A5-2 was a detailed and holistic analysis of social and economic strategies pursued by the members of local rural households. Research focused on the three main targets: household economy, social organization, and water economy. These issues were embedded into socio-political conflict areas through the following complexes and state indicators: Water consumption and access, property structures, work, consumption and market activities, cotton, budget, social structures, witchcraft, identity, institutionalization, time allocation, and spatial organization.

The following methods were applied by means of triangulation: 1.) *Qualitative data*: ECRIS (Enquête Collective Rapide d'Identification des conflits et des groupes Strategiques), open and semi-structured interviews, participant observation, life histories, case studies, and group discussions; 2.) *Quantitative data:* Survey in 30 villages, survey of a representative, stratified sample, longitudinal case studies (6 months), time allocation studies (4 months), water consumption analysis (6 months), continuous monitoring of household budgets and patterns of consumption (12 months), market studies (5 respectively 8 months); 3.) *Cognitive data:* Mental maps, wealth rankings, ratings, pile sorts, methods of analysing verbal conceptualization; 4.) GPS-based village-mapping.

Social organization and economic strategies in the north of Benin can only be described adequately by making gender one of the key-variables. Additionally the structural phenomena "hierarchy" and "witchcraft" effect an important influence on strategies of risk and decision making. Differences between strategies on household level are based primarily on the following issues: Access to resources, religious affiliation (e.g. Islam, Christianity), marital status (e.g. polygamous, monogamous), ethnic affiliation, occupation (e.g. peasant, craftsman) and household size. The important influence of gender on economy and social structure is supported by longitudinal studies. One result of the budget survey in Bougou (12 months, 20 participants) was that men gained a 28% higher income than women (especially through the production of cotton), while the latter tended to have higher degrees of indebtedness. At the same time monetary transactions of women often turned out to be designed on a long term perspective and are influenced more by seasonality (e.g. retail: agricultural products are bought at low-cost and retailed high-priced in times of shortage). Any form of savings were only rarely existing due to educational deficiencies and other criteria - except for the participation in *tontines* ("saving clubs"). In cotton production the accumulation of monetary gain was not only rendered more difficult by the fluctuating prices of the world market and a lack of technical know how. The analysis of local knowledge showed the additional aspect of lacking capacities to draw up a balance sheet and to calculate the final profitability.

While farming in the catchment was a male task – with the exception of female help during seedtime and harvest ("a woman doesn't handle a hoe") – the local market was dominated by women. Just about 80% of the commerce and the traded products in Bougou were in the hands of female agents. Water management also turned out to be a domain which was deeply influenced by gender issues: Supply and management of drinking water were explicitly female activities. Men only took part in the cooperative use of pumps. In the catchment the access to water resources was highly heterogeneous and differed from village to village. Although freshwater is a limited good in the Sub-Prefecture Donga (one rainy season per year), peasants emphasized in surveys on emical perception land as the most important limiting factor.

The objectives of the second phase concern the operationalization and generalization of emical perceptions of the identified key-variables in a regional scenario. The focus of attention will rest on the vulnerability of households and individuals, focusing on the central variables ‘gender’ and ‘hierarchy’.

Workpackage A-5-3: Water and health conditions: indigenous medicines in the upper Ouémé catchment

The target of research was a detailed analysis of different perceptions and practices related to water-dependent diseases. Local disease and health concepts as well as the corresponding preventive and curative measures of the local medicines were analyzed focusing on water, health conditions, and therapeutic pathways.

Based on the quantitative data of a micro-census and qualitative data from interviews, questionnaires, pile sorts and participant observation three longtime studies have been carried out in the local setting of Dendougou, a village of about 500 inhabitants 10 km to the northeast of Djougou. From Autumn 2001 to January 2002 a longitudinal health survey concerning the emic perception of health and disease was undertaken in eight selected residential units, covering thus the rainy as well as the dry season. A second longitudinal health survey in Dendougou with a more biomedical focus included the analysis of blood and stool samples taken from the village population. Samples were analyzed twice monthly at a laboratory in Djougou. The tests concentrated on malaria and intestinal parasites. The third study focused on patterns of water consumption. It was undertaken in close cooperation with the IMPETUS-subprojects A4-1 and A5-2, thus allowing a comparison of different rural and urban settings. Additional data on a regional scale was collected by means of questionnaires administered in 30 villages of the catchment.

Therapeutic pathways

Practitioners and patients did not operate in only one medical system. There was a synthesis and/ or coexistence with other existing systems to provide the best way for a better health. Often biomedical (frequently self-administered) treatment coincided with the different forms of non-biomedical treatment. 54% of all cases and 79% of all expenses for medical treatment were invested in biomedical products or resulted in biomedical care. This is due to the fact that biomedical products were readily available and affordable on the local markets. The often cited demand for quality control of herbal remedies seemed to be rather odd considering that it was only one third of all medical treatments resulting in the administration of herbal drugs. On the other hand more than 50% of the therapeutic approaches included the (often inaccurate) administration of biomedical products of unknown origin and/or age.

Five different therapeutic pathways were documented: (1) self-administered treatment based on a) pharmaceutical products and b) the local pharmacopoeias), (2) treatment by indigenous medical specialists, (3) treatment by the local nurse, (4) biomedical treatment at the hospitals or by pharmacists, and (5) no treatment at all.

Self-administered treatment was observed as prime choice. There was a strong tendency to rely more on shop drugs and herbal remedies used at home than on indigenous or biomedical specialists. In 67% of all cases this was the selected pathway to medication. This percentage was unexpectedly high. Two household surveys, which have been carried out by the Ministry of Health in Benin, showed that in 1989 half of the illness episodes analyzed were treated at home while in 1991 this amount decreased to only 25%. (SOUCAT, 1997).

Although local nurses (9%) were more frequently visited than the indigenous medical specialists (7%), they had a certain contested reputation. In most cases people attended local nurses rather to buy a product than to get any advice. These products were cheaper than on the local market, but many considered them to be old or less powerful. In nearly 8% of the recorded cases people decided to go to the hospital or to visit a pharmacy. No treatment at all due to lack of time and/or money was the choice for 9% of the sample population.

Gender, decision taking, and expenses

Gender could be identified as an important aspect of medical care on the village level. Women took the decision for therapeutic measures in about 68% of the investigated incidents. Despite contrary assumptions and statements in interviews, the female household members turned out also to provide the money in 69% of the cases. It can be noted, that women living in the village took even more economic and personal responsibility for the members of their RU than women living in remote areas.

Health conditions

The average of days per month perceived as being too sick to work was 1,8 for non-well users and 2,3 for well-users, reflecting a higher sickness-rate for the last group. In each case the number of reported illness episodes was significantly higher than stated by SOUCAT, 1997, who reported just one illness episode per person per year.

Malaria, respiratory and gastrointestinal infections were the leading diseases in Dendougou, highlighting hookworms as predominant parasites. The biomedical tests were concentrated on malaria and intestinal parasites, showing that 55% up to 73% of the population had actual manifestations or at least former contact.

With an increasing scarcity and a decreasing quality of water, the infant mortality as well as the incidence of severe infections will rise. The consequences are e.g. higher work loads for the remaining healthy members of society, agricultural shortfall, and shortage of livestock. This supports a higher financial burden which enhances the conflict potential and the vulnerability of individual, household and society. Therefore alternative scenarios have to be developed focusing on water, gender, health conditions, and therapeutic pathways in the second period of the IMPETUS-project.

Workpackage A5-4: Water and infection: quality of drinking water and epidemiology of waterborne associated infectious diseases in the upper Ouémé -region

and

Workpackage A5-5: Water and viral contamination: proof of viral indicators in various drinking water sources in the upper Ouémé-basin

The aim of both medical workpackages was the microbiological analysis of various drinking water sources in the upper Ouémé –region. Water-transmitted bacteria as well as virological indicators (Enteroviruses, Norwalk-Viruses and Hepatitis E-Virus) have been detected, characterized and quantified both in order to assess their effects on the local epidemiology.

Due to the restricted infrastructure especially in the countryside of Benin a stationary laboratory and a mobile unit had to be established before starting the analysis. In addition more than 900 watering places (wells and surface water) have been mapped in the area between Parakou, Djougou and Bassila. These locations served as primary objects for taking water samples with respect to WHO advice. Waterborne bacteria were detected by cultivation on special media and differentiated by serological, biochemical and genetical methods, followed by investigation of resistance patterns. The analysis of the 3 virological indicators combined the pre-analytical concentration of water samples in a newly developped transportable system with the detection by cell culture (Enteroviruses) and polymerase chain reaction (Enteroviruses, Norwalk-Viruses and Hepatitis E-Virus), respectively.

During the first project phase more than 150 water samples were taken from different locations in the catchment. Nearly 50 % (74) out of these were positive for Enterococcus spp., Escherichia coli and Enterobacteria spp. indicating faecal contamination. Clostridium spp. were found in 8 samples and characterized as Clostridium perfringens in 4 cases. 16 samples showed the presence of Salmonella enteridis spp. belonging to the usually rare subspecies II – IV (see Tab. A5.1). These findings and the lack of typically water associated Salmonella spp. of the subspecies I (e.g. S. typhimurium and S. enteridis) rise questions about the pathogenicity and virulence of these rather unknown serotypes being addressed in the second project phase.

72 samples were also virologically analysed and showed only one positive result for Enteroviruses. A possible explanation for this matter can be seen in difficulties associated with the air transport as total time and storing conditions were not ideal. Therefore also bacteriological testing was badly influenced as no thermosensible Campylobacter spp. and Yersinia spp. could be found in any sample. Meanwhile changes were made in order to improve the situation.

Still there remain nearly 850 watering places to be analysed. The results so far show clearly that the former manner in Benin to check wells only once after construction is unsatisfying. From a microbiological and chemical perspective there is a clear need for regular analysis and – in case of positive finding – sanitation measures. Also a „quantitative risk assessment“ according to existing surveillance systems in the field of toxicology (e.g. EPA/USA) has to be developed and applied in Benin in order not only to describe the real epidemiological danger of waterborne diseases but also to connect microbiological findings with climate and socio-economic scenarios.

Tab. A5.1: Unusual *Salmonella* subspecies II – IV found in various watering places of the upper Ouémé catchment.

Village	**Pathogen**
BAKU (14[1])	[4[2]] ***S.Sada*** (30:z10:1,2[3])
BOUGOU (22)	[11] ***S.Teshie*** (1,47:l,z13,z28:e,n,z15), [13] *Clos.fallax*, [18] ***S.Virchow*** (6,7:r:1,2)
DARINGA (36)	[6] *Clos.perfringens*
DENDOUGOU 31P (4)	[M3] ***S.Hofit*** (39:i:1,5), [M4] ***S.Dahomey*** (47:k:1,6)
KAKIKOKA (13)	[7] ***S.Pomona*** (28:y:1,7), [8] ***S.Kaneshie*** (42:i:l,w), [9] ***S.Koketime*** (44:z38:-)
KOBRIKONTO (16)	[4] ***S.Elisabethville*** (3,10:r:1,7), [6] *Clos.perfringens*, [11] ***S.Minnesota*** (21:b:e,n,x)
KPASATONA (7)	[2] ***S.Yaba*** (3,10:b:e,n,z15)
KPAWA (8)	[M4] ***S.Rubislaw*** (11:r:e,n,x)
SEBOU (18)	[1] ***S.Mango*** (38:k:1,5), [14] ***S.Apapa*** (45:m,t:-)
SEROU (7)	[2] *Clos.bifermentans*, *Clos.fallax*
TOUROU (17)	[1] *Clos.sordellii*, [4] *Clos.perfringens*, [5] *Clos.perfringens*, *Clos.bifermentans*
WOLOU (2)	[2] ***S.Nima*** (28:y:1,5)
YAKOUA (2)	[2] ***S.Elisabethville*** (3,10:r:1,7)

[1] Number of mapped watering places in the village
[2] Identification number of the watering place with a positive finding
[3] Antigen formula of the analysed *Salmonella spp.*

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Part B

Water-balance of the Drâa-catchment area and socio-economic implications

Subproject B1

Spatial and temporal variability of precipitation

Participants	Discipline
Prof. Dr. P. Speth (Coordinator) Institute of Geophysics and Meteorology, University of Cologne	Meteorology: Climate Diagnostics
Prof. Dr. A. Hense Institute of Meteorology, University of Bonn	Meteorology: Climate Dynamics
Prof. Dr. M. Kerschgens Institute of Geophysics and Meteorology, University of Cologne	Meteorology: Small-scale Modelling
Prof. Dr. C. Simmer Institute of Meteorology, University of Bonn	Meteorology: Modelling / Remote Sensing

Summary

Semi-arid regions, particularly the southeast of Morocco, are confronted with high year-to-year precipitation variability and therefore are highly sensitive to climate change. In order to assess possible future changes in the 2nd phase of IMPETUS, this present study was based on a twofold strategy: (i) diagnosis of the large- and regional-scale conditions for precipitation in different regions of Morocco with an emphasis on the area south of the High Atlas mountains and (ii) implementation of a hierarchy of atmospheric models for dynamical downscaling purposes.

It was found that for the Drâa catchment the subtropical North Atlantic is a major source of moisture in winter and that a transport along the southern flank of the Atlas due to the air flow south of cyclone centres located west of Morocco and the Iberian Peninsula is a decisive factor for winter precipitation in the area of interest. In addition precipitation appears to be linked to the occurrence of upper tropospheric troughs or cut-off lows which reduce the static stability and/or lead to dynamical uplift downstream of the trough axis. The observed relation of precipitation to southerly weather types suggests that orographic lifting at the southern slopes of the AtlasMountains plays an important role, too. The foothills of the Atlas, however, receive also significant contributions to their annual rainfall amounts from rainy episodes in late summer/early autumn and in spring (up to 40% of the annual mean rainfall). This is due to a tropical-extratropical interaction mechanism identified in the course of the investigations. Common to the associated rainfall events is the presence of an upper-level trough in the subtropics that extends into the tropical belt, of a subtropical jet streak at the eastern flank of the trough that is collocated with a tropical moisture outburst, of a low-level moisture source in the deep West African/East Atlantic Tropics from which the water vapour is advected at mid-troposheric levels into the Atlas Mountain region, and a forcing of rainfall due to dynamical lifting under the inflection point of the subtropical jet.

*A hierarchy of atmospheric models from the global to the local scale (ECHAM / ERA → **REMO** and GME / NCEP → **LM** → **FOOT3DK**) were successfully adapted to local conditions and nested for dynamical downscaling purposes in an area where observational data coverage is*

extremely poor. This tool will allow us to estimate the bandwidth of possible future changes with respect to precipitation and evaporation in the Drâa catchment planned for the 2nd phase.

The principal objectives of the meteorological subproject B1 consisted of the quantification and understanding of the atmospheric branch of the water budget for the Drâa catchment and the assessment of the mechanisms that control regional precipitation/evaporation variability. These objectives were pursued by a twofold strategy based upon diagnostic and model studies. In workpackage B1-1 a dynamical down-scaling approach is described using a chain of nested atmospheric models. A satellite-based rainfall monitoring system to overcome the lack of ground-based rainfall observations is also outlined in this section. Despite Morocco's recurrent exposition to extreme weather conditions (extended droughts and heavy flooding) the understanding of the mechanisms responsible for precipitation variability in different parts of the country on intraseasonal to decadal time scales has been rather incomplete. Thus in workpackage B1-2 the large-scale influences on precipitation variability were analysed in detail. A dynamical-statistical model was developed in workpackage B1-3 in order to assess the rain- and snowfall distributions in the Atlas Mountains on a 1 km scale.

The following results have been achieved in the above-mentioned three workpackages:

Workpackage B1-1: Diagnosis of precipitation variability

Against the background of an extremely data sparse region, delivery of high-resolution – both in space and time – meteorological fields required by the other subprojects is a major challenge. For this reason a hierarchy of atmospheric models from the global to the very local scale (ECHAM / ERA → **REMO** and GME / NCEP → **LM** → **FOOT3DK**) were adapted to local conditions and nested for dynamical down-scaling purposes. In addition, the establishment of a satellite-based monitoring system allows the derivation of rain rates on instantaneous to climatological time scales.

Model chain: REMO

The main issue of the first IMPETUS phase was to create a rainfall climatology by means of the continental-scale climate model REMO (Hagedorn et al., 2000). So far, a continuous 6-year integration from January 1991 onward has been accomplished, which will be going on until 2002. For most climatological applications, it is sufficient that the model reproduces the observed features of rainfall with respect to mean and variability over a certain period in time. Comparing REMO output with observational data at different spatial and temporal scales revealed that the model is able to simulate the northwest African rainfall amount and distribution at time scales from 10 days onward quite realistically. Daily rainfall is only comparable when averaged over several grid boxes (Paeth et al., 2003). A cluster analysis based on rainfall, temperature, annual temperature amplitude, mean cloud cover, sea-level pressure and wind components demonstrates that REMO reproduces the basic feature of near-surface climate (Fig. B1-1), even if the method is applied to a single year instead of 30-year climatological periods. The clusters are arranged from climate zones with abundant (blue) to deficient (brown) annual rainfall and correspond fairly well to usual climate classifications. Further validation studies showed that REMO also draws a realistic picture of mid- and upper-tropospheric dynamics, including the position and magnitude of the Subtropical Westerly Jet (STJ), the Tropical Easterly Jet (TEJ) and the African Easterly Jet (AEJ) (Paeth et al., 2003).

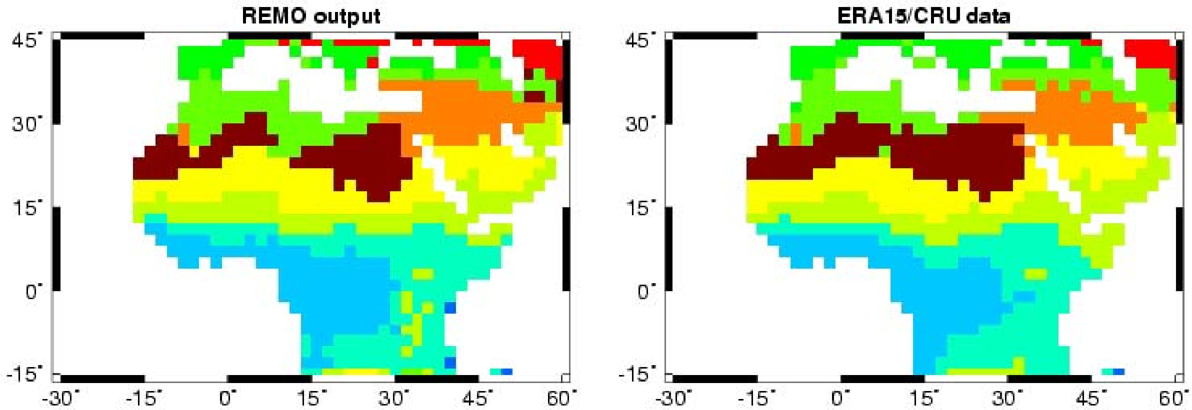


Fig. B1-1: Results of a cluster analysis for the year 1991 based on near-surface climate parameters. Left: REMO, right: observational data.

This promising result holds the prospect that REMO may provide a reasonable description of real climate at a regional scale. Focussing on Morocco, where precipitation observations were available from about 30 synoptic stations, the model excellently fits the spatial distribution of the 1991 annual rainfall and day-to-day variability as suggested by the isolated station data (cf. Fig. B1-2). A transect of simulated annual and diurnal rainfall cycles at six locations from Morocco to Benin, each one representative of a typical climate zone in West Africa, is shown in Fig. B1-3. The winter rainy season in Morocco (Rabat and Ouarzazate) is clearly prevailing. Tamanrasset in the midst of the Sahara is characterized by almost no rainfall throughout the year 1991. Niamey, Parakou and Cotonou are affected by the West African monsoon circulation and describe the Sahel-Sudan-Guinea Coast gradient over sub-Saharan West Africa with rainfall amount decreasing from south to north (cf. subproject A1).

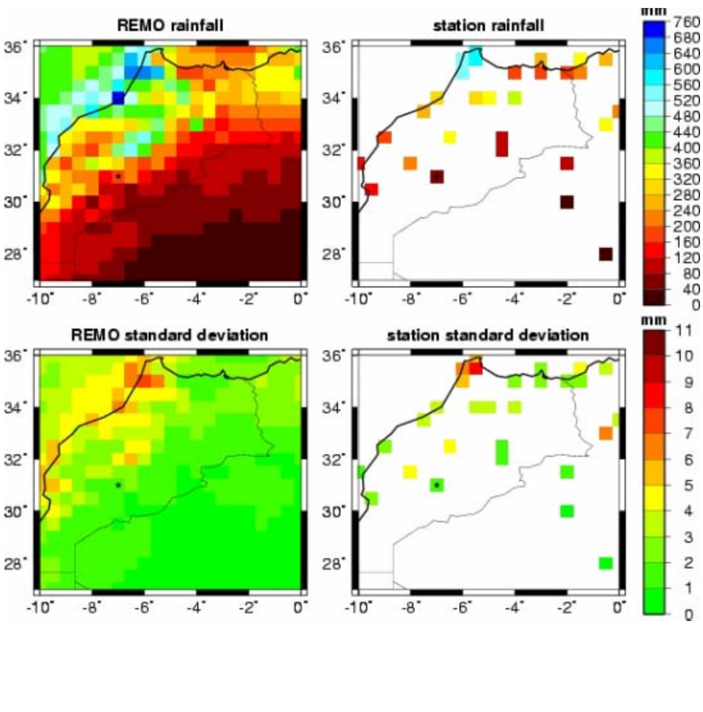


Fig. B1-2: Annual sums (top) and day-to-day standard deviation (bottom) of simulated (left) and observed (right) rainfall for 1991.

In order to evaluate the model's ability in simulating the interannual variations of West African rainfall, case studies of wet and dry years have been carried out (Paeth et al., 2003). It is found that REMO largely reproduces the year-to-year changes over the Iberian Peninsula, Morocco and adjacent countries in terms of phase and amplitude. This indicates that information about the interannual fluctuations is imposed by the lateral boundary conditions in the form of the large-scale extratropical circulation and partly of the regional sea surface temperatures (SST).

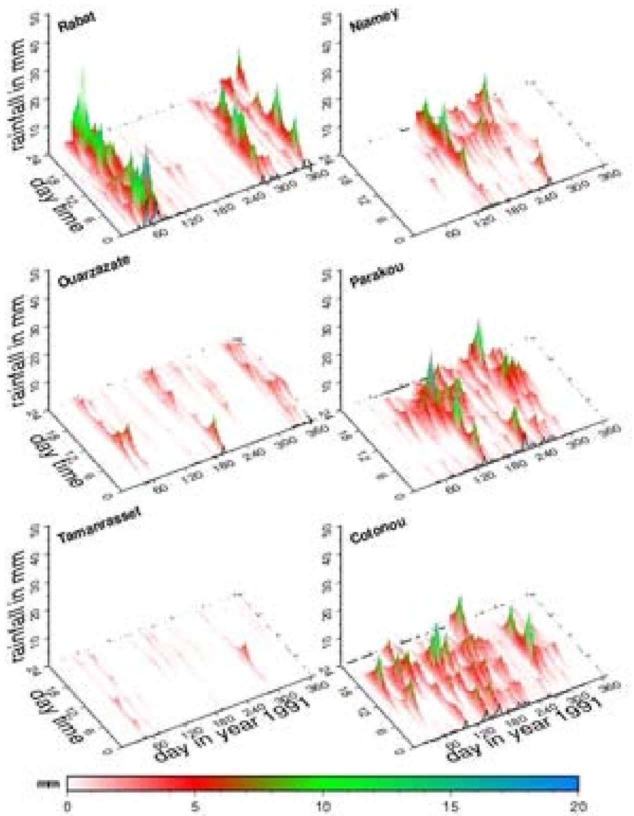


Fig. B1-3: Annual and diurnal cycle of simulated rainfall for 1991 shown as a transect of 6 locations from north-western Africa down to the Guinea Coast.

However, independent analysis based on global climate model data has revealed that the impact of SSTs is minor (Paeth and Hense, 2003). Nevertheless these results suggest that there may be a certain potential of seasonal forecast for Morocco.

<u>Model chain: LM</u>

Simulations on the regional-scale with the non-hydrostatic *Lokalmodell* (LM) of the German Weather Service (DWD) operated on two grids: a larger one covering North Africa from 30°W to 60°E and 15°S to 45°N on a 0.25° grid, and a smaller grid with 0.0625° (ca. 7 km) grid size covering the area around the Atlas Mountains. The smaller grid can be shifted arbitrarily in order to focus on interesting phenomena. The implementation of the LM and the surface boundary database is described in subproject A1. The LM-related research in the first phase of IMPETUS comprised model tests, case studies and studies of extreme events.

A first series of idealized test cases with the LM yielded simulations of rainfall and convection over a Gaussian mountain barrier. The LM represents mountain waves – even with turbulence parameterisation – surprisingly well. The rainfall showed some dependence on the chosen grid size especially in the warm rain scheme which parameterises the grid-scale rainfall. This may lead to an overestimation of rain rates on smaller grids, but the effect is significant only on grid sizes smaller than 4 km. This problem turned out to be connected with the Kessler-type parameterisation and was detected in different atmospheric models, as communications with other modelling groups has shown. Due to the secondary relevance of non-convective precipitation in West Africa, the warm rain scheme was not changed in the LM. A correction via post-processing may be possible when sufficient spatially distributed rainfall data on longer time scales are available. This will be the case at the beginning of the second phase of IMPETUS.

The basis for sufficient longer-term simulation of rainfall is the correct simulation of any processes connected with precipitation events by the atmospheric model. Therefore, examples of different events were analysed in order to determine the strengths and possible error sources of the LM. The classification of rainfall in the Atlas Mountains revealed that precipitation events can be categorized into four groups:

(1) frontal rainfall at extratropical cyclones,
(2) convection triggered by mountains,
(3) mountain lee or Saharan cyclogenesis,
(4) advection of moist tropical air from lower latitudes either across the Sahara or along the West African Atlantic coast.

For each type of rainfall, simulations of single events served as substitutes for their class. In addition to the rainfall-bearing situations, further case studies of days with no rain were also carried out.

Frontal rainfall in the vicinity of the Atlas Mountains becomes stronger, when at the southern flank of the mountains moist, tropical or maritime air is advected. Usually this is connected with an upper level trough west off the coast of Northwest-Africa (see WP B1-2). Some cases in the years 2000-2002 have been chosen to prove the quality of the LM forecasts. The model predicted translation velocity and development of fronts sufficiently. Usually the predicted rainfall was qualitatively and qualitatively comparable to observations. Especially on the smaller (7km) grid the 2-5 day forecast skill of the LM/GME-analysis system in general was good, but on this scale, the dependence from the quality of the forcing analysis data was quite strong. Thus, deficiencies in the rainfall forecast – especially in December 2001 – were mostly connected with insufficient GME analyses.

Atlas lee cyclones have often been associated with Saharan (Sharav) cyclogenesis. Sharav cyclones are relatively important for (rare) cases of summer rain in the inner Sahara and are often responsible for severe dust storms. They occur about 3-10 times per year. Two different types of Saharan cyclogenesis can be distinguished. In the more frequent case, cyclogenesis is connected to an upper-air positive potential vorticity (PV) anomaly which crosses the Atlas Mountains from the Mediterranean. A second kind of Saharan cyclogenesis takes place west of the Hoggar Mountains, the cyclone moves after its birth towards northwest, sometimes reaching the southern flank of the Atlas Mountains. This type of cyclogenesis is caused by a displacement of the AEJ, resulting in a south-easterly mid-tropospheric flow over the Sahara. Both types of cyclogenesis could be simulated with the LM.

The mesoscale structure of a severe Saharan cyclone in October 2000 was studied in more detail. The cyclone developed in a trough of cold air. The prevailing westerlies of the STJ in 30°N advected cold air without any rainfall or even cloud formation from the Mediterranean toward the Sahara. The trough was connected with a strong positive isentropic potential vorticity (IPV) anomaly in the tropopause region. In the zone of strong baroclinicity at the eastern side of the trough, warm and moist air moved from the tropics north-westward towards the Northern African coast. This warm air shaped the warm sector of a developing cyclone and formed a kind of conveyor belt. In this belt, slantwise instability caused the formation of heavy thunderstorms in the middle of the Sahara. It could be shown that this convection could only be resolved properly with the smaller scale gridsize of 7 km. A very elongated frontal system with a cold front in 15° N and a warm front moving toward the Mediterranean was found.

For a special case of severe thunderstorms triggered by mountains on 25th August 2001 at the southern slope of the Atlas Mountains, a tropical-extratropical interaction was responsible for the moisture supply. While hot, dry air originating from the lower troposphere over the Algerian Sahara lead to a sufficient destabilisation of the atmosphere, moisture stemming from large mesoscale convective systems (MCSs) in the AEJ/African easterly wave (AEW) regime was advected along the West African coast toward the southern flank of the High Atlas Mountains. In this situation, strong thunderstorms developed and moved northeastward along the Atlas Mountain devide.

In order to improve short-range rainfall predictions, an assimilation technique for rainfall and liquid water data from radar or the tropical rainfall measuring mission(TRMM) satellite using the idea of physical initialisation was implemented in the LM (Haase and Crewell, 2000; Haase et al., 2000; Haase, 2002). It turned out that the additional data assimilation improved the short-range forecast up to 12 hours. The impact of the data assimilation is limited to a short time, because the water cycle of the LM depends mainly on the dynamical behaviour of the model. Thus, improved initial fields of moisture are adjusted to the dynamics and result in fields which are more similar to the uncorrected ones after 12-15 hours of forecast. This is a well-known problem of the assimilation of moisture related data (Macpherson, 2001).

In cooperation with PIK, TU Cottbus and the GKSS steps toward regional climate modelling with the LM were performed. Hitherto, the LM was used mainly for short- and mid-range operational forecasts. The program developed from the LM – now called CLM – was designed to perform long-term runs. Therefore, the CLM contains a restart technique. Additionally, a pre-processor allows the use of ECMWF re-analysis (ERA) data as forcing.

A view on statistics of natural hazards in the region of the Atlas Mountains shows a remarkable increase of the frequencies of flash or mud floods in the last 20 years. Because these events may play a larger role in a future climate, observed cases with extreme rainfall have been investigated. In these studies, causes for tremendous rainfall and typical weather situations leading to extreme precipitation could be identified. The examination of these case studies is also important for identifying extreme events in future scenarios. The winter rains of 2001/2002 and December

2002 will serve as a test phase for the interpretation of model data with respect to frequency of extreme events.

For longer simulation times of the model, forecasts of convective rainfall are especially dominated by stochastic behaviour. Statistical analysis of model output data is necessary to obtain reliable predictions of rainfall amount and probability. Even for the mid-range forecast time-scale, estimates of the expected rainfall could be improved significantly, when the data was postprocessed with the relatively inexpensive statistical method of constructing a probability distribution function for rainfall by kernel estimates of the spatio-temporal neighbourhood. Additionally, quantiles of the probability of extreme rainfall serve as risk assessment.

As a preparation of scenario-runs the rainy season 2001/2002 was chosen to be modelled with the LM in the second phase of IMPETUS. For this purpose, 12 hourly analysis and 6 hourly forecast data from the GME from November 2001 to December 2002 have been acquired from the DWD. Sensitivity studies will show the influence of boundary data and vegetation. Validation of the LM output will be undertaken with observational data of that rainy season. With these data, LM runs over the whole period, forced with 6-hourly updated boundary conditions, will be conducted. The LM will reproduce - similar to the method described in subproject A1 – wet and dry years of REMO climatologies and scenarios.

Model Chain: FOOT3DK:

Since evaporation and transpiration are the main water sinks for the soil in the investigated area, it was necessary to derive a reliable dataset for these quantities, capable of reproducing the high spatial and temporal variability. The research area is known for its strong vegetation heterogeneity and aridity. Thus, to cope with data sparseness, simple extra- or interpolation of station measurements is not sufficient. To obtain distributed horizontal fields of the surface energy balance, the mesoscale meteorological model FOOT3DK was employed at the high resolution end of the meteorological model chain.

In the beginning, FOOT3DK was successfully nested into the Local Model (LM) of the German Weather Service (DWD). Some problems, occurring from different model formulations had to be solved to obtain nesting results without artificial errors. Due to the higher resolution, results obtained with the model FOOT3DK are more suited to capture small-scale variations in atmospheric fields, especially in the lowest atmospheric layers, where surface influences are largest. Topographic effects at the scale of the model particularly influence near surface wind fields, as well as temperature (due to shading effects and advection). Distribution of near surface atmospheric humidity is more dominated by vegetation distribution, as will be shown below. Adjusting the model FOOT3DK, originally constructed for use in mid-latitudes, to the climate of the research area led to good results. Different sets of parameterisations were tested to find the best one for the investigation purposes.

Sensitivity studies were realised to determine the relevance of different input parameters for the specific area. It turned out, that soil moisture has the largest influence on simulation results. In the research area temperatures are normally high while atmospheric as well as soil moisture contents are low. Therefore, plant available soil water is usually the limiting factor for evaporation and transpiration. Water for soil evaporation and plant transpiration is mainly supplied by two different processes: i) irrigation, using either water delivered from the artificial lake in Ouarzazate or pumped groundwater, and ii) deep plant roots reaching to the low groundwater table. To successfully simulate these two processes, for each of these processes an extension to the model FOOT3DK was employed. The first one simulates irrigation by artificially enhancing soil water content in vegetated areas for a given period of time. The second one simulates plant access to a groundwater table below the lower boundary of the soil model by assuming no transpiration limitations caused by water scarcity. Simulations using these extensions lead to very satisfactory results.

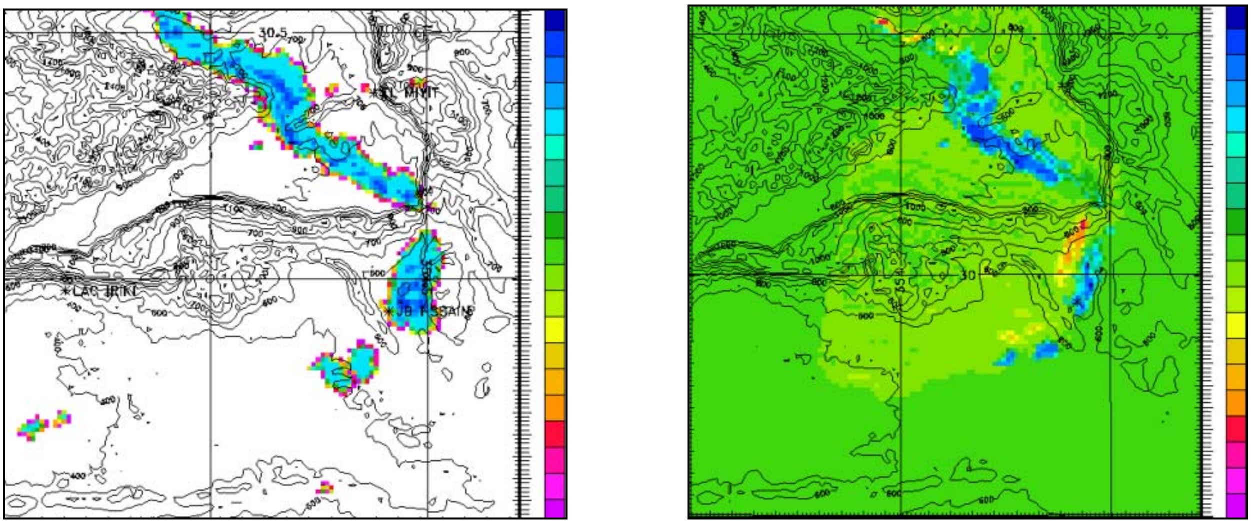


Fig. B1-4: Vegetation cover in % USGS GLCC dataset (left) and difference (GLCC minus LANDSAT dataset) in vegetation cover in 1/10 (right).

Additionally, a preliminary version of the new surface dataset of land use / land cover obtained from subproject B3 was applied, substituting the previously used United States Geological Service Global Land Cover Characterization (USGS GLCC) dataset (see Fig. B1-4 (left) for vegetation cover of the old dataset, and Fig. B1-4 (right) for difference old minus new dataset). This has remarkably improved simulation reliability (see example in Fig. B1-5).

The amount and type of vegetation, as well as plant type specific transpiration indicators (e.g. stomata conductance, leaf area index), have substantial influence on simulation results, in particular on surface energy fluxes and distribution among sensible and latent heat fluxes. This can be seen in the evapotranspiration fields, simulated for a clear sky day, 6th June 2002, (Fig. B1-5 left and right). It is clearly depicted, that the reduced vegetation cover in the new LANDSAT dataset (see Fig. B1-5, right) leads to drastically reduced transpiration in the wadi, compared to a simulation with the USGS GLCC vegetation dataset (see Fig. B1-5, left). Clearly this effect only shows up when enough soil moisture is available for the plants to transpire, so the aforementioned groundwater extension to the model was used for this simulation.

Implementation of different underlying soil types does not lead to significant changes in simulated atmospheric properties, particularly evapotranspiration. Days with dry soil and no rainfall show no differences. Only when the soil surface is moistened by rainfall, small changes occur between different soil types. However, even then they are small compared to differences originating from changes in soil moisture or vegetation properties.

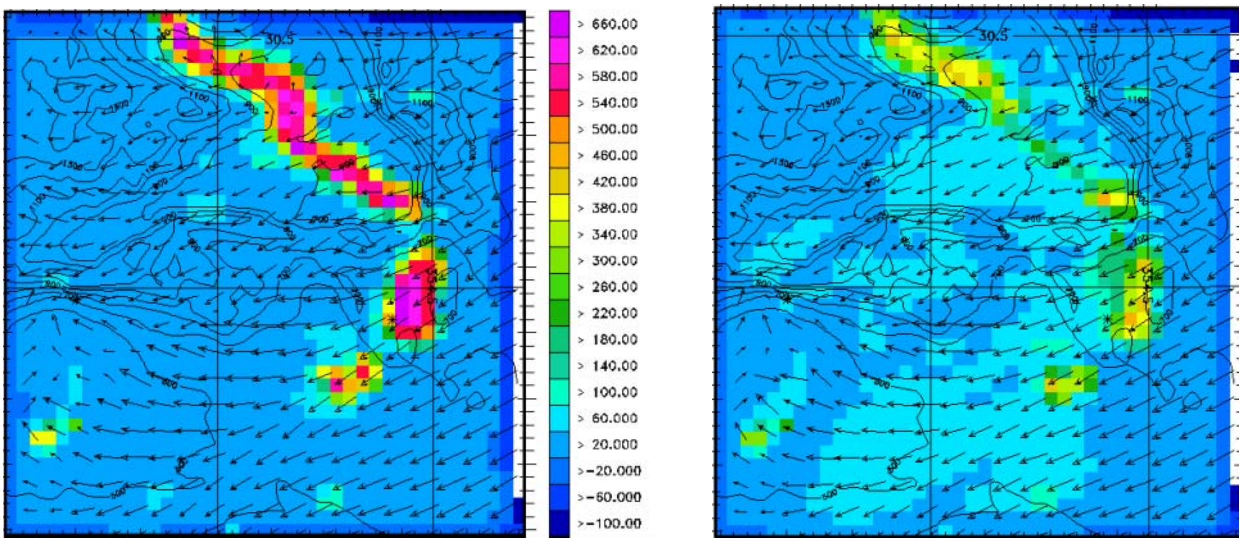


Fig. B1-5: Evapotranspiration in the research area [W/m^2] for a clear sky simulation, 6th June 2002, 12 LST, a) with the GLCC, b) with the LANDSAT dataset.

Using IMPETUS station measurements, a preliminary measure is obtained to outline the quality of the model performance. The results are very encouraging in terms of reproduction of diurnal variations in temperature, atmospheric humidity, and wind systems near the surface.

Simulation of typical weather events (one to three days) has begun and proceeds hand in hand with further validations. The results of the first project phase enable us to deliver surface energy balance fields in temporal resolution up to 10 minutes and spatial resolution up to 300 m grid mesh width (simulations with rainfall can only be resolved down to 1 km grid mesh width, because of parameterisation limitations). Horizontally and vertically heterogeneous fields are now available to the other projects.

The next steps will include producing an evaporation and transpiration climatology for the research area via statistical recombination of typical weather situations for the current climate and then proceed on to simulations for possible future scenarios. Possible changes of climate, hydrology, vegetation, land use etc. will determine the simulations necessary to predict the influence on the atmospheric branch of the hydrological cycle. The obtained results with the model FOOT3DK prove it a powerful tool for this purpose.

Satellite remote sensing of precipitation and evaporation

As in subproject A1, the lack of ground-based rainfall observations, which are especially sparse south of the Atlas Mountains, is sought to be overcome by the establishment of the satellite-based rainfall monitoring system mentioned in workpackage A1-1. Because of the topography of the High Atlas Mountains and the fact that a certain portion of the precipitation over Morocco fell as snow the retrieval of rainfall is far more difficult than over Benin, i.e. higher errors should be expected. Additional techniques and data from other satellite platforms for the discrimination of clouds and snow areas on the ground were not applied. It was decided that they are too time consuming to be implemented in the planned quasi-operational monitoring system. To elucidate

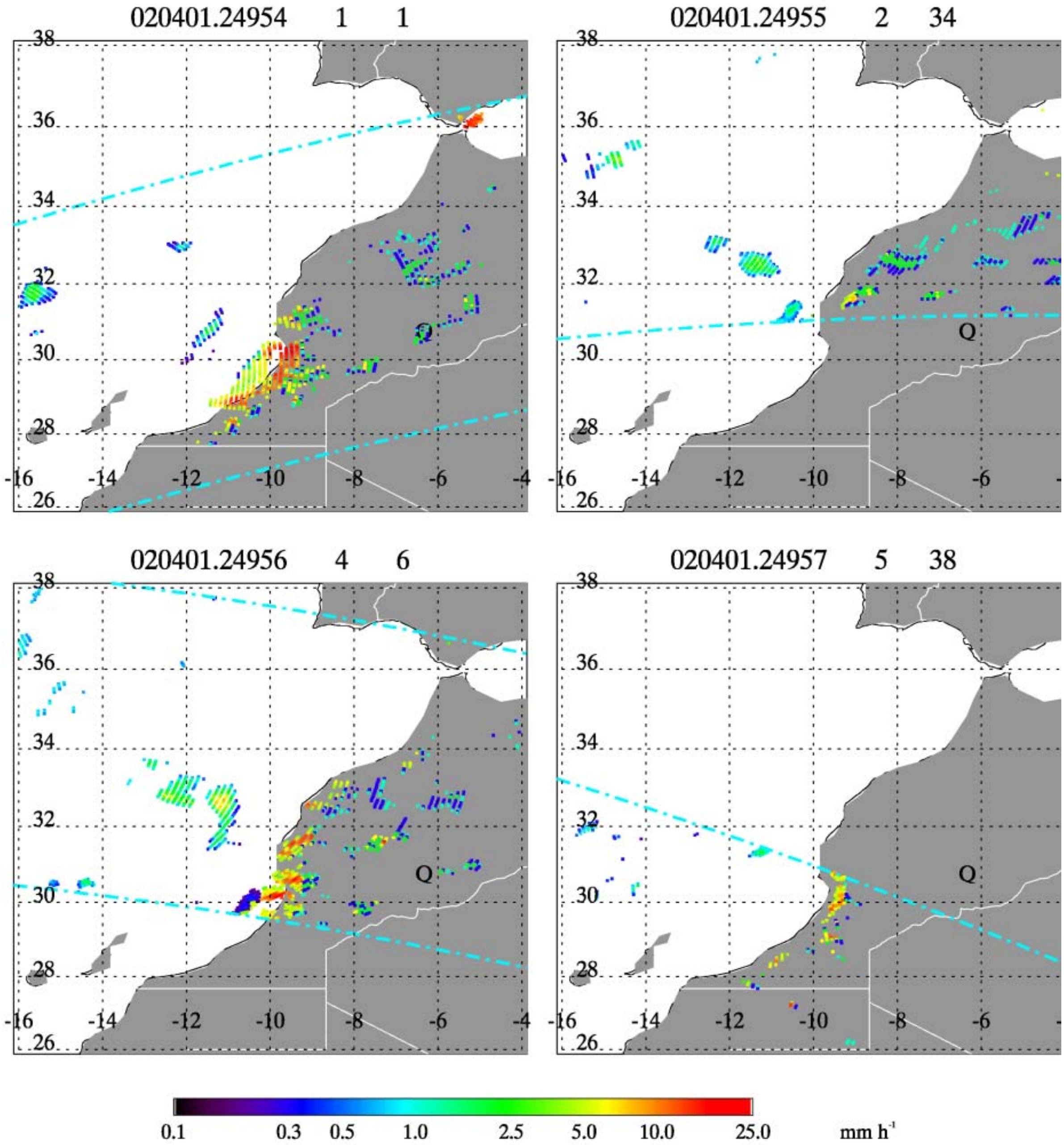


Fig. B1-6: TRMM derived rainfall rate over Morocco during the extreme rain event in the region south of the High Atlas on 31st March and 1st April 2002. Shown are orbits 24954-24957 at 01:01, 02:34, 04:06, and 05:38 UTC. Overland values were derived with the algorithm described in subproject A1-1, over ocean values were filled in from the TRMM standard product. Dashed lines denote orbit boundaries of the TMI. The "Q" denotes the synoptic station of Quarzazate.

the capabilities of the rainfall algorithm described in A1-1 over this difficult terrain the algorithm was applied during the extreme rain event in the region south of the High Atlas on 31st March and 1st April 2002. Four orbits between 01:01 and 5:38 UTC on 1st April gave partial coverage of this rain event. Fig. B1-6 shows the derived rain rates where overland values were derived with the algorithm described in workpackage A1-1 and over ocean values were filled in from NASA's

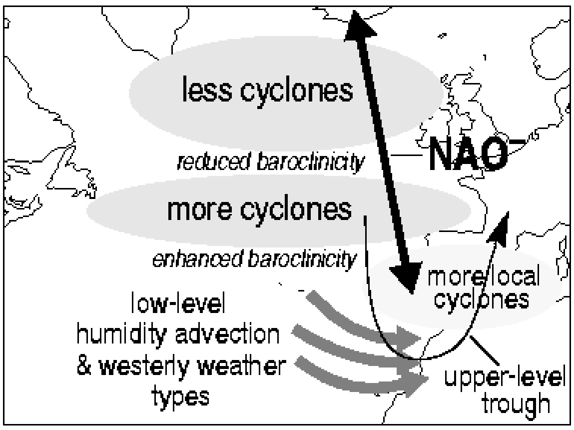
Tropical Rainfall Measuring Mission (TRMM) standard product. The spatial resolution corresponds to that of the 19 GHz channel of the TRMM Microwave Imager (TMI) which is about 18 km × 30 km. Dashed lines denote orbit boundaries of the TMI. The region around Quarzazate was only seen during the first and the third orbit. The TMI detected rainfall from a number of convective cells exhibiting very high rain rates (>15 mmh^{-1}) near the coast and moderate rain rates of about 1-2.5 mm h^{-1} around the IMPETUS stations. This is in relative close qualitative agreement with the findings from Fink and Knippertz (2003) who found rain rates around 2 mm h^{-1} (see Fig. 5 in their paper) at the stations northwest of the wadi Dades. Because the number of rain events south of the High Atlas is rather low and therefore also sample sizes are very low, a statistical comparison of the satellite estimates with the ground based measurements have not been undertaken. This will be done during the second phase when data from the Special Sensor Microwave/Imager (SSM/I) and the Advanced Microwave Scanning Unit (AMSU) will contribute to the monitoring system.

By identifying remote water vapour source regions for precipitation events in the Atlas region, satellite-based data were also used to derive the evaporation over the sea surface in the tropical Atlantic and the Mediterranean Sea. The use of satellite data concentrates upon the derivation of the basic state variables wind speed, sea surface temperature, and near surface atmospheric specific humidity. Moreover, TRMM data allows for the first time estimates of evaporation from instrumentation onboard the same platform. Data from the Visible Infrared Scanner (VIS) and the TMI have been used to derive monthly averages of the mentioned basic state variables and evaporation. These new estimates were used to assess the quality of the Hamburg Ocean-Atmosphere Parameters and Fluxes from Satellite data (HOAPS) dataset (Graßl et al., 2000) and subsequently for some improvements. A new version of the HOAPS dataset will become available during the year 2003 at the web site of the Max-Planck-Institute for Meteorology in Hamburg (www.hoaps.zmaw.de). It consists of the basic state variables, turbulent heat fluxes, cloud liquid water, rainfall, and total precipitable water. The new version utilises SSM/I data from all platforms during the period 1987-2002. The data will be delivered in instantaneous satellite pixel resolution as well as in weekly and monthly resolutions on grids with 0.5° × 0.5° spatial sampling.

Workpackage B1-2: Analysis of large-scale forcings of precipitation fluctuations

The aim of this workpackage was to enhance the poor understanding of the relations between precipitation events in different parts Morocco, and patterns of the large-scale atmospheric circulation and synoptic activity on the basis of observational data. The associated physical processes were examined on different time-scales. The relations found were used to explain different aspects of the spatial, seasonal, interannual and decadal precipitation variations and will serve as a basis for the evaluation of the output from climate change experiments with the global general circulation model ECHAM in the second phase of IMPETUS.

In the analysis, we distinguished between tropically and extratropically induced rainfalls. The investigations for the extratropically dominated wintertime were mainly carried out with the help of composite and correlation studies based on monthly data. In addition, a routine for the identification of the axes of upper-level troughs was developed. Three regions with different precipitation regimes were defined, whose deviations are mainly caused by the orography. The precipitation in the northern and western parts of Morocco reveals a clear dependence on the strength and position of the North Atlantic storm track (represented by baroclinicity, storm track intensity, frequency of surface cyclones). Rainy synoptic situations are often accompanied by an upper-level trough and/or a shallow cyclone west of the Iberian Peninsula as well as predominantly westerly weather types and water vapour advection from the Atlantic Ocean (see also Knippertz et al., 2003 b). In this area, a strong negative correlation to the North Atlantic Oscillation (NAO) was observed, particularly, when the subtropical NAO-centre is at a relatively eastern position (see Fig. B1-7, left). The region close to the Mediterranean coast in northeast Morocco/northwest Algeria reveals a distinct relation to the frequency of upper-level troughs and the storm track and cyclone activity over the western Mediterranean, that is accompanied by enhanced moisture transports from northwesterly or northerly directions. The region south of the Atlas Mountains in Morocco and Algeria is affected by extratropically induced precipitation only in cases of far southward stretching upper-level troughs and/or surface cyclones, that lead to a humidity advection from the Atlantic Ocean along the southern flank of the Atlas. In these cases precipitation often appears to be connected to orographic lifting. The spring precipitation in all three regions shows a weakly negative, temporally variable correlation to the El Niño/Southern Oscillation. Preliminary results suggest that the predicted northward shift of the entire storm track system over the North Atlantic due to anthropogenic greenhouse gas emissions implies a reduction of winter precipitation in the northern and western parts of Morocco. In particular for the region south of the Atlas, a regionalization of the climate change impacts as proposed for the second phase is necessary to determine future precipitation conditions.



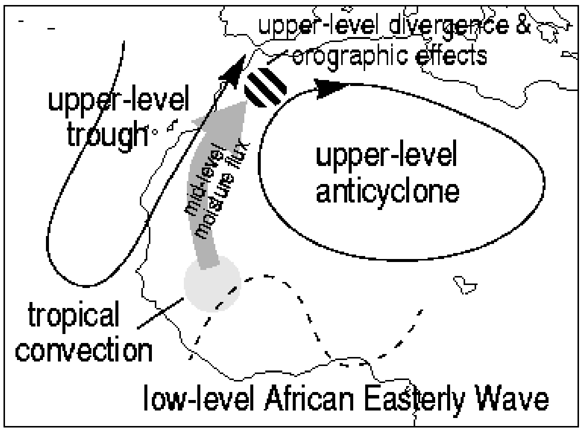


Fig. B1-7: Schematic overview over the most important mechanisms of precipitation generation in northwest Africa. Precipitation caused by extratropical synoptic disturbances (predominantly in winter; left) and in connection with tropical-extratropical interactions (predominantly in the transition seasons, right).

In contrast to former studies a considerable influence of precipitation in connection with tropical-extratropical interactions could be demonstrated, particularly in the region south of the Atlas. This phenomenon was observed throughout the year, but is most pronounced in the transition seasons. The typical synoptic evolution and involved physical mechanisms of such tropically induced rainfalls were analysed by investigating in total 12 rainy episodes in late summer/early autumn (cf. Knippertz et al., 2003 a). Results demonstrate that a moisture input from convective clusters or squall lines over tropical Africa and the adjacent Atlantic Ocean, which is transported to northwest Africa on the eastern side of a subtropical upper-level trough to the west of northwestern Africa, is a decisive factor. The involved tropical convection is often triggered by African Easterly Waves (AEWs). The precipitation over northwest Africa is predominantly caused by upper-level divergence ahead of the trough and/or by surface heating of elevated terrain in the Atlas Mountains (Fig. B1-7, right).

In addition, an extreme rain event in the region south of the High Atlas on 31st March and 1st April 2002 was investigated, among others based on half-hourly measurements from the 12 IMPETUS climate stations. Precipitation totals (of up to 77 mm in 23 hours) range in the order of magnitude of more than half of an average annual sum and constitute the heaviest storm of the last 25 years in this region (cf. Fink and Knippertz, 2003). The immediate run-off caused flooding and damage to buildings. Besides, a substantial filling of water reservoirs (+23.6% of the total capacity of the great storage lake Mansour Eddahbi) and a storage of water in the High Atlas snow cover (up to 1 m) and in the soil was observed, which positively impacted on the region's water supply until the summer. The precipitation event reveals similarities to the late summer/early autumn cases, but additionally shows the formation of a 'tropical plume' (TP) on the eastern side of the upper-level trough. A trajectory analysis revealed that on the equatorward side of the TP, mid-level moisture transports from tropical West Africa occurred, while the high clouds connected to the actual TP originated close to tropical South America (Fig. B1-8). In contrast to the cases of tropical-extratropical interactions in late summer/early autumn, large-scale dynamical and frontogenetic effects seem to dominate over local factors as the triggering of convection in the moist tropical air through the daytime heating of elevated terrain.

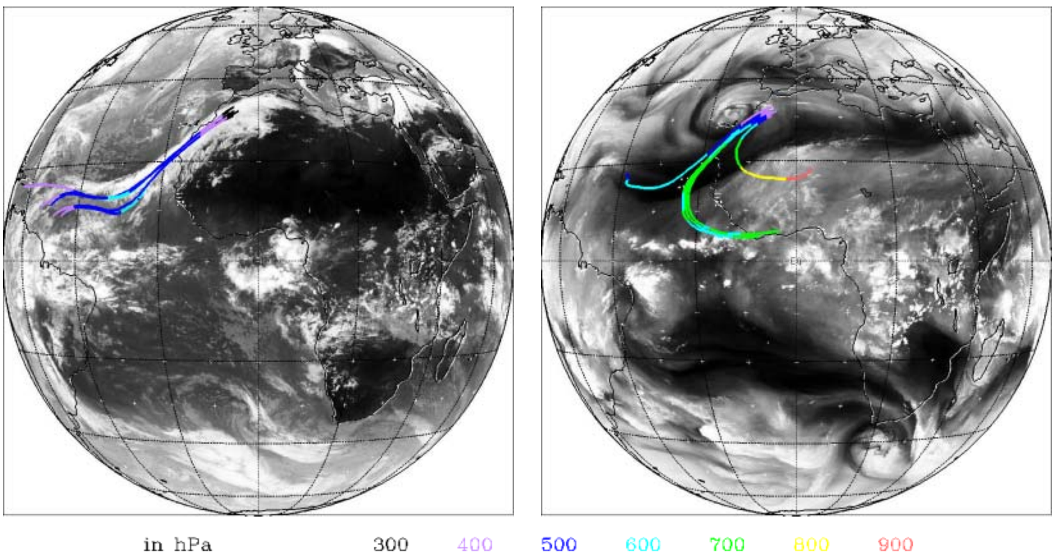


Fig. B1-8: Four-day backward trajectories starting from five different points over the southern margin of the High Atlas at 12 UTC, 31.3.2002. Different colours indicate the height of the trajectory (see figure legend). In the left panel the infrared image of 12 UTC, 31.3. (corresponding to the beginning of the backward trajectories), and in the right panel the water vapour image of 12 UTC, 27.3. (corresponding to the end of the backward trajectories) is underlaid. The starting level is 300 hPa (left) and 400 hPa (right).

A climatological attribution of rainfall to tropical or extratropical sources on the basis of the origin of mid-level trajectories that reach the Atlas region revealed that rainfalls in connection with tropical-extratropical interactions account for up to 40% of the annual precipitation (cf. Knippertz, 2004).

Workpackage B1-3: Prediction of run-off from snow melt in the High Atlas Mountains

Snowfall plays a role for water supply in the beginning of the dry season in the upper Drâa valley. Evaporation and sublimation from snow is expected to play a larger role in the High Atlas Mountains than in the European Alps. Observations showed a decrease in annual precipitation and snowfall in subtropical mountains over the last decades. In order to study the variability of the snow cover and the water supply by snowmelt, cooperation with the subproject B2 focussed on this topic. The meteorological part of a snowmelt-model was developed in order to calculate downscaled rainfall data and atmospheric surface fluxes from larger scale forcing.

For the assessment of distributed rain- and snowfall in the Atlas Mountains on a 1 km scale, a dynamical-statistical model was developed. Due to the purposed simplicity of the model, only approved techniques of boundary layer meteorology were preferred to new scientific developments. A mass-consistent, stationary flow model describes atmospheric dynamics. Analysis/reanalysis data on a coarse grid (typically 50 km grid size) describe the atmospheric forcing. A K-closure turbulence parameterisation has been included. The flow is calculated iteratively in order to produce a wind field consistent with the surface momentum and energy balance. A bulk-snow model computes snowmelt, evaporation of melt water and sublimation of snow from the surface energy and water vapour fluxes. The statistical distribution of vertical winds in form of an estimated probability distribution function was used to generate a similar distribution of rainfall rates, where the conservation of the area-integrated rainfall prescribed from analysis or reanalysis data, is used as a constraint.

With the mass consistent model, typical cases have been investigated with respect to the relative amount of evaporation/sublimation compared to snowmelt runoff. In these cases, the amount of evaporation/sublimation was of the same order as the snowmelt runoff. In Contrast to the European Alps, evaporation of snowmelt water and sublimation of snow plays a major role in the loss of available water from snow cover in the mountains; on some days, nearly all loss of the water stored in the snow cover was due to sublimation.

The month of December 2001 was investigated. Due to the mass consistence the results turned out to be very sensitive to changes in the upper impermeable model surface, because this leads to an acceleration of the flow over high mountains due to a pipe effect: the smaller the channel between the mountain ridge and the impermeable layer, the stronger the winds. In addition, the estimation of the boundary layer height influences the distribution of the vertical velocities. Since the rainfall is connected with the distribution of vertical velocities, also the snow cover was very sensitive to changes in input parameters. Although the model is able to reproduce the snow cover and its variability qualitatively correct, we are not able to decide if the correct physical mechanisms lead to better representation of the snow cover. From this point of view, the mass-consistent flow model is an empirical model, which was extended by some physical considerations. The empirical part consists of a definition of parameters from statistics of observed rainfall and/or snow cover. The model can be applied to arbitrary periods, but parameter estimation has to be accomplished very carefully for each case. Development in this workpackage is discontinued in the next phase of IMPETUS for the benefit of regional climate modelling with the hierarchical model chain.

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Subproject B2

Water availability and soil degradation

Participants	Discipline
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Summary

During the first phase of IMPETUS the main objective of subproject B2 was to measure, quantify and model water availability and soil degradation at selected sites along an altitude and aridity gradient, 350 km in length and 2500 m in height within the Drâa catchment of southern Morocco (cf. subproject C2, Fig C2-1). The transect stretches from the arid, middle parts of the catchment to the periodically snow-covered mountains of the High Atlas in the north. Characteristic rainfall patterns include short low-frequency and high-magnitude events in the south and more frequent, low-magnitude rain- and snowfall events in the mountainous north. As a result of sparse rain- and snowfall events, the main dam at Ouarzazate has experienced suboptimal filling rates and the irrigated regions are increasingly degraded due to extensive salinization. Soil erosion is problematic in almost all regions due to the sporadic nature of events, poor vegetation cover and the removal of protective topsoils.

All 12 automatic climate stations installed by the project have been in function since the autumn of 2000. First eco-climatological interpretations show that there is a distinct gradient in soil temperatures with no soil frost below 1500 m altitude. Seasonality in air temperatures are largest above 2500 m. Analyses with relation to aridity show that with decreasing altitude and increasing distance from the mountain ranges, rainfall amplitudes increase as frequency decreases.

Snow-hydrological processes in the Atlas mountains, especially accumulation and depletion of snow cover, were measured and subsequently modelled and validated using the Utah Energy Balance(UEB) model by Tarboton and Luce (1996). Little snow is delivered directly into the ground- or surface water system in winter since most snow is lost by sublimation as a result of typical subzero temperatures and high wind speeds. Satellite image analyses show that snow cover is no longer continuous in winter and that it may repeatedly and entirely deplete between events.

Soil hydrological analyses encompassed detailed field measurements, especially infiltration and high-resolution spatial and temporal modelling of soil water content and soil temperatures for

various sites. Detailed soil profiles and analyses allowed calculation of soil erosion rates and degree of salinization.

Hydrogeological analyses were carried out over a variety of scales. Detailed investigations of groundwater flow as well as isotope and chemical compositions were carried out. Strong seasonal as well as spatial variations were measured and allowed the origin of water to be traced into the nearby mountains.

The middle to upper Drâa catchment is characterised by an extreme gradient in altitude and aridity. In the Atlas mountains, large amounts of snowfall sublimates directly into the atmosphere without feeding valuable groundwater reservoirs or the surface channel network. The soil's high variance in infiltration capacity causes significant differences between individual hydrological basins as a result of variable geomorphological, geological and hydrogeological settings. Reliable discharge and surface runoff occurs only in regions with good groundwater storage (limestone) and/or surface runoff due to an impermeable underground (e.g. marls). These local and regional differences are reflected by land use, vegetation and agricultural productivity. Problems of soil erosion occur especially in association with intensive nomadism on very erosive soils.

The main objective of the subproject B2 is to provide a regional analysis of the three-dimensional nature of the water balance and its interaction with the human and environmental system.

The aims of this subproject include:

– implementation of a climatological network based on 12 automatic IMPETUS stations, local Moroccan stations and measurements of snow water equivalent,
– analysis of eco-climatological gradients from the middle Drâa via the basin of Ouarzazate to the High Atlas mountains,
– quantification and modelling of the temporal and spatial snow dynamics and its influence on the regional water balance,
– analysis of soil water dynamics, groundwater renewability, and discharge formation as a function of topography, climate, vegetation and soil, and
– evaluation of recent and past soil degradation as a function of soil erosion and salinization.

To achieve these common goals, the subproject B2 was divided into five workpackages: the analysis of eco-climatological gradients from the middle Drâa valley to the High Atlas mountains (B2-1), the analysis of the snow dynamics in the High Atlas mountains (B2-2), the analysis of soil water dynamics and runoff generation along an altitude and aridity gradient in the Drâa valley (B2-3), the analysis of the anthropogenic soil degradation due to water erosion in the upper and middle Drâa catchment (B2-4), and the analysis of groundwater resources in the wadi Drâa (B2-5).

The following results have been achieved in the different workpackages:

Workpackage B2-1: Analysis of eco-climatological gradients from the middle Drâa valley to the High Atlas mountains

The objectives of this workpackage are to monitor and quantify the most important eco-climatological variables from the middle to upper Drâa catchment area, including the High Atlas mountains on the basis of an extensive regional climatological database. In addition to local Moroccan stations, the project is based on information from 12 automatic climate stations installed along a S-N gradient between 445 – 3900 m a.s.l. The purpose of this altitudinal- and aridity gradient is to analyse regional hydrological differences in the water balance as well as significant climatic controls for each vegetation zone as a basis for subproject B3.

A total of 12 automatic climate stations, powered by solar panels, were installed after the 16.11.2000 and have been in operation since then. Data with a temporal resolution of 15, 30 and 60 minutes as well as daily and monthly averages are stored in the IMPETUS database. Each station is described with its geographic location, a photograph and diagrams of precipitation, radiation, air and soil temperature, relative humidity and soil moisture. The upper three stations (between 2960 –3900 m) include snow height sensors for snow monitoring (cf. subproject C2, Fig. C2-1).

Altitudinal variability of temperature gradients in the Drâa basin (445- 3900 m a.s.l.)

An example of the comparative analysis of climate data derived from the IMPETUS database is presented for daily temperature data over a period of one year beginning on the 1st October 2001. Important eco-climatological thresholds and gradients are derived. In Fig. B2-1, the frequency distribution of temperatures is depicted for 10 stations. An important ecological threshold is the occurrence of frost. As such the uppermost station M'Goun, 3850 m a.s.l. in the Ameskar valley, experiences 140 days per year with average temperatures below 0°C at 15 cm soil depth and 20 days around melting point. During the summer months there are only 30 days with temperatures between 8-14°C. In contrast, the mean air temperatures reflect smoother patterns and show 20 days per year with temperatures as low as between –7 to –17°C. From an ecological perspective at M'Goun, there are only approximately 100 days per year with plant growth potential at temperatures above 6°C. At lower altitude stations such as Tichki, 3260 m a.s.l., only 40 days were measured with soil frost and 40 days with temperatures around 0°C. At the station Tizi Tounza, 2960 m a.s.l. in the neighbouring valley, the number of days with soil frost are reduced to 20 and only one or two days with temperatures below 0°C. Even at altitudes as high as 2250 m, e.g. Imeskar in the Ameskar valley, the air temperatures rarely drop below 0°C and the soil no longer records frost. At this location there is no pronounced threshold between summer and winter months, the air temperatures are evenly distributed through the year. On the basis of the thermal conditions, a frost-induced threshold can be defined at around 2500 m a.s.l. The variability of this threshold requires further analyses with respect to aspect and surface properties. Below 2000 m, e.g at Taoujgalt, the growth period is no longer limited by temperature.

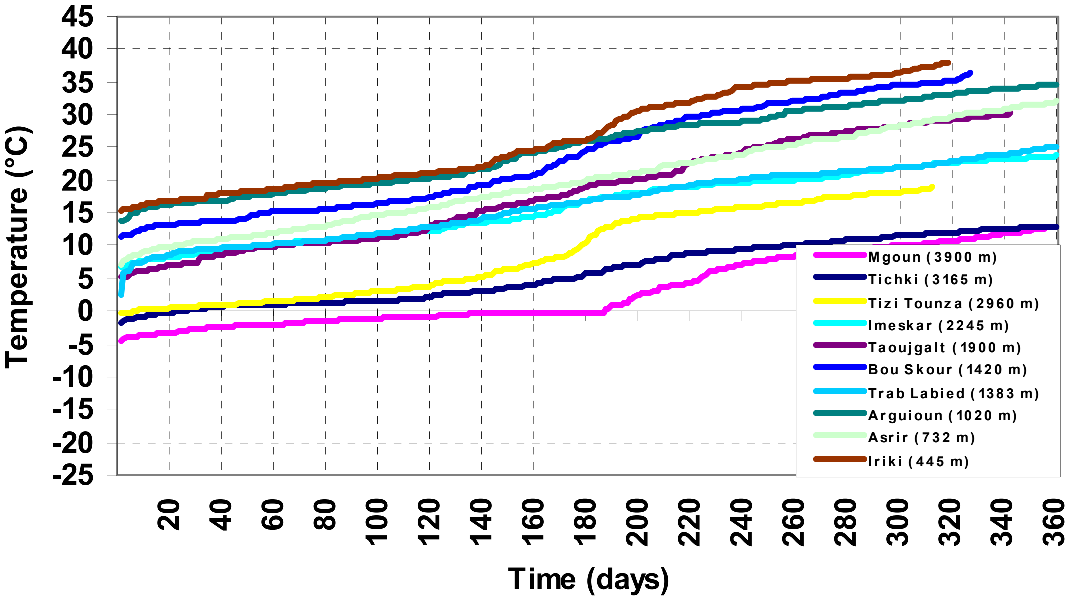

Fig. B2-1: Distribution of soil temperatures (15 cm depth) ordered by size for 10 climate stations in the Drâa catchment starting at 1st October 2001.

At the station Iriki (445 m a.s.l.) in the arid middle basin of the Drâa, soil temperatures range between 15-40°C and the air temperatures indicate clear seasonal thresholds at 12°C and 25°C. In contrast to the frost-dominated regime of M'Goun, Iriki experiences more than 120 days with temperatures above 30°C. During the summer months the air temperatures reach the same values as soil temperatures in 30 cm depth.

<u>Altitudinal variability of aridity and rainfall intensity gradients in the Drâa basin (445- 3900 m a.s.l.)</u>

In addition to altitudinal temperature gradients, the lengths of the dry periods were analysed in relation to precipitation intensities within the Drâa catchment. The length of an arid period was defined by the period between events with daily precipitation sums exceeding 1 mm. The average air temperature between two precipitation events was defined for the duration of each dry interval. The winter snowfall events at M'Goun were calculated via their snow water equivalent. The aridity analyses showed that for the year 2001 to 2002, dry periods only lasted for up to 1 month in the High Atlas mountains, in the valley sites this period extended to 2 months and in the arid middle Drâa around Lac Iriki it increased to 3 months. The average temperatures for these arid phases varied from a minimum of –10°C to a maximum of 36°C. These temperatures are an important indicator for potential evaporation during the dry periods, although plant transpiration for certain species such as the xerophytes on the mountain slopes are well adapted to the dry conditions.

The intensity of precipitation events is an important indicator for the erosivity of rainfall events. With the help of the 15 minute precipitation measurements, the intensities were calculated for 5 representative stations. As expected, there is a clear trend between the mountains and the arid basin in the foreland. From M'Goun to Tizi Touna (3850 – 2960 m) precipitation events are smaller in magnitude but larger in frequency in accordance with the orographic effects. Below Imeskar (2250 m) there is a significant change, the rainfall amplitude increased together with decreasing recurrence. At Asrir (730 m) rainfall is no more than episodic but with the highest intensities. The data show that with increasing aridity the erosivity of rainfall events increases.

The climatological analyses along the 350 km transect of the middle to upper Drâa catchment show that the strongest seasonality is captured by the stations above 2500 m along the final 25 km in the mountains. Below 1500 m. a.s.l. south of the basin of Ouarzazate there are virtually no soil-frost limitations. These results are an important basis for defining thresholds in scenarios of climatic and hydrological change. Indeed, there is a clear trend in rainfall patterns between the High Atlas mountains and the arid forelands. With decreasing altitude and increasing distance from the mountain ranges, rainfall amplitudes increase as frequency decreases. Although precipitation is more difficult to model, understanding regional patterns will be an important step towards managing scenarios in cooperation with subproject B1.

Workpackage B2-2: Analysis of the snow dynamics in the High Atlas mountains

The aim of this workpackage is to analyse snow storage and depletion in the High Atlas mountains using field measurements, remote sensing and physically based modelling. Discharge in the upper Drâa/Dadès catchment is generated mainly by snow and rainfall events during the winter and is the main source of freshwater and groundwater for the pre-saharan arid lowlands. Monitoring and modelling of snow accumulation, distribution and depletion (snowmelt and sublimation) will enable better forecasts of regional water availability and will support modelling efforts for regional environmental change scenarios.

Three test sites are analysed in the catchment of the M'Goun river, a tributary of the upper Drâa/Dadès at altitudes between 2960 and 3900 m. Investigation methods include field measurements from climate stations and distributed snow samples, remote sensing from medium resolution MODIS satellite images and physically based modelling of snow melt. For snow distribution monitoring, NOAA-AVHRR remote sensing images have insufficient resolution (1.1km). The highly variable topography with narrow valleys and ridges cause a very patchy snow distribution at the sub-pixel scale. Therefore, analyses of TERRA-MODIS images using snow masks with 500 m resolution and the Normalized Difference Snow Index (NDSI) after Hall et al., 2001, are more reliable for the M'Goun catchment. To differentiate between highly dominant sublimation versus snow melt, the Utah Energy Balance Model (UEB) according to Tarboton and Luce, 1996, was applied.

Snow was scarce during the winters of 2001–2003. Records from three automatic climate stations within the snow survey region above 2000 – 2500 m indicate that between November to April/May several snowfall cycles were separated by almost complete depletion (Figs. B2-2 and B2-3). Maximum snow depths in the period of April 2001 to March 2003 reached 65 cm at the highest climate station M'Goun (3850 m). Calculated precipitation (snow water equivalent and rainfall) for the hydrological year 2001/2002 amounts to 520 mm for this station. Snow depths exceeding one meter were observed in the gullies and on leeward slopes. Results of snow depletion from simple lysimeters in the field show a gradient in snow melt and sublimation forced by altitude and aspect. From mid-January to mid-February 2003, 94% of snow depletion at the station M'Goun (3850 m, southerly aspect) was achieved by sublimation (47 mm), with only 3 mm of melt due to positive temperatures. During three days following a snowfall event on the 14th / 15th February, all water losses were caused by sublimation. Transitional phases in air temperatures between the 27th February and 3rd March 2003 cause rapid changes from dominant sublimation (90 %) to dominant melt (90 %) for southerly aspects at 3600 m a.s.l. For northerly aspects near the M'Goun station melt and sublimation are reduced or absent during this period and snow temperatures remain below zero. The Utah Energy Balance Model (UEB) accurately simulates the temporal amounts of melt/sublimation.

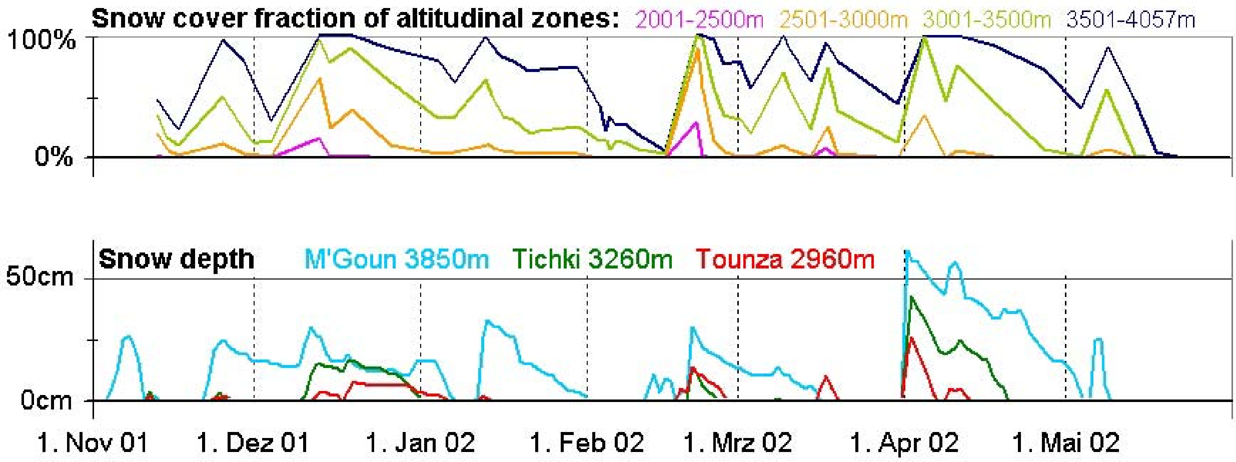

Fig. B2-2: Snow survey in the M'Goun catchment for the winter period from November 2001 to May 2002: Snow depth at climatic stations M'Goun (3850 m), Tichki (3260m) and Tounza (2960 m); snow cover fraction calculated using NDSI in MODIS satellite data for four altitudinal zones (2001–2500 m, 2501–3000 m, 3001–3500 m, 3501–4057 m) of the catchment.

The structure of the snow surface, snow metamorphosis, high wind speeds and prolonged snow cover in gullies and leeward slopes reflect the strong influence of snow redistribution processes. The patchy development and distribution of snow is analysed by GIS, remote sensing images, photos and soil temperature loggers (UTL) in the field. During field campaigns snow courses were undertaken to measure snow depths, snow densities and temperatures at several points in a profile from the valley floor to the ridge (2100 – 3950 m). Snow densities reached from 100 kg/m³ for new snow to 540 kg/m³ for melting snow close to the snow boundary. Penitentes reaching maximal heights of 70 cm were observed during every winter. These depletion forms develop under extreme climatic conditions with high incoming solar radiation, low air temperature and low air humidity (Lliboutry, 1954). Model results from the Utah Energy Balance (UEB) model show high sublimation losses in the higher altitudes of the M'Goun catchment. Even during the transitional phase from winter to spring 2002 with air temperatures above zero, sublimation losses amounted to 35%. MODIS derived snow cover maps allow sufficient differentiation of snow distribution for quantification of water storage at the catchment scale (approx. 1500 km²). The dominant aspect in the M'Goun catchment is towards the south. Considering results from snow melt modelling and dominant climatic parameters such as high incoming solar radiation sublimation plays a very significant role in higher altitudes during subzero temperatures. Snow pack on the northern slopes maintains lower temperatures and lasts longer.

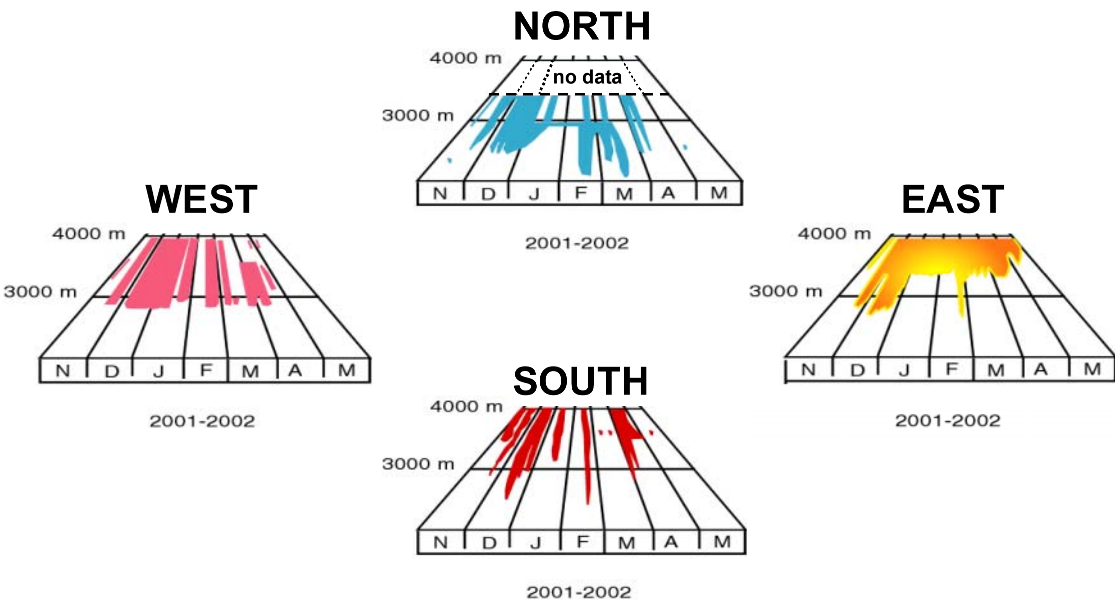

Fig. B2-3: Altitudinal variation of snow distribution for different aspects during the winter season 2001/2002 based on UTL temperature probes inserted along in two slope profiles (criterion: standard deviation of the daily mean is lower than 0,5°C).

It is anticipated that the UEB snow modelling results will be further evaluated with data from the winter of 2002/2003 and from automatic snow pillows measurements in the future. Snow losses by sublimation and melt are very significant for the hydrological budget of the neighbouring catchments. Snow distribution mapping from MODIS images will be complemented by high resolution satellite images such as ASTER to optimize snow melt interpretations over the highly variable topography.

Workpackage B2-3: Analysis of soil water dynamics and runoff generation along an altitude and aridity gradient in the Drâa valley

The aims of this workpackage are to quantify and model soil hydrological processes in the arid to semi-arid catchment of the Drâa. The investigations are focused on water balance and its relations to climate, soil characteristics, topographic attributes, surface properties and vegetation. During the first phase, six test sites were analyzed in accordance with other IMPETUS subprojects along an altitude and aridity gradient ranging from the pre-Saharan desert to the High Atlas. The data were used to calibrate and apply a distributed simulation model for soil water dynamic considering rainfall, interception, evapotranspiration, surface runoff as well as groundwater recharge.

Six test sites were discretized into units of homogeneous characteristics with respect to the soil-hydrological behaviour. The spatial heterogeneity of soil and surface properties in addition to the vegetation cover was investigated according to the approach of Lange, 1999. For each terrain unit, infiltration experiments and rainfall simulations were carried out to estimate infiltration characteristics and surface runoff generation. Hydrologically relevant surface properties such as roughness, rock fragment cover and vegetation density were mapped. The high stone content only allowed disturbed soil samples to be taken. In the laboratory additional basic soil properties such as soil texture, stone content, Corg, as well as the water holding capacity of the disturbed soil samples were analyzed.

In order to measure soil water dynamics, 3 TDR sensors were installed to a maximum depth of 30 cm at selected test sites near the climate stations (cf. workpackage B2-1). The measured water content was used to calibrate and validate the simulation model. Furthermore, 6 discharge gauges were installed at selected test sites to monitor runoff, 4 of which are south of the basin of Ouarzazate and 2 in the mountains. At most test sites a good discharge-water level relationship could not be established due to the ephemeral nature of most streams. Therefore discharge was calculated using the Mannings equation.

Since rock fragments have a significant influence on hydraulic properties (e.g. Poesen & Lavee, 1994; van Wesemael et al., 2000) the amount of rock fragment and texture affects the ability of water storage as well as vertical water fluxes. These characteristics are modified by predominant geologic, climatic, and topographic properties as well as the type of vegetation cover. Ephemeral channel networks such as wadis in the south and bedrock creeks in mountainous regions play an important role in the water regime. Those channels with a high percentage of sand or coarse-grained material have a low water holding but high infiltration capacity. Terrain units with accumulations of fine-grained soil, such as colluvial pediments and topographic depressions, tend to store moisture and therefore have the highest water contents with the lowest infiltration rates. A third typical regime comprises lithological units with shallow soils, low infiltration losses and lower moisture contents. It can be found on steep rock slopes and in topographic convexities. These three typical regimes can be found at all test sites in the Drâa catchment. A total of 23 terrain units were identified on the basis of measured infiltration behaviour, dominant soil and hydrological properties in addition to topographic characteristics derived from high resolution DEMs. These units can be aggregated into categories based on their infiltration behaviour, their predominant soil hydrological properties and topographic characteristics (Fig. B2-4).

The grid-based model applied in this study is a new development based on the approach of Boer, 1999. It has been modified to a high spatial and temporal (hourly) resolution. In order to consider spatial heterogeneity the investigated catchments are discretized into grids of variable sizes containing information of each associated terrain units. The model computes infiltration (Horton approach), surface runoff (Bates & de Roo, 2000), interception (max. storage approach), evapotranspiration (Penman-Monteith), and soil water dynamics in two layers as well as groundwater recharge. Evaporation, transpiration, infiltration, and percolation are considered at the upper soil layer while transpiration and percolation is computed for the second soil layer. Furthermore, soil temperatures are simulated in 5 depths for derivation of the soil heat flux required to compute evapotranspiration.

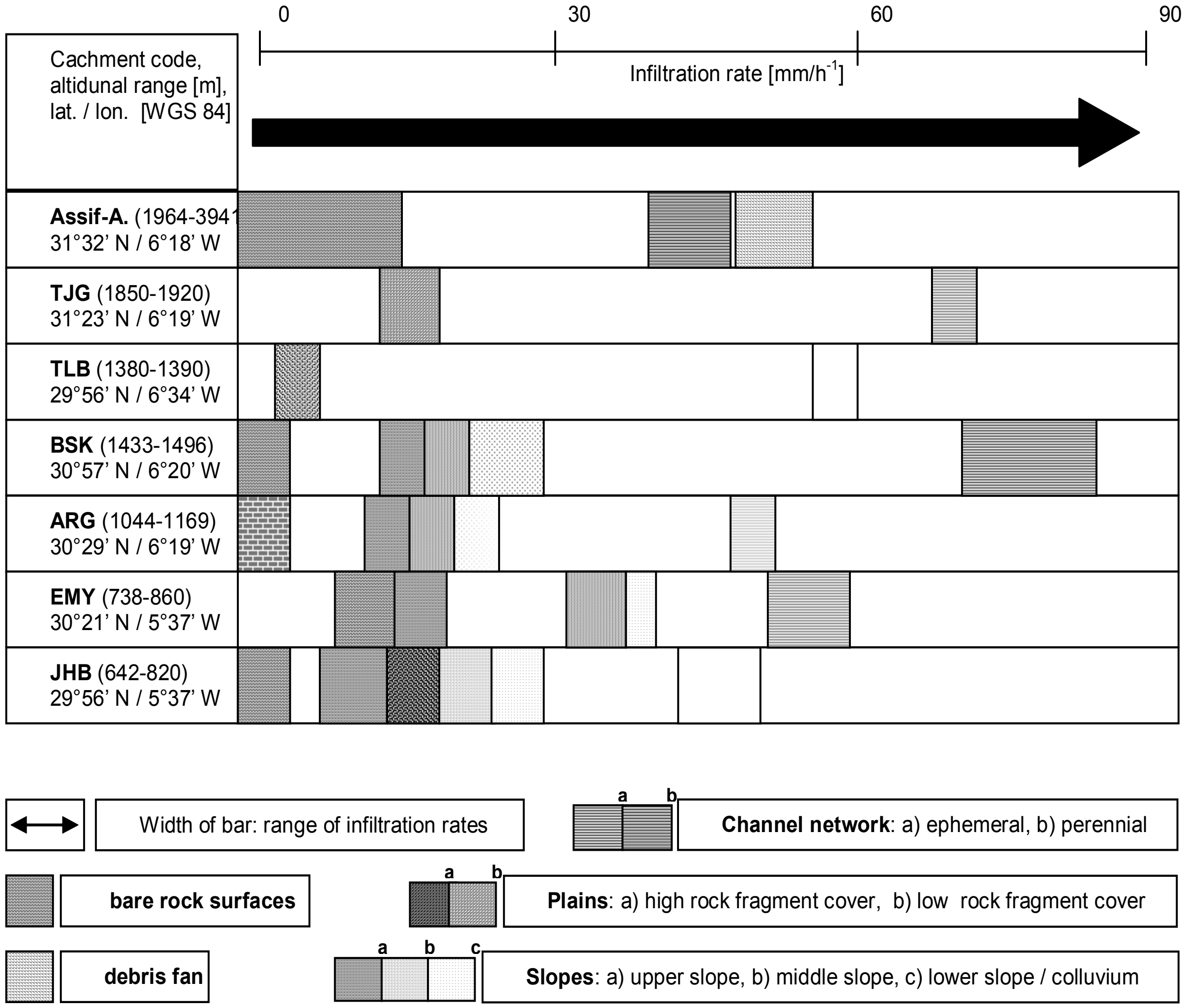

Fig. B2-4: Infiltration rate of selected land units within measurement transect (JHB=Jebel Brâhim, EMY= El Miyit, ARG=Arguioun, BSK= Bou Skour, TRL= Trab Labied, TJG= Taoujgalt, Assif-A.= Assif-n-Ait-Ahmed)

The model was first applied and tested at the El Miyit [EMY] test site (1.1 km^2, Gruhlich, 2002). The model was calibrated by tuning soil thermal properties, as well as parameters of the equation describing bulk stomata resistance (Boer, 1999). Soil water content measured by TDR and measured soil temperature were used for model evaluation. The total measurement period was divided into a calibration and a validation period. Due to the scarcity of measured discharge data at the catchment scale the model could not be calibrated from the discharge.

Due to the spatial variability of hydrological processes, calibration was repeated for the test sites Jebel Brâhim [JHB], Arguioun [ARG], and Bou Skour [BSK]. A goodness-of-fit (here r^2) for simulated and TDR-measured soil moisture contents (0.74 [JHB], 0.94 [EMY], 0.83 [ARG], 0.66 [BSK]) and soil temperature (0.98 [JHB], 0.99 [EMY], 0.98 [ARG], 0.97 [BSK]) shows moderate to high agreement. As an example, model results for water content and soil temperatures are given in Fig. B2-5.

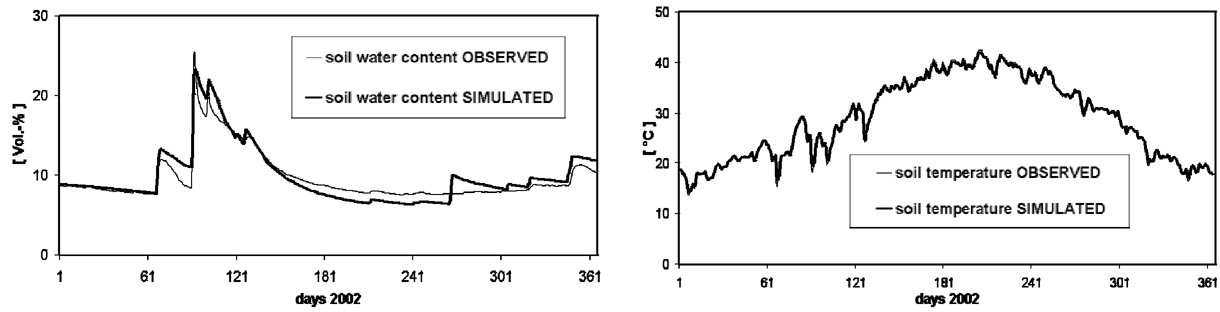

Fig. B2-5: Comparison of observed and simulated volumetric water content (left) and soil temperature in 5cm depth (right); test site El Miyit, 2002.

The water balance at the four test sites is summarised for 2002 in Tab. B2.1. Due to the sparse vegetation cover all catchments achieve low transpiration rates but comparably high evaporation rates. The transpiration rates of single plants such as *Acacia tortilis* ssp. *raddiana*, *Ziziphus lotus* or *Retama retam* may be underestimated due to the unknown root distribution. The dynamics of the evaporation and transpiration corresponds to rainfall events. Analysis of the simulated water balance within a catchment indicates that the total amount of surplus water depends on the spatial distribution and the size of the terrain units. With the exception of the EMY test site, the annual water surplus enables recharge of the aquifer.

Tab. B2.1: Simulated water balance for four selected test sites in the year 2002 (JHB=Jebel Brâhim, EMY= El Miyit, ARG=Arguioun, BSK= Bou Skour)

Testsite	**JHB**	**EMY**	**ARG**	**BSK**
Altitudinal range [m]	**642-820**	**738-860**	**1044-1169**	**1433-1964**
Area [ha]	**89.6**	**109.3**	**1.8**	**3.1**
Precipitation [mm]	**11.0**	**50.8**	**43.2**	**165.5**
Groundwater recharge [m]	**2.8**	**0**	**3.0**	**96.1**
Cumulated act. evaporation [mm]	**9.8**	**35.3**	**24.4**	**25.2**
Cumulated act. transpiration [mm]	**0.1**	**0.7**	**0.9**	**5.9**
Average water surplus [mm/m^2]	**1.1**	**14.8**	**17.9**	**134.4**

Detailed local soil hydrological studies were supported by satisfactory modelling results. In a next step, results from transpiration experiments of single species from subproject B3 will be used for model calibration. Further regionalization methods will be developed to simulate the regional water balance. This will be accomplished by combining GIS analyses of detailed Digital Elevation Models, geomorphology, soil properties and remote sensing to identify land use patterns.

Workpackage B2-4: Anthropogenic soil degradation due to water erosion in the upper and middle Drâa catchment – soil loss in mountain relief in a semiarid- to arid subtropical winter rain climate

This workpackage focuses on the status and potential hazard of soil degradation for typical soil associations in the Drâa catchment with the help of both field and laboratory studies. The aims are to test whether land use in the middle and upper Drâa catchment causes increased exposure of soils to degradation. For this purpose, 9 transects with 95 soil profiles were investigated in the calcareous southern High Atlas, in the crystalline Anti Atlas, in the sedimentary escarpment of the middle Drâa valley, at the Drâa oasis of Arguioûn and in the dry quaternary fills of Lac Iriki. Transects were selected in accordance with the extreme prevailing altitudinal- (445 – 3200 m a.s.l.) and aridity gradient (< 50 – 600 mm rainfall per year). Investigated soils were grouped as follows: soil associations on slopes with predominant pastoral usage and commonly degraded by water erosion; and soil associations on alluvial deposits with valuable arable land under partial salinization.

Soil associations and soil patterns were studied using the catena method at 9 sites. The soils were comprehensively classified according to the ISSS-ISRC-FAO 1998 system. Physical and chemical properties of 284 soil samples were determined after van Reeuwijk, 2002. Basic soil characteristics such as texture, aggregate size and aggregate stability (Sekera & Brunner, 1943), pH_{H2O} and pedogenic oxides were determined. Soil organic matter was characterized from the content of organic matter and the C/N ratio. Potential and effective Cation Exchange Capacities (CEC), exchangeable cations and the main nutrient anion PO_4^{3-} content were measured additionally. The available field water capacity was calculated down to a depth of 1m. Soil erosion was determined by erosion pins and sediment traps. Volumes of rill and gully erosion were quantified by changing point extrapolation and the transverse method (DVWK, 1996). Actual and past erosion derived from the soil stratigraphy was interpreted via the geomorphological setting. Potential soil loss was estimated using the Universal Soil Loss Equitation (Wischmeier & Smith, 1978). Soil salinity was assessed via electrical conductivity of the saturated-paste extract (EC_e) and contents of readily soluble salts. In addition, exchangeable sodium percentage (ESP) was calculated (Rhoades et al., 1999) and the quality of irrigation water was characterized by the Sodium Absorption Ratio (SAR). Contents of $CaCO_3$ [%] and $CaSO_4\,2H_2O$ [%] were also measured.

<u>Soils catena on slopes - example of the escarpment of El Miyit</u>

The slope investigated is exposed towards the south and has an inclination from between 4 % to 26 %. Parent rocks consist of sandstones and metamorphites, including quarzites and slates. Two different pediments join to form a common glacis at the slope foot which is dissected by a wadi. The escarpment is covered with the following soils (Fig. B2-6): Epileptic Calcisols (Cambic) (P 1) on the top, Episkeletic Calcisols (Cambic, P 2; Cambic, Arenic, P 3) on the steepest part of the upper slope, Calcari-Episkeletic Cambisols over pediment 2 (Arenic, P 4) and most glacis positions (P 5), Endoskeletic-Calcaric Fluvisols (P 6) lining the wadi and Calcari-Episkeletic Regosols (P 7) below the glacis. The soil distribution described is representative for similar geomorphologic units within the catchment. The soils have a mildly alkaline soil reaction. High portions of coarse fragments generally reduce the exchange capacity to less than 10 $cmol_c\ kg^{-1}$.

Base saturation is high (up to 100%) due to the soil pH. The content of organic matter in topsoils is (very) low (0.2 – 0.7 %) except for the Cambisol (P 5) on the glacis and the Calcisol (P 2) with 1.4 % organic matter at the upper slope position. An important ecological parameter in this dry climate is the available field water capacity. The lowest value of 21 mm is found on the top of the escarpment (P 1) and the highest one of 93 mm on the glacis (P 5). Hence, water availability is low considering that there is no groundwater access for plants. Furthermore, water infiltration into the topsoil of the glacis (P 5) can be reduced by gypsum which tends to harden to a petrogypsic horizon. Caliches in the soils (P 1-3 & 6) can also limit plant growth. Thus, upper slopes and glacis positions are only suitable for pasturing.

Soil degradation due to water erosion at El Miyit

Different stone pavements with black desert varnish cover most of the slope and the glacis (except for the wadis) indicating geomorphological stability. Soil stratigraphy displays multiple layered soils from pure debris to stony layers of sandy loam and loamy sand. These soils can only be defined as “pedisediments”. It is suggested that the A horizon has been eroded at the top of the escarpment (P 1) since the remaining calcified B can only form beneath a protective A horizon. All investigated soil associations are effected by soil erosion.

Sediment discharge was measured in a wadi that erodes the weathered slate. The sediment trap gathered only 0.042 t ha^{-1} from a 1.4 ha catchment after a single rainstorm (with 17.8 mm in 14.5 hours). Rill erosion on a slope with 50 % inclination causes 11.3 m^3 soil losses over an area as small as 400 m^2 over an unknown period. Assessment of erosion sensitivity of the soils is carried out with the USLE. The K-factor varies between a minimum of 0.3 on the glacis (P4) and a maximum of 0.44 on the pediment (P 5). The USLE postulates a soil loss within the transect of 0.53 t ha^{-1} for the year 2002. In comparison with the investigated escarpment slopes of Arguioûn (about 100 km NW) and Jebel Hssain ou Brahim (about 40 km S) - where Leptosols and Regosols dominate - the soils in El Miyit are more differentiated and thicker. They have higher field capacities and they are more suitable for pasturing.

Soil associations on alluvial deposits - the river oasis near Arguioûn

The river bank terrace (Soltanien) of the middle Drâa valley has a thickness of about 5 m with homogeneous stoneless sandy loam and silt loam (silt contents up to 70 %). The soil reaction is mildly alkaline and the contents of $CaCO_3$ range from 12 % on the top of the escarpment to 5 % on the slope positions. A new farm (established in 1999) producing cereals and date palms is irrigated with pumped ground water. The topsoil has been ploughed to a depth of 40 cm and has a poor humus content (0.62 % C_{org}) with a CEC of only 4.4 $cmol_c\,kg^{-1}$. Plant available phosphate contents are low to medium (about 5 ppm) therefore soils require fertilizing.

Soil salinization

Soil salinization of the maize field studied above is very low (EC_e 0.7 dS/m). There is no actual degradation risk by dispersion of soil aggregates. In contrast, the soil profile in the rangeland above the bank terrace indicates high salinity (EC_e 16.2 dS/m). The vegetation indicates saline stress (yellow dwarf growth of Tammarix). The high ESP (34 %) definitely restricts agrarian land use under the absence of amelioration measures (salt leaching). The quality of irrigation water is very low (EC 2.64 dS/m) thereby restricting land use (Khana 1989). The chance of soil rehabilitation by salt leaching is reasonable since the underlying bank terrace layer mainly consists of gravels functioning as a natural drainage system. In Tamgroute (approx. 150 km south of Ourzazate) the quality of irrigation water (EC 7.5 and 8.5 dS/m) is even worse and causes medium to high soil salinization on the Hypersalic Gypsisols forming salt crusts in some places. In Tagounite excessive salinity of irrigation water (EC 23.8 dS/m) prohibits irrigation. Cultivation has been neglected here due to both continuing drought and soil and water salinization. In contrast, soil associations located on alluvial deposits in the north are actually not effected by salinization.

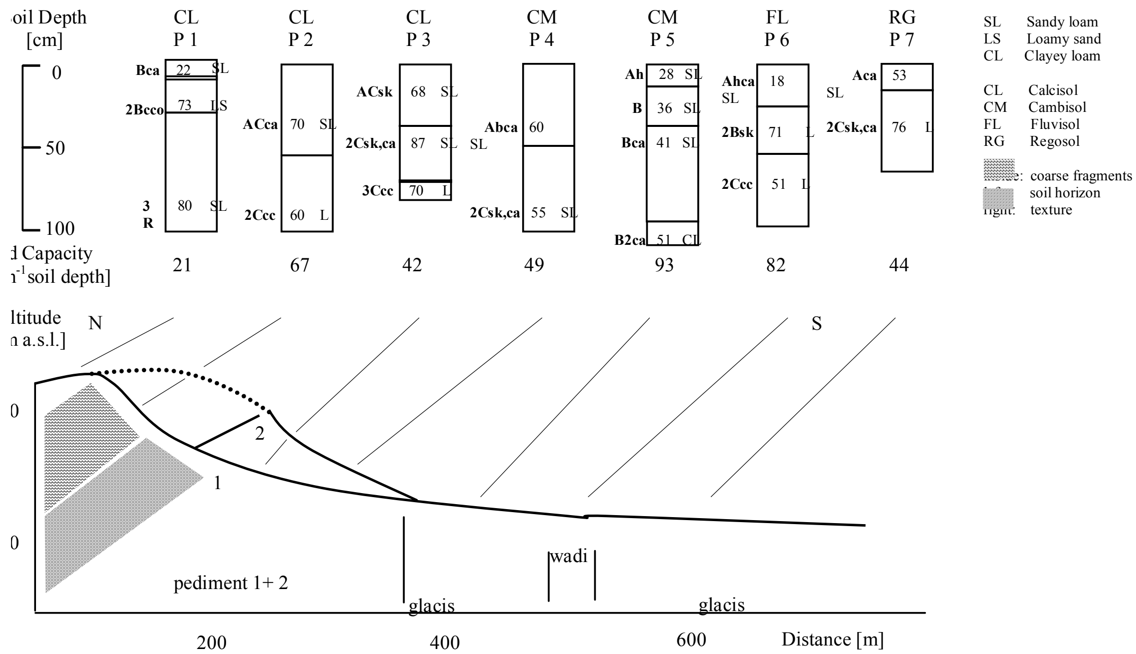

Fig. B2-6: Soils on the escarpment slope of El Miyit (65 mm rainfall per year; 26 °C average annual temperature)

All soil associations investigated on the slopes suffer from soil erosion problems, independent of altitude and aridity. Erosion impact mainly depends on soil depth which differs within and between the soil associations. It is anticipated that a regional soil map will be produced for the middle Drâa including the most important associations. Soil salinization is most problematic in the southern alluvial deposits. As the quality of irrigation water decreases towards the south, soil degradation by salinization increases. This is an important result for the development of scenarios for the next project phase in cooperation with B3.

Workpackage B2-5: Groundwater resources in the wadi Drâa

In order to identify the potentials of groundwater resources in the Drâa catchment research during the first project phase was focused on the water quality and quantity of several important aquifers. The main goal was to develop a conceptual hydrogeological model for the region. Detailed local studies were carried out in jointly investigated test areas situated along an altitudinal and aridity gradient (Fig. B2-8). To enhance process understanding, the volume and temporal dynamics of various groundwater reservoirs was quantified.

The hydrogeological evaluation of the different aquifers required a sound knowledge of the general geological setting including the structural pattern of the area under investigation. Therefore, detailed geological mapping accompanied by thorough literature surveys was necessary.

In order to understand groundwater provenance, its renewability and the subsurface processes affecting its quality and quantity, hydrochemical analyses and environmental labelling were performed with ^{18}O and ^{2}H. Ground- and surface water were sampled during low and high flow conditions since 2001. The seasonal variation of selected key parameters depends on the hydrodynamic behaviour of various aquifer systems. Analyses of ^{14}C, ^{3}H and CFC's for selected water samples provide a measure of circulation time and thus for groundwater renewability. Meso scale investigations (e.g. Assif-n-Ait-Ahmed catchment) were chosen in addition to local scale investigations (e.g. IMPETUS test sites at Bouskour, Arguioun, Taoujgalt) to understand the regional hydrogeological framework.

A detailed hydrogeological overview has been accomplished for the Assif-n-Ait-Ahmed catchment (Fig. B2-7) based on geological and structural mapping at the IMPETUS test sites of Ameskar and Tichki. The catchment is 100 km^2 in size and characterised by five different hydrogeological units which differ significantly in terms of hydrodynamics, volume, and discharge (Tab. B2.2, Fig. B2-7). Each unit reflects the hydrochemical influence of the rock matrix from the underground water passage. While groundwater discharging from the fractured aquifer in the Triassic basalt contains a low Ca/Mg ratio (0.89) and a high silicium content (6.30 mg L-1), groundwater that was in contact with Triassic clays is rich in halite and gypsum and is characterised by a high conductivity (3100 µs cm-1) resulting from high concentrations of Ca^{2+}, Na^{2+}, SO_4^{2-}. Groundwater from the main aquifer developed in the karstified Liassic limestones and dolomites of the Toundoute nappe reflects a typical karst water composition with a low conductivity (800 µs cm^{-1}) and Ca/Mg ratios of 1.9 together with Sr/Ca ratios of 2.9 ‰.

The Assif-n-Ait-Ahmed catchment is representative for the aquifer system of the High Atlas Mountains and is one of the three principal hydrogeological units of the upper Drâa. The other two hydrogeologically different units include the Ouarzazate basin in the forelands and the Precambrian basement of the Anti Atlas. In the basin of Ouarzazate a first hydrogeological screening was carried out along N-S oriented profiles accompanied by piezometric mapping of various wells. The investigations in the Anti Atlas system were focused on the IMPETUS test sites of Arguioun and Bou Skour. Different water types were analysed. A first specification of the origin of water was achieved by means of environmental labelling and a local altitudinal gradient was established from isotope samples (Fig. B2-8: -0.26 $\delta^{18}O$ [‰] per 100 m altitude). The results from several sampling points within the Basin of Ouarzazate demonstrate that the recharge of the basin aquifer originates from the nearby mountains. This will be verified by ongoing analyses of ^{14}C, ^{3}H and CFC's sampled during baseflow conditions in the Autumn of 2002. The deviations in isotope composition from surface water samples are the result of enrichment by evaporation.

Regionalization of hydrogeological information from the local- and meso scale to the heterogeneous regional scale of the wadi Drâa is momentarily only possible using a low parameterised storage cascade model. Each hydrogeological storage unit is clearly defined by geological and hydrogeological parameters, the input and output relations are described by an internal transfer function derived from the Maillet method and by environmental labelling from a Dispersion and/or Piston Flow Model.

Tab. B2.2: Hydrogeological units in the Assif-n-Ait-Ahmed Catchment area (High Atlas) with estimated mean aquifer volume, permeability coefficient K, mean annual discharge of the groundwater springs as well as geogene determined chemistry.

Formation	Lithology	Hydrogeological classification	Aquifer volume [106 m3]	K [m.s-1]	Discharge [106m3.a-1]	Water type	Key values Ca/Mg %	Sr/Ca ‰
Quaternary	Sand, gravel, limestone clasts	Porous aquifer	40	10-3 to 10-2	0.14	Ca-Mg-HCO$_3$	1.7	4.0
Lias (carbonatic)	Limestone, dolomite	Fractured to karstified aquifer	1.780	10-6 to 10-2	1.02	Ca-Mg-HCO$_3$	1.9	2.9
Lias (siliciclastic)	Sand-, limestone, dolomite	Fractured aquifer	117	10-6 to 10-3	0.62	Ca-Mg-HCO$_3$	1.7	-
Lower Lias/ Upper Trias	Clays, siltstones	Aquitarde		10-9				
Trias	Doleritic basalt	Fractured aquifer	529	10-8 to 10-3	0.46	Mg-Ca-HCO$_3$	0.9	2.6

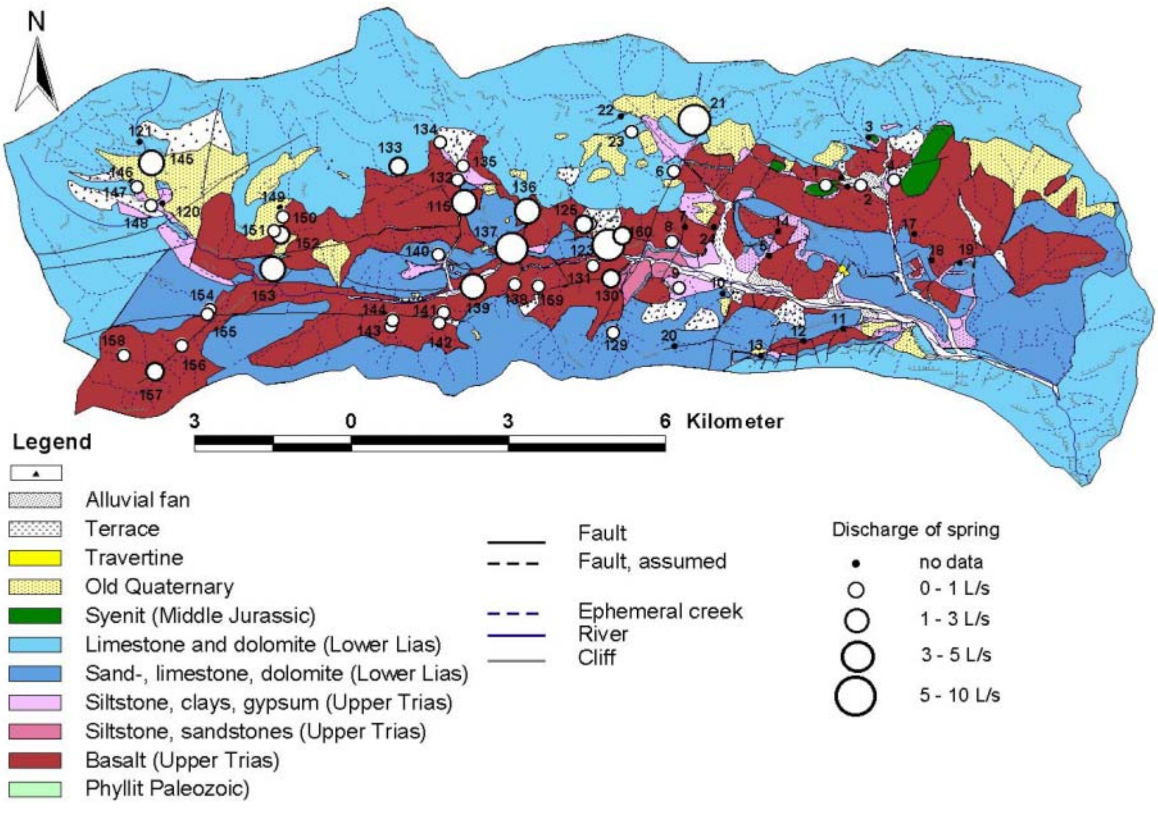

Fig. B2-7: Hydrogeological map of the Assif-n-Ait-Ahmed catchment with the discharge of springs.

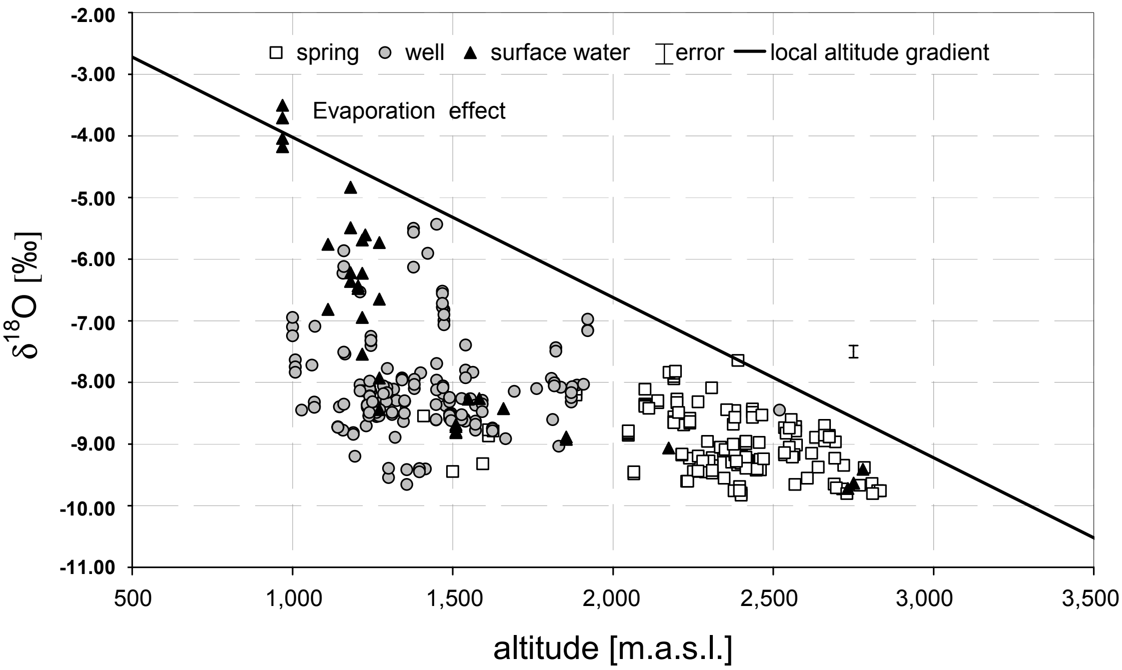

Fig. B2-8: δ^{18}O-content versus altitude for all water samples in the upper Drâa catchment area. The local altitude gradient (-0.26 δ^{18}O [‰] per 100 m altitude) is derived from regularly sampled precipitation at the IMPETUS meteorological stations.

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Subproject B3

Functional relations between vegetation dynamics, water cycle and human influence

Participants	Discipline
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Prof. Dr. H. Goldbach / PD Dr. J. Burkhardt Institute for Plant Nutrition, University of Bonn	Ecophysiology / plant nutrition
Prof. Dr. G. Menz Geographical Institute, University of Bonn	Geography: Remote sensing

Summary

Subproject B3 focused in the first phase on spatial vegetation patterns, vegetation dynymics, and water consumption of the vegetation.

A preliminary land cover map, based on Landsat data, was developed for the Drâa-catchment, showing the actual vegetation coverage. A large set of ground based geobotanical data is actually analysed in order to assemble ecological profiles of plant species and communities and to further differentiate the actual mapping units. The so derived ecological profiles will be compiled in the second project phase to GIS-based vegetation-models, with special emphasis on the regionalisation of climatic parameters like evapotranspiration.

The water use of the dominant plant species was analyzed in detail at two test sites. At El Miyit, transpiration rates were limited by local precipitation rates and depended on actual plant biomass, leading to large intraannual fluctuations with a maximum in spring. Contrary to this, transpiration rates were found to be higher in autumn in the intramontane valley of Taoujgalt, which was mainly caused by the phenology of the Artemisia *steppes, showing a maximum in autumn both for biomass and for leaf area based transpiration rates. In addition and also contrasting to El Miyit, areal transpiration rates were less linked to and occasionally exceeded local precipitation, indicating the influence of lateral water fluxes within this mountainous region. Additional measurements of transpiration were conducted at different oases. Transpiration rates of single cultivated plants in the oases were surprisingly low, but due to the large biomass and stand conditions, much higher areal transpiration rates result as compared to the rangelands.*

A change detection study based on Landsat data didn't show a clear long-term trend for the southern Drâa oasis. Agricultural surface fluctuated strongly between "dry" and "wet" years, increasing slightly over the last 30 years. A certain extension of the arable land has been established in the last 30 years due to the increasing amount of diesel-pump irrigated fields outside the traditional oasis.

Vegetation dynamics is being monitored in 35 permanent plots alongside the Impetus transect. Biomass increase is significant under non-grazing conditions at Trab Labied and Taoujgalt test

site, whereas the Saharan test sites of Lac Iriki, Jbel Brahim and El Miyit showed a lesser response. The absolute gain of biomass at Trab Labied showed strikingly similar values in all plots, independent of the number of individuals. Seedling survival rates have been surprisingly high. At the two oromediterranean test sites Tichki and Tizi -n- Tounsa great differences between fenced and unfenced sites in seedling numbers were detected. Differences in recruitment behaviour between different species seem to be intensified by browsing.

Agricultural experiments with the application of super absorbers to the soil helped to establish perennial plants and showed a general increase of productivity. The results were dependent on the soil type, indicating the need to maintain the soil water content above lower thresholds as compared to pure soils. The results indicate an optimized use of small water amounts in areas with low rainfall and high risk of degradation.

Seminatural steppes and deserts cover more than 95 % of the Drâa-catchment. These regions constitute the source areas for the water resources of traditional Oasis-agriculture and modern farmlands, irrigated by motor pumps. Vegetation cover of the source areas influences to a great extent the fate of the precipitation water in the catchment. Spatial patterns and temporal dynamics of the vegetation control largely the relation between infiltration, run off and transpiration.

Additionally, natural vegetation is the base for pastoral activities and therefore an important economic base for both, nomadic and sedentary rural communities all over the catchment.

Integrative resource management schemes depend therefore on a sound understanding of natural (climate driven) and human impacts on the vegetation cover and their repercussions on the hydrological cycle. In order to cope with the scientific demands of our subproject the research is composed of three workpackages:

Workpackage B3-1 is focused on spatial vegetation patterns and the ecological characterization of vegetation units and dominant species. Vegetation mapping is conducted by means of remote sensing techniques and ground based vegetation records. Water consumption of the different vegetation units is assessed by porometer and leaf wetness measurements.

Workpackage B3-2 analyzes spatio-temporal vegetation changes at different scales. At the macroscale, time series of Landsat data since 1972 offer the possibility to detect long-term changes, especially in land use patterns. At the microscale, the individual based observation of 35 permanent monitoring plots allows an analysis of temporal vegetation dynamics, and a discrimination between climatic and anthropogenous driving forces. Ecological data at the microscale are basically necessary to model future scenarios.

Workpackage B3-3 finally pays attention on the improvement of agricultural techniques and management schemes, regarding the water use efficiency of the land use system.

The following results have been achieved in the different workpackages:

Workpackage B3-1: Remote Sensing

The overall goal of this WP was to produce for the first time a land cover map of the Drâa-catchment which represents the actual vegetation coverage. A sub-pixel classification approach was chosen to transform the multispectral data space into a so called mixture space.

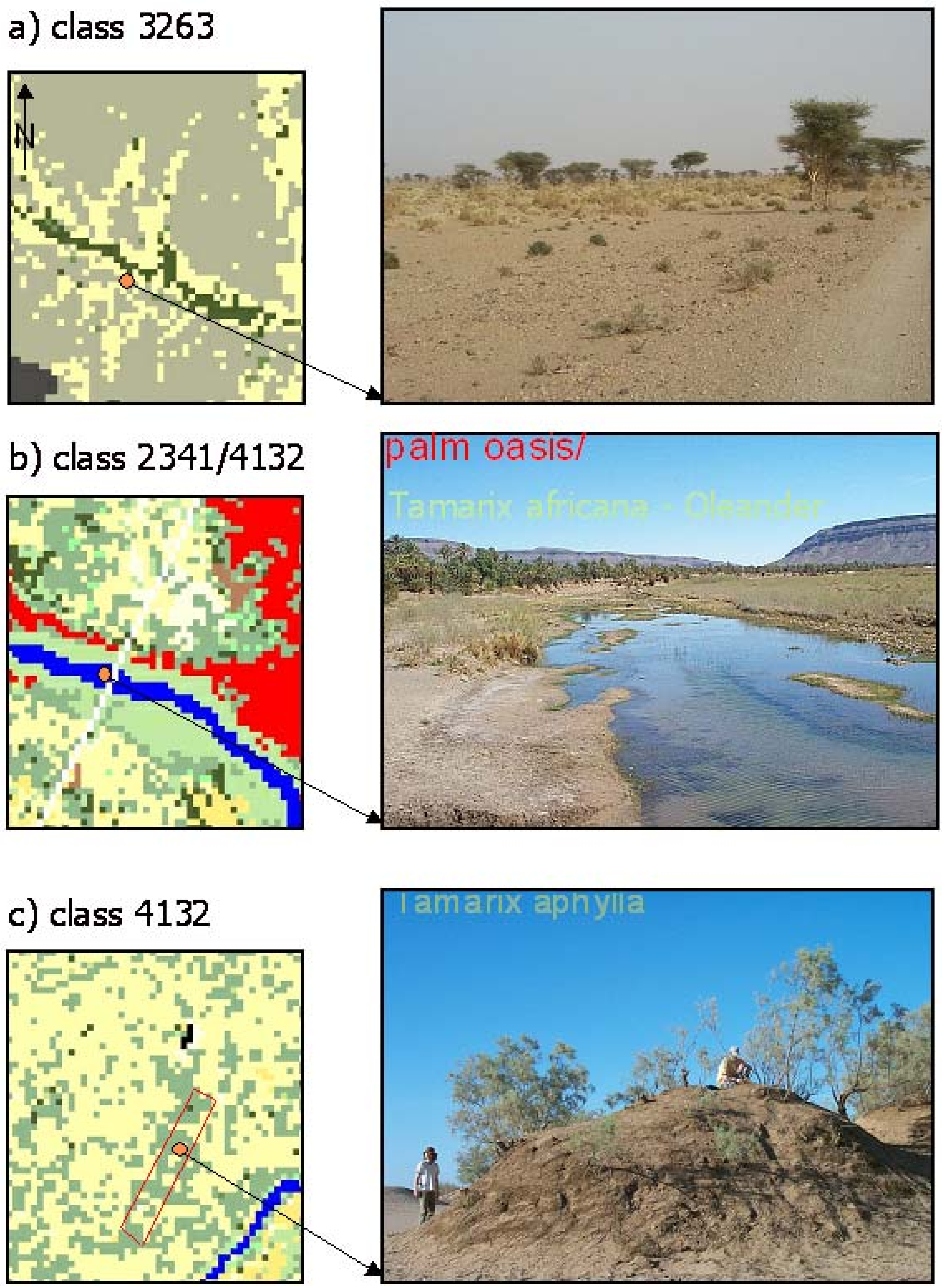

Fig. B3-1: Examples of the Landsat ETM+ land cover classification of the Drâa catchment (Landsat data recorded in May 2000)

This mixture space comprises the interpretation of the satellite data in a physically related context. The resulting information layers are the output of a sub-pixel analysis, in this case a linear spectral unmixing. Based on the mixture space information, decision rules were formulated to calculate a land cover classification according to a pre-defined classification scheme. The applied classification is based on the CORINE land cover classification scheme with 44 classes, which was originally designed to map Europe with Landsat data. Regional modifications to this classification scheme were necessary, as well as a class differentiation in more detail and the introduction of a fourth classification level, resulting finally in a total of 64 land cover classes. Based on this classification scheme a land cover map for the Drâa catchment could be generated. Fig. B3-1 shows three examples from the Drâa valley.

Ground truth data were used to compile a validation dataset of about 500 polygons for the Drâa catchment. The overall classification accuracy of the region shown in Fig. B3-1 is 93.14 % with a Kappa coefficient of 0.918.

The vegetation map derived from Landsat data shows clearly the strengths and limitations of exclusively remote sensing based vegetation mapping. The high resolution and reliable identification of densely covered vegetation units (predominately agricultural lands) contrasts with a poor internal differentiation of sparsely covered steppe vegetation. Large areas of the Drâa catchment appear as bare surfaces which do not correspond to the geobotanical field observations. Additionally, large Corine mapping units like "Hammada – Artemisia - steppes", covering areas from the southern Drâa Basin up to the middle altitudinal belts of the High Atlas, constitute a conglomerate of heterogeneous vegetation differing strongly in species composition, dynamics and growth potential.

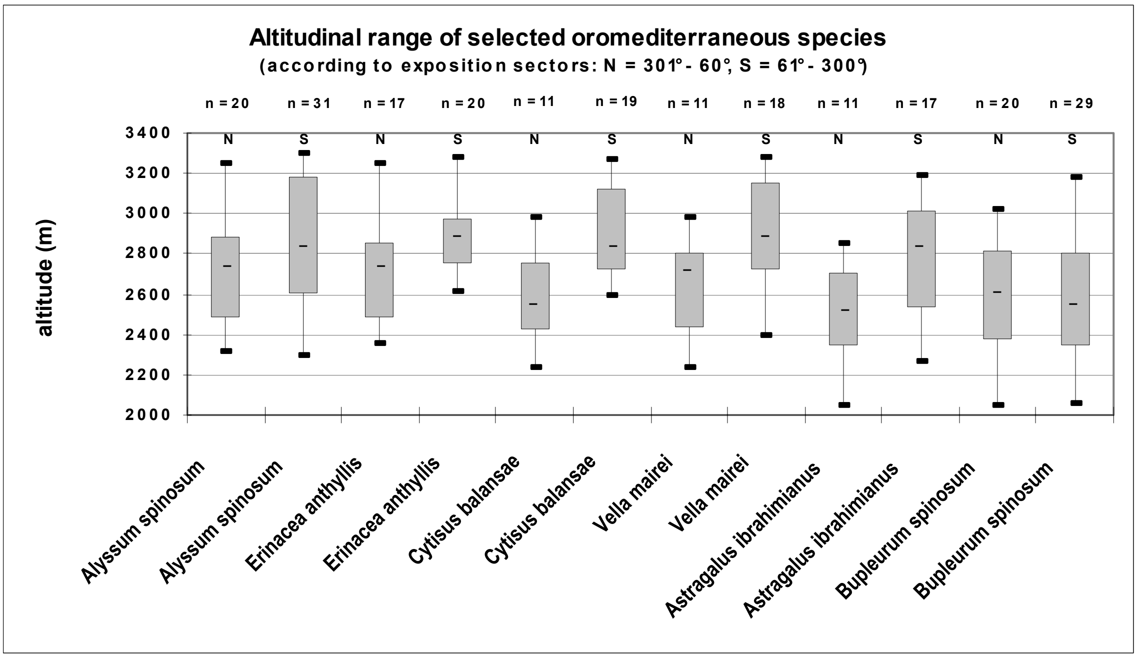

Fig. B3-2: Slope preferences and altitudinal range of selected oromediterranean species.

Ground based geobotanical data don't reach the spatial resolution of the remote sensing approach. Nevertheless, a dataset of actually about 600 releves, scattered all over the catchment, allows us together with a landscape-GIS to assemble ecological profiles for species and communities to split and differentiate the remote sensing mapping units. Ecological profiles will be compiled in the second project phase to GIS-based vegetation-models. These vegetation data will be especially useful for the regionalisation of climatic parameters in the study area, intended for the second phase.

Fig. B3-2 shows slope aspect and altitudinal distribution of dominant species in the oromediterranean cushion shrub belt. For most of the species, the altitudinal range is depressed by 150 m to 350 m on northern slopes in comparison to other aspects. This indicates that the duration of snow cover is a limiting factor at the upper vegetation border, whereas the lower one seems to be determined to a great extent by the water balance. A special case is *Bupleurum spinosum*, which prefers windy edges and ridges at lower altitudes, independent of aspect.

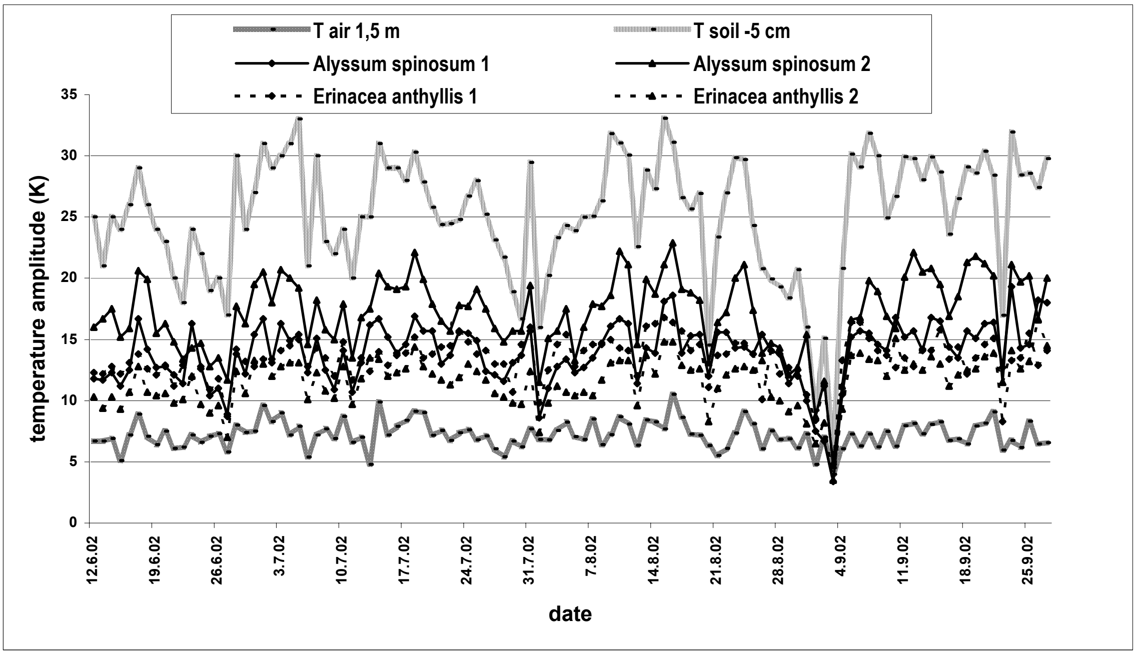

Fig. B3-3: Diurnal temperature amplitude at test site Tichki.

Comparisons with B2 climate station data allow us to quantify microclimatic site conditions and to evaluate the ability of the species to deal with them. Fig. B3-3 shows the microclimatic conditions in *Alyssum spinosum*- and *Erinacea anthyllis*-cushions. The mean temperature amplitude for both species differs at the same site by about 5 K, with *Erinacea* showing a higher capability of microclimatic regulation. The analysis of the permanent monitoring plots with exclosure experiments gives us finally information about the susceptibility of important species to strong grazing pressure (link to B5).

Water relations and water use of the dominant plant species at the two test sites of El Miyit und Taoujgalt was investigated, in order to extrapolate these findings to larger areas. Gas exchange of the dominant plant species was measured, and by accounting for their spatial abundance, the results were summed up to an areal based transpiration estimate. El Miyit (792 m a.s.l.) is located within a large basin at the foot of the Jebel Bani and is characterized by large areas and small wadis where most of the vegetation concentrates. The dominant species are *Acacia raddi-*

ana, *Retama reatam, Withania adpressa, Ziziphus lotus.* Taoujgalt (1900 m a.s.l.) is located at the southern slope of the High Atlas mountains with a homogenous plant cover. The dominant perennial plant species are *Artemisia herba-alba* and *Teucrium mideltense.*

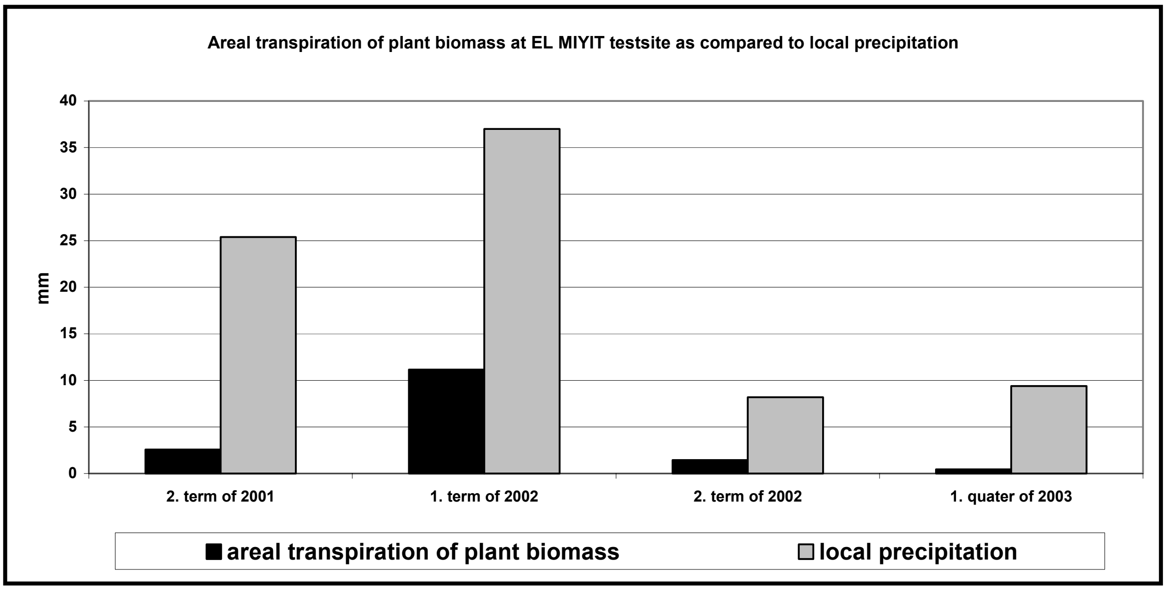

Fig. B3-4: Areal transpiration of plant biomass, based on gas exchange measurements of dominant perennial plant species at El Miyit test site, as compared to local precipitation.

Fig. B3-4 indicates a strong dependence of plant transpiration of local rainfall at El Miyit. Areal transpiration rates depend on actual plant biomass. As plant biomass is affected by different factors, large intraannual fluctuations of plant biomass are possible. Local precipitation is the limiting factor for transpiration in this area. In case of precipitation in late spring or early autumn, conditions for biomass production improve and high transpiration rates will result. In case of low or delayed precipitation, little water is used for transpiration, due to reduced biomass (first quarter of 2003).

Fig. B3-5 indicates higher transpiration rates at Taoujgalt to take place in the second half of the year. This is mainly due to the dominating dwarfshrub *Artemisia herba-alba* which represents two thirds of total biomass, with a maximum in autumn both for biomass as for leaf area based transpiration rates (1. term of 2002: 1,4 l water m-2 leaf area; 2. term of 2002: 4,2 l water m-2 leaf area). The second species Teucrium mideltense represents one third of total biomass. It has higher transpiration rates on a plant basis (1. term of 2002: 7,7 l water m-2 leaf area; 2. term of 2002: 2,7 l water m-2 leaf area), but maximum of biomass and leaf area based transpiration rates in spring. Contrary to El Miyit, areal transpiration rates are less linked to local precipitation, and may even exceed precipitation. This indicates the influence of local water storage in the soil, and/or the influence of groundwater fluxes within this mountainous region.

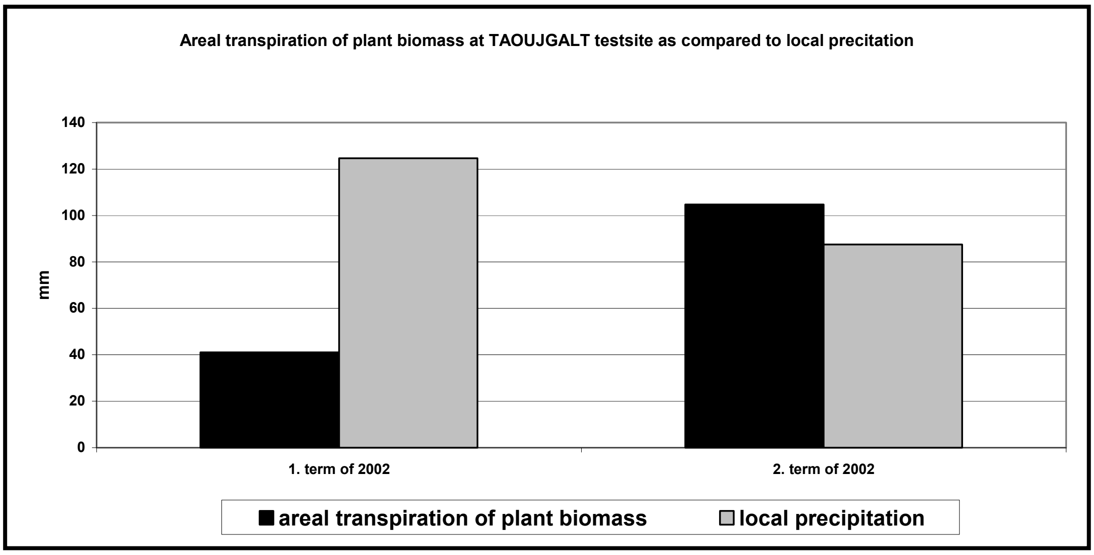

Fig. B3-5: Areal transpiration of plant biomass, based on gas exchange measurements of dominant perennial plant species at Taoujgalt test site, as compared to local precipitation.

		biomass 2001 (m^2 leaf area per plant)	biomass 2002 (m^2 leaf area per plant)		biomass 2003 (m^2 leaf area per plant)	
	species	autum	spring	autum	spring	autum
rangeland						
El Miyit	Acacia raddiana					
	min.	14,0	28,7	7,2	14,1	
	max.	130,1	121,6	38,9	16,6	
	average	53,0	75,7	17,6	15,4	
	Ziziphus lotus					
	min.	not available	2,3	5,9	1,0	
	max.	not available	83,4	17,9	24,8	
	average	not available	38,3	10,2	7,7	
	Retama reatam					
	min.	not available	not available	2,0	1,5	
	max.	not available	not available	9,0	4,4	
	average	not available	not available	5,2	3,3	
Taoujgalt	Teucrium mideltense					
	min.	0,02	0,02	0,02	0,03	
	max.	0,22	0,06	0,03	0,16	
	average	0,10	0,04	0,03	0,08	
	Artemisia herba-alba					
	min.	0,01	0,02	0,03	0,02	
	max.	0,35	0,03	0,12	0,07	
	average	0,13	0,03	0,07	0,04	
oasis						
ZAGORA	Phoenix dactylifera					
(Asrir/Tissergate)	min. big plant	not available	100,1	not available	not available	
big plant height=10 m	max. big plant	not available	121,0	not available	not available	
small plant height=3 m	average big plant	not available	113,9	not available	not available	
	min. small plant	not available	44,5	not available	not available	
	max. small plant	not available	67,4	not available	not available	
	average small plant	not available	52,2	not available	not available	

Fig. B3-6: Transpiring biomass of selected dominant plant species, as compared between spring and autumn.

Additional measurements of transpiration were conducted at the oases of Zagora (732 m a.s.l.), Ameskar (2245 m a.s.l.), and Tichki (2350 m a.s.l.). These investigations targeting the water consumption within oases will be intensified during the second phase of IMPETUS. Transpiration rates of cultivated plants in the oases were surprisingly low in spite of more abundant water supply. The transpiration of dat palm (*Phoenix dactylifera*) in Zagora oasis was about 1.5 L H_2O m^{-2} leaf area d^{-1}, which was very constant throughout the year, thus being similar to the lowest values measured for *Acacia raddiana*, *Retama reatam, and Artemisia herba-alba*. However, biomass and stand conditions within oases are strongly different from the rangelands, resulting in much higher transpiration rates on an areal basis. Due to canopy boundary layers within the oases, scaling up from leaf measurements to the stand is not as straightforward as for the disperse vegetation of the rangelands.

Total and transpiring biomass were determined on the test sites, generally indicating higher biomass values in spring. In the rangelands, transpiring biomass was up to four times higher for big trees and about twice for bush, as compared to autumn, relatively. *Artemisia herba-alba* was an exception, having higher transpiring biomass in autumn than in spring. High variations were obvious in all cases and are most likely to be caused by water availability (Fig. B3-6).

Workpackage B3-2: Vegetation dynamics in the Drâa catchment

Seven Landsat satellites provide data recorded with basically three different sensor systems. Data of these sensors have been used in a change detection study close to Zagora. The applied method was based on a linear spectral unmixing technique applied to the satellite data at different time steps. Just the vegetation information is utilized to derive the class palm oasis. Changes in this class are shown in Figure B3-7:

The land cover class "palm oasis" covered in 1974 16,7 % of the observed area, in 1987 11,6 % and in 1999, after two successful agricultural years 18,8 %. During a drought in the 80'ies agricultural production was only possible in areas with deep wells and diesel pumps (Fig. B3-7e). Extensions of the traditional oasis area started when migrant worker returning from Europe invested money in diesel-pumps and wells (Fig. B3-7e, f). The extensions of the traditional palm oasis as well as periods of drought increase the grazing pressure for the remaining rangeland vegetation.

In 2001 we established 35 permanent plots of 100m² each, covering 10 different ecosystems, in order to evaluate biomass production under grazing exclosure. Vegetation dynamics and biomass increase have been measured in an individual based way. Alterations of each individual have been documented by measuring lengths parameters manually in a non destructive way and by taking digital photographs. Dry weight of reference individuals (*Hamada scoparia* n=13; *Farsetia occidentalis* n=11) outside the fenced area has been determined in g/cm³ plant volume. Seedlings have been counted seasonally. Biomass increase is significant under non-grazing conditions at the Trab Labied test site in the basin of Ouarzazate and in Taoujgalt situated in an intermontane basin of the High Atlas Mountains. The former represents a *Hamada scoparia* - *Farsetia occidentalis* dominated steppe community, the latter an *Artemisia herba-alba* steppe.

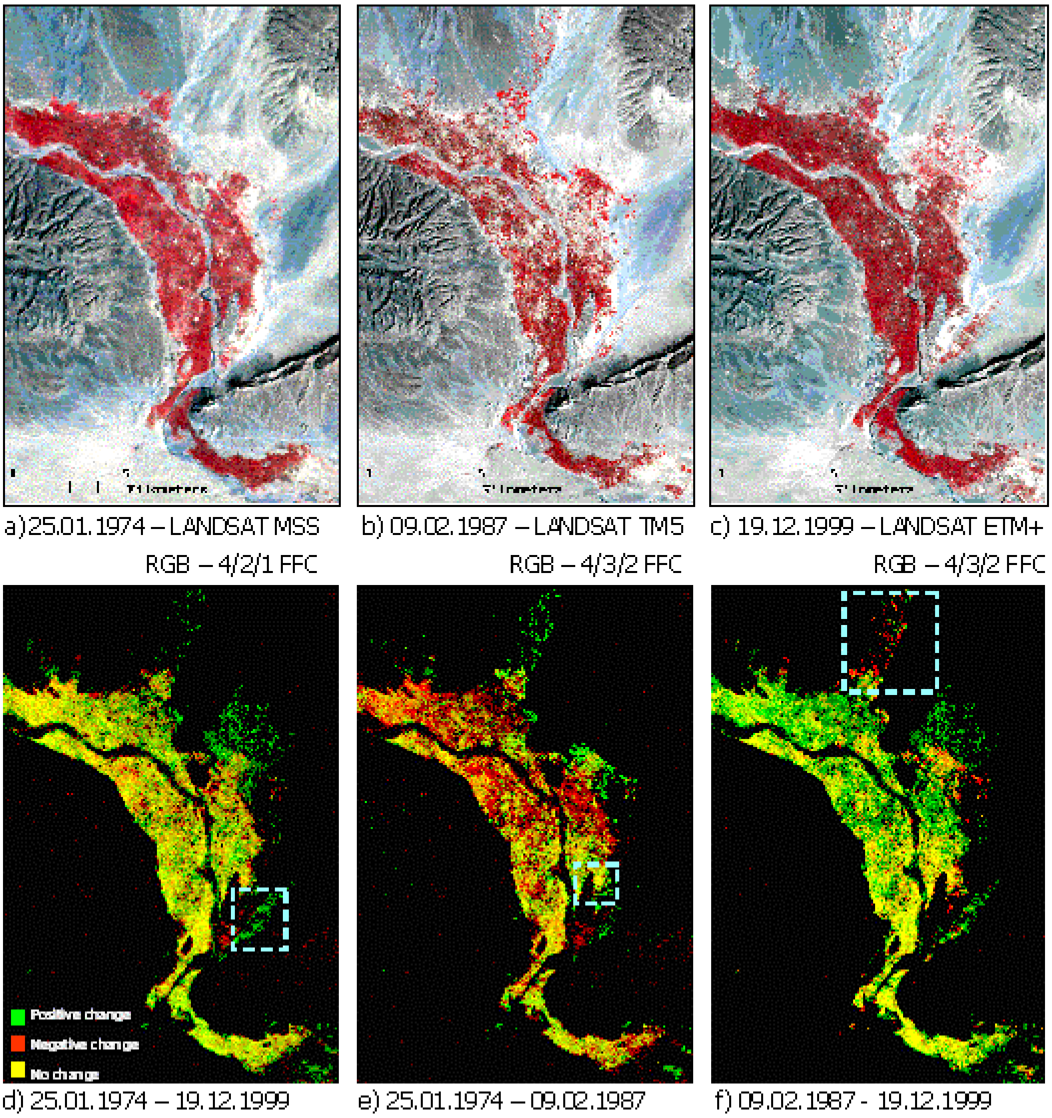

Fig. B3-7: Visualization of vegetation changes, displayed in a RGB false color composite a) – c) and image1/image2/zero composition d) - f); marked are areas of: d) positive changes (increase of vegetation cover) f) negative changes (decrease) e) no change.

The Saharan test sites of Lac Iriki, Jbel Brahim and El Miyit show a minor response. The Trab Labied test site shows a biomass increase for the perennial species from spring 2001 to spring 2003 between 800 – 900 g dry weight per 100 m^2. Interestingly there are nearly no differences between the more sandy and the finer textured sites. At the sandy site 120 individuals of *Farsetia occidentalis* showed a biomass gain of 871,2 g DW/100 m^2, corresponding to an increase of 75 % to the standing biomass of the year 2001. At the finer textured site only 65 individuals showed an increase of 852,6 g DW/100 m^2, representing a 2,5 fold increase in biomass. The absolute gain of DW shows strikingly similar values independent of the number of individuals. *Hamada scoparia,* growing predominately at the finer textured plots, showed an increase in biomass of 889,9 g DW/100 m^2 with only 27 individuals. This also resembles closely the above-mentioned values. Most surprisingly, seedling survival rates after the heavy rain event of April 2002 were very high. From the 345 seedlings of *Hamada scoparia* counted last year at the finer textured site, 215 were recounted this spring which sums to a mortality of only 38 % in the first year. The sandy site showed far less seedlings, with a mortality rate for *Farsetia* of 40 % and for *Hamada* of 44%. Further observations of seedling survival and development will enhance knowledge of the ecological capacity regarding vegetation density under non-grazing conditions of these heavily degraded steppe communities.

The two test sites Tichki and Tounsa, situated in the oromediterranean zone of the High Atlas, representing the thorny cushion belt, showed unexpected numbers of seedlings. In autumn 2002 we counted up to 2300 seedlings of *Alyssum spinosum* per 100 m². We detected great differences between fenced and unfenced sites in seedling numbers (Fig. B3-8), what we interpret as grazing effect, mainly due to browsing of seeds and flowers. Differences in recruitment behaviour between different species are also intensified by browsing. *Alyssum spinosum* germinates predominately in the surroundings of mother plants, whereas *Vella mairei* favors sites disturbed by browsing dromedaries (Fig. B3-8). Due to their divergent inflorescence architecture they are differently vulnerable to grazing pressure regarding seed production. These findings will be used as parameters in a raster-based model of vegetation dynamics as shown in Fig. B3-8.

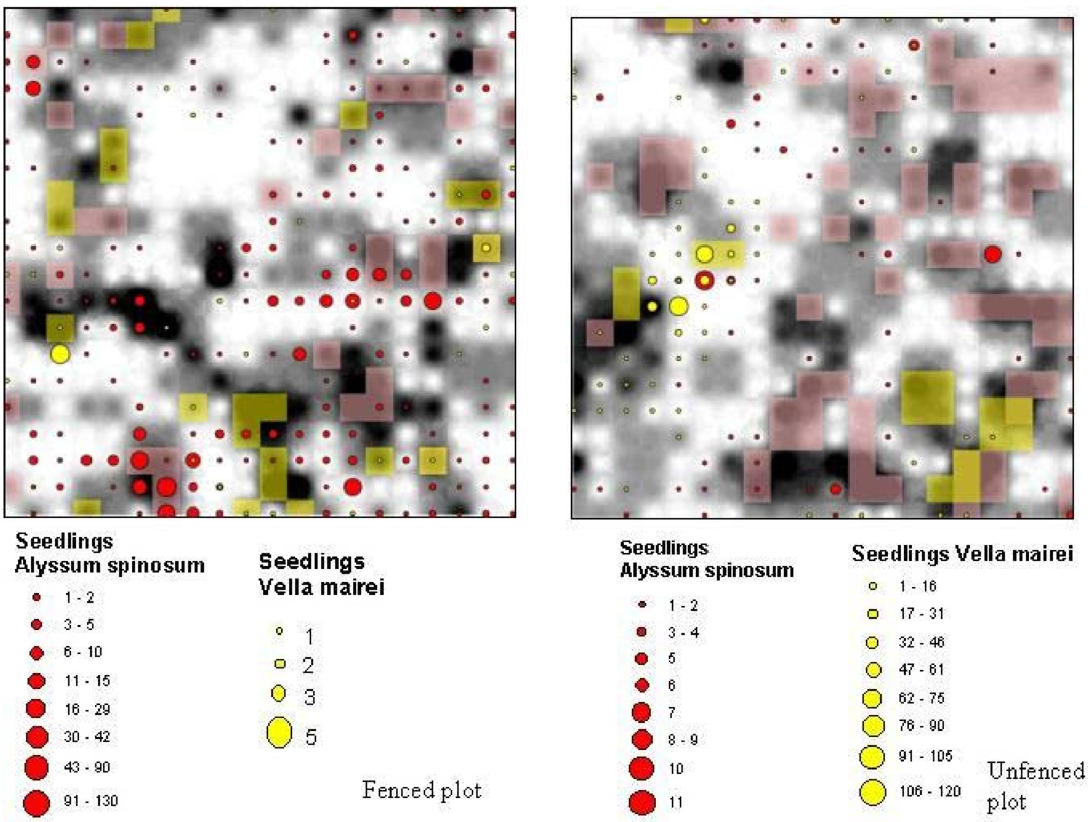

Fig. B3-8: Patterns of seedling establishment in fenced and unfenced plots at test site Tizi -n- Tounsa.

Workpackage B3-3: Transpiration and water use of different wild and cultivated plants

Experiments with the addition of super absorbers to the soil helped to establish perennial plants and showed a general increase of productivity (Fig. B3-9).

The results using super absorbers were dependent on the soil type, indicating the need to maintain the soil water content above lower thresholds as compared to pure soils. However, these thresholds existed and were obligate, especially on soils with high clay content.

The results indicate an optimized use of small water amounts in areas with low rainfall and high risk of degradation. The technology may be used in uncultivated areas, or in the outer parts of oases, using perennial plants for reforestation or to stop the migration of sand. It might also be used to help in reforestation projects on degraded soils within valleys of the High Atlas. This would help to produce biomass for house use and grazing. The experiments using super absorbers as a management tool will go on in the second phase of IMPETUS.

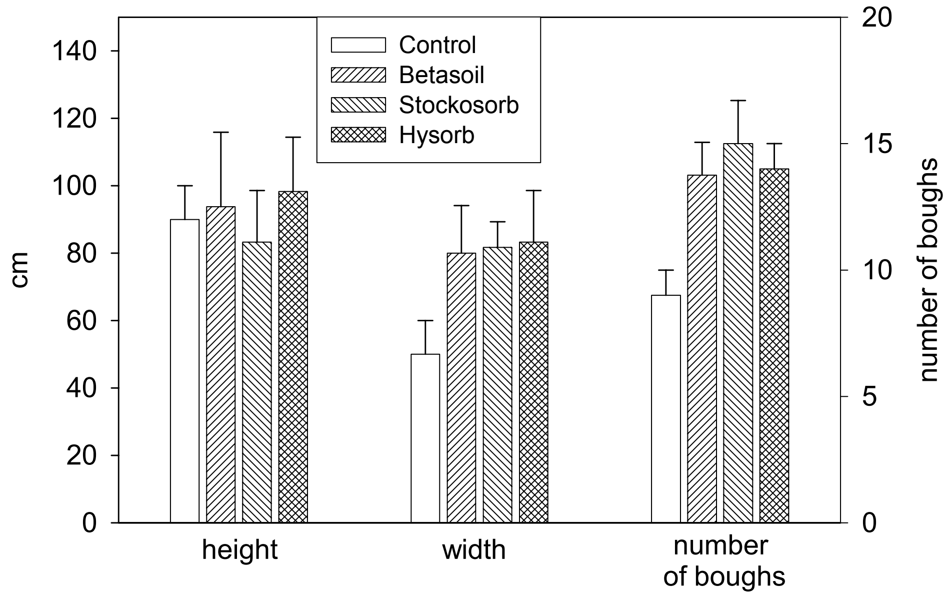

Fig. B3-9: Biomass development of *Atriplex halimus* under dry conditions using different types of super absorbers.

Subproject B4

Water distribution, rights and conflicts

Participants:	Discipline
Prof. Dr. M. J. Casimir (Coordinator) Institute of Social & Cultural Anthropology, University of Cologne	Social Anthropology: economic and cognitive
Prof. Dr. M. Rössler Institute of Social & Cultural Anthropology, University of Cologne	Social Anthropology: economic, socio-politic and cognitive

Summary

Water as a vital but scarce resource determines the everyday-life in the Drâa Valley. Especially in the southern Oasis, the arid environment is the limiting factor for economic development. The results of interdisciplinary research demonstrate that water resources are decreasing both as a consequence of environmental constrains and anthropogenic influences, while the degradation of soils and vegetation is increasing. The recent droughts have further aggravated these conditions.

In addition to the growing scarcity of natural resources and the limited options for the local population to manage these resources, the increasing speed of social change due to external forces is one of the major problems in coping with the local conditions. Socio-economic changes on the national level alter modes of access to resources on the local level, particularly by modifications of production systems and production relations, by technological innovation, and through new modes of commercialisation. On the local level, a rising demand for water, an increasing individualisation of property, and a weakening of social relations and social ties within the communities are consequences of this development.

Case studies from the Drâa Valley point to a tendency towards smaller households, often accompanied by residence in "better" equipped domiciles/houses, and an increasing domestic water demand. A similar pattern can be found not only in urban centres like Ouarzazate, but also in rural settlements. This development is closely linked with labour-migration, which was identified as a major factor in the socially embedded negotiation about water use, with an increasing significance in recent years.

In southern Morocco local decision making structures are characterized by the co-existence of modern state institutions and local or "tribal" (qabila) institutions. In order to understand patterns of emerging conflicts and conflict settlement concerning water rights and use, this co-existence must be analysed thoroughly before any recommendations can be made.

Technological innovations like the massive introduction of motor pumps, often financed by labour migrants, led to a barely controllable abstraction of groundwater and weakened traditional structures of water distribution and water ownership. The resulting modification of income distribution is one factor that will alter rural social structures. Yet, conservative kinship structures,

group membership, social status, and patterns of production that range from sedentariness associated with agricultural production to nomadic pastoralism, but also "non-traditional" economic activities, determine the handling of water resources. Therefore, to accomplish the task IMPETUS is confronted with, it is essential to include social anthropological data. Otherwise the impact of environmental and climatic change on the local populations cannot be investigated and understood fully. In addition, every intervention into an established setting needs a thorough understanding of the complexity of local traditions and the associated socio-cultural processes of contemporary institutional changes. Any development cooperation can only be sustainable if the historically rooted cultural norms, values, and strategies of survival are considered in the early stage of planning. Consequently, the social-anthropological workpackages are investigating the embeddedness of indigenous systems of water use in the spheres of religion, economy and socio-political institutions.

The following results have been achieved in the different workpackages of B4:

Workpackage B4-1: Anthropology

<u>Localisation and description of water resources in Tiraf and Blida (Ktaoua oasis)</u>

In the lower Ktaoua Oasis, in the villages of Blida and Tiraf (including Tagounite and adjacent pasture-land), 89 and 113 water sources respectively, were localised and described. Six different modes of water supply exist:

1.) traditional, modern, and renovated wells; 2.) covered cisterns, (*matfia*); 3.) individually or collectively used water taps; 4.) sources (*l'ayin*) at the mountains or close to rivers; 5.) natural reservoirs in the mountains (*laouina*); and 6.) supply by road tankers. Water is distributed according to different criteria by:

a.) State institutions in the case of water taps and road tankers (water is sold or expenses for transportation are paid by the users),

b.) by private use in the case of the individually developed sources (water is free for owner, who can allow access to non-owners), and

c.) by patterns negotiated between the different social groups, in the case of the collectively owned public water points (water is for free).

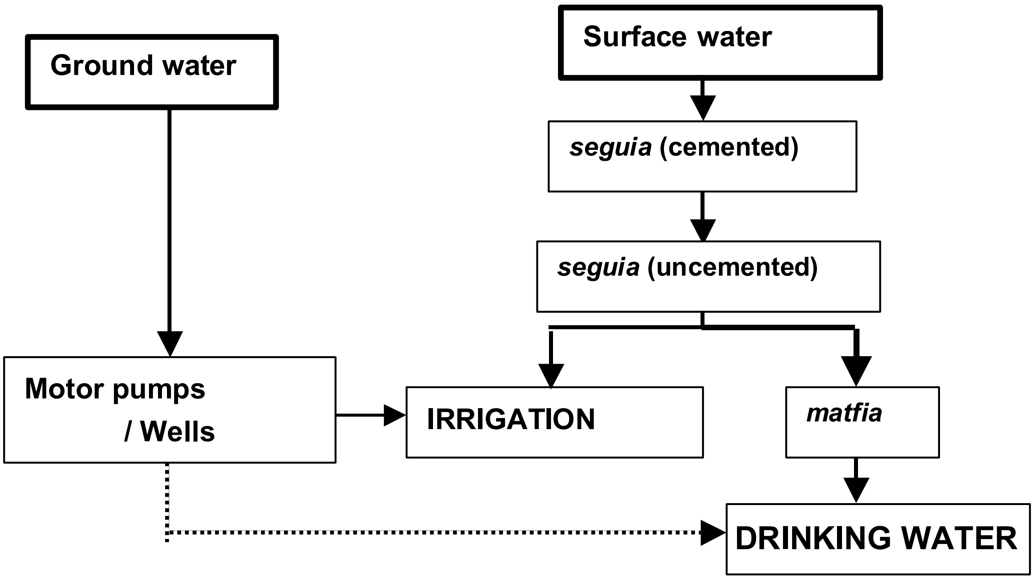

Fig. B4-1: Water distribution in Blida

Because of the lack of cash, the majority of the rural population favours public water sources, despite of their sometimes poor water quality (high salinity with conductance between 13,2 µS and 0,3 µS; MW = 4,26 µS; N = 48). Wells outside the palm-oasis, where water is often of better quality, are frequently the cause of conflicts between nomads and the sedentary population.

There are no water taps in Blida, but many wells that are generally provided with motor pumps. Together with the covered cisterns (*matfiya*) they supply the village with water for drinking and irrigation. Water is distributed according to the pattern shown in Fig. B4-1 (thick arrows indicate primary supply lines).

Social structure and land tenure

In Blida, social inequality is mirrored in the distribution of cisterns and wells equipped with motor pumps. Fig. B4-2a shows an equal distribution of cisterns among the various social groups, while Fig. B4-2b illustrates an unequal distribution of wells equipped with pumps. Here the Draoua are clearly less privileged. Counting 32% of the total population, they possess only 13% of the motor pumps. This situation well reflects the underprivileged socio-economic position of the Draoua. While even poorer Draoua families can afford the construction of cisterns, expensive wells or even more expensive water pumps could only be purchased by families having access to external means of income. The only Draoua families who own pumps had one or more family members working abroad.

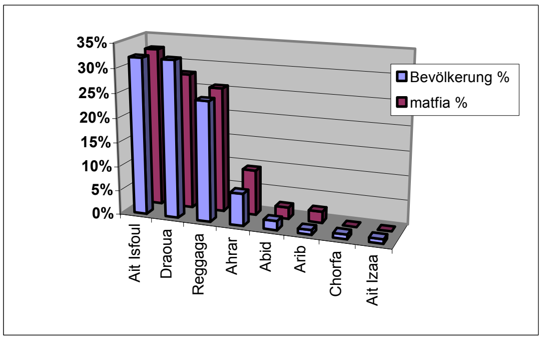

Fig. B4-2a: Possession of cisterns *(matfia)* (%) in relation to ethnic groups (%) in Blida.

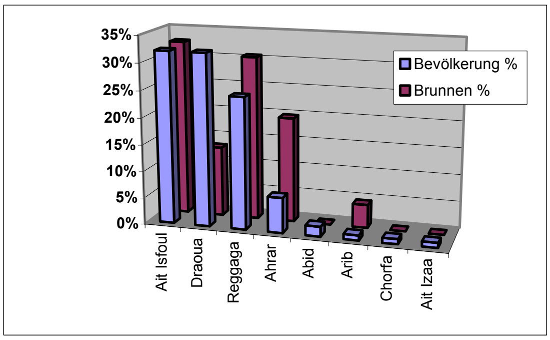

Fig. B4-2b: Possession of wells/motor pumps (%) in relation to ethnic groups (%) in Blida.

Water consumption

Data about domestic water consumption of the Ait-Unzar Nomads and the village people of Tiraf were obtained by conducting interviews that were cross-checked by selective measurements (Tab. B4.1). In November 2001 and in April 2002, measurements were taken in five households of different size. The average daily consumption per person was 8,8 l during the cold season (November measurements) and 15 l during the hot season (April measurements). These consumption figures are clearly lower than in Tagounite, where an average of 30 l/day of water is consumed.

Tab. B4.1: Tiraf – round up means of daily water consumption (litre) in 5 households, measured during November and April (left table) and used water sources (right table).

Household	**Nov. 2001 (2 weeks)**	**Apr. 2002 (1 week)**	**Type of source**	**Consumption Nov. 2001**	**Consumption Apr. 2002**
Sedentary (small)	13	29	Water Tap	50,8 %	41,2 %
Sedentary (medium)	11	14	Cistern	35,2 %	26,1 %
Sedentary (large)	9	12	*Matfia*	8,5 %	14,8 %
Nomads (medium)	6	11	Well	5,5 %	4,8 %
Nomads (small)	5	9	Well	0 %	13,1 %

small= 1-4 Persons; **medium**= 5-10 Persons.; **large**= 11-25 Persons.

During dry periods and throughout the summer months when all the cisterns of the village are dried up, the village people of Blida fetch their water from three wells where water for domestic use is available free of charge. For irrigation purposes, the water of all the 46 wells equipped with motor pumps is sold. One hour of pumping water to the fields costs 15 MDH (1,50 €).

In the summer of 2001, a Luxembourgian aid project dug a new well and built a water tower near the village of Beni Semguin to provide water to all the villages of the Lower Ktoua Oasis. The fact that wells situated in this region had formerly been used by nomads created a new potential for conflicts between them and sedentaries. Since then, road tankers deliver water to the villages that pay the transport costs. Soon, the *Commune Rurale* will install new water pipes on the left bank of Lower Ktaoua Oasis, to allow the installation of individual water taps in every village.

<u>Local water management in Tiraf</u>

In Tiraf as well as among the Ait Unzar Nomads, administration and access to local water resources is guaranteed by the integration of the various social groups. The two largest parts of the population in Tiraf are the Draoua farmers and the Ait Unzar nomads, a tribe belonging to the huge Berber Ait Atta confederation. The Draoua consist of three groups: Two belong to the Shaqaf, the founding group of the village, while members of a third group arrived later. The Ait Unzar nomads are subdivided into four sub-groups, the Ait Hammou, the Ait Ali Wishou, the Ereidat and the Ait Yussef. Most of them are still nomads or settle temporary in Tagounite, but all of them own land and water rights in Tiraf.

The village assembly, composed of 8 representatives of the Ait Unzar *qabila* and 6 representatives of the Draoua *qabila*, should ideally settle all conflicts in consensus. This "tribal" association, which is not officially recognized by the state, controls the collective social life in the village. It is responsible for planning the agricultural campaign, organizing the distribution of irrigation water, concluding contracts with nomadic watchmen during the date harvest, regulating the access to non-private drinking water resources and guarantying the just distribution of common duties.

Fig. B4-3: Weekly system of water distribution in Tiraf

<table>
<tr><th></th><th colspan="2">groups having water rights</th></tr>
<tr><td>Nahar Ithlâta
(Tuesday)</td><td rowspan="2">SHAQAF
(founding Draoua)</td><td>LHADDI</td></tr>
<tr><td>Nahar larba’
(Wednesday)</td><td>LMEDANI</td></tr>
<tr><td>Nahar lkhamîs
(Thursday)</td><td colspan="2">BARRANYIN
(religious foreign groups of Zawyia Sidi Salah, Ksar Kebir, Lansar)</td></tr>
<tr><td>Nahar ljuma’a
(Friday)</td><td colspan="2">AIT UNZAR</td></tr>
<tr><td rowspan="2">Nahar ssebit
(Saturday)</td><td colspan="2">AIT UNZAR</td></tr>
<tr><td colspan="2">Draoua not Shaqaf</td></tr>
<tr><td rowspan="2">Nahar lhâd
(Sunday)</td><td colspan="2">AIT UNZAR</td></tr>
<tr><td colspan="2">Draoua not Shaqaf</td></tr>
<tr><td>Nahar lithnin
(Monday)</td><td colspan="2">AIT UNZAR</td></tr>
</table>

Fields are irrigated according to the local traditional distribution scheme (*nouba*). In Tiraf it follows a seven-day cycle. Each day of irrigation is assigned to a specific plot of fields which in turn is associated with one of the ethnic or social groups of the village. Two days of irrigation fall to the Shaqaf, two days to the Ait Unzar, two days to non-Shaqaf Draoua and Ait Unzar, and one day is reserved for all tenants who are no direct members of the village like some religious groups (cf. Fig. B4-3).

In addition, the use of water from public water taps – the only source of drinking water before the arrival of the water tankers in 2001 – was managed by the "tribal" assembly. A dichotomy between nomadic and sedentary users is evident. Four out of seven public taps were use by the Ait Unzar Nomads which corresponds with the factions of the nomadic *qabila*, while three taps were used by the three Draoua groups. Apart from this basic pattern of distribution, access to drinking water is negotiated according to current needs, water availability, existing conflicts and other social factors.

Water use in the community of Oulad Lagraier

In Oulad Lagraier a water tower that now supplies all households was built in 1992. The 18 water meters installed were read at irregular intervals, once or twice a year. The maintenance costs of the plant are equally divided among the users. The collected data for water consumption suggest that variations in quantity are due to seasonal effects (cf. Fig. B4-4). Since 1997, the rise in consumption has been marginal and affected only few households. The increase in the number of animals and the growth of families probably caused the rise in water consumption.

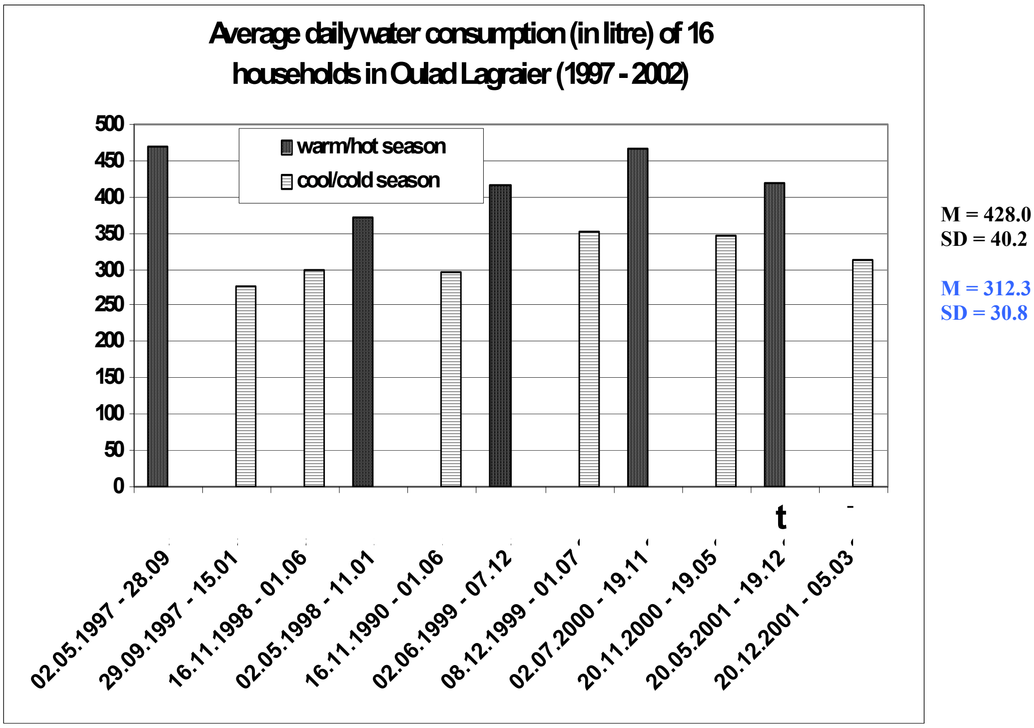

Fig. B4-4: Average daily water consumption (in litre) of 16 households in Oulad Lagraier (1997 - 2002).

High consumption rates are only found in households with "foreigners" like schoolteachers or students. Large fluctuations are visible in migrant households, where parts of the family have a second domicile, allocated for example in the tribal grazing land (*koudia*).

Most of the wells were localised and documented using a Global Positioning System (GPS) and the quality and salt content of the water was analysed.

In the whole work area of workpackage B4-1, interviews about identity, ethnicity and household economies were conducted. Data from the 1994 census is available for Tinzouline, Ouled Yahia Lagraier (data from the "Commune Rurale") and Ktaoua. Based on the settlement patterns and ethnic composition of the villages, patterns of political organisation and hierarchical structures were recorded. This material constitutes the base for research about correlations between power positions and access to land and water, as well as juridical systems, potential for land and water conflicts, and local strategies for reconciliation.

Workpackage B4-2: Classical islamic water rights

The focus of this workpackage is classical Arabic water and land rights as they were documented in early European and Arabic sources. Caprona's fundamental 1973 FAO-Study "Water Laws in Muslim Countries" was used as the basis for this research. From the sources it could be deduced that irrigation technology, originating in Iran and Iraq, entered Morocco via Spain in the 11th Century.

According to Islamic values, water is a public good that can be used by everybody as long as nobody is disadvantaged. On the other hand, Islamic Law acknowledges and protects private ownership. Therefore wells constructed by individuals are private property of the builder. Nevertheless, (in theory) the owner must not deprive others or sell a surplus of water.

Rights of water use related to the different irrigation systems vary according to the numerous Islamic Law schools. These relationships were documented and systematised. In addition the specific Moroccan situation which is characterized by the predominance of the Maliki Law, was analysed. The scripts of later law experts such as the al-Wansharisi collection of fatwas from the Maghrib, and Khalil Ibn Ishaq Mukhtasar's work from the 14th Century are important sources. Regarding the situation in the Drâa-Valley, Roman reports, early travel accounts and recorded oral traditions have yet to be analysed.

Because of the plurality of regional laws and land rights-systems in Morocco, there are a large number of treaties dealing with this topic, most of them based on Hanafi Law. There are hints in various texts that lease payments or a share in harvest should be generally prohibited. Nevertheless, a special lease contract with a fixed down payment was considered lawful. The reality, however, is different: Landowners and tenants usually share the yields according to a negotiated distribution key.

Workpackage B4-4: Urban and rural water users around Ouarzazate

During the last fifty years the Oasis of Ouarzazate became the provincial capital and a tourist centre. This development was accompanied by institutional, socio-political, and economic changes. The related growth of the urban population led to an increase in water consumption[3]. The increase was further accelerated by the remittances of temporary labour migrants and an increase in non-agricultural labour. The money is invested in durable consumer goods and modern buildings with improved sanitary infrastructure and a more comfortable water access. In the rural context earnings from temporary migration or wage labour are spent to buy motor pumps.

Urban water production and distribution is managed by the *Office National d'Eau Potable* (ONEP). Conflicts arise on the local level between consumers (private households) and the ONEP about excessive water bills, access to the urban water supply in reconstruction areas and the bad water quality in times of drought. Some households react by searching for informal ways to get connected to the urban water supply. Only households with a regular income from migration or wage labour can afford private water taps. To date, only 82% of the households in Ouarzazate are connected.

The production of drinking water in Ouarzazate depends on the water preparation plant at the Mansour Edahbi dam and on wells in Oued Fint. Although water supply is currently sufficient, the ever-increasing demand and long dry periods could make matters critical. For instance in April 2002, after four years of drought, the reservoir was at the lowest level for urban water production.

To reduce urban water consumption, the ONEP runs a "progressive price policy". The more a private household consumes, the more it has to pay per unit. Large consumers like the tourism sector[4] are privileged by paying less for a higher consumption. The urban water distribution is clearly linked to economic power. The rich receive and consume more water, while the urban poor obtain their water from public water taps and use it more efficiently.

In the rural areas water distribution is managed according to the local water rights systems. State institutions like the *Office Régionale de Mis en Valeur Agricole de Ouarzazate* (ORMVAO) and the *Association d'Usager d'Eau Agricole* (AUEA) did not alter the traditional distribution system. Nevertheless, the agricultural users are heavily affected by the recent water scarcity. Since 1998, no annual crops could be cultivated in Ouarzazate with the local *seguia* systems. To cope with the water scarcity farmers whose land is situated near the outlets of the urban sewage system use sewage water for irrigation purposes. In other settings, irrigation water is pumped up from a well by motor pumps. As a result of the droughts and socio-economic changes the importance of the agricultural sector is declining. Market production is practically nonexistent, and agriculture is reduced to subsistence production.

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[3] The main water consumers are the private households 62%, followed by the administrative sector 22% and the industrial (tourism) sector 16%.

[4] The average daily tourist water consumption in a high class hotel is more than 800 litres per day, whereas the daily per head consumption of an urban citizen is nearly 70 litres per day and the urban dwellers without own water supply consume only 10-20 litres per day from the public water-taps.

The local land and water rights are traditionally passed on by agnatic descent. Today, the trade of land- and water rights is common. People with sufficient financial means could now purchase land and water rights. As a result the hierarchical and stratified structure of the society is modified. Some of the historically disadvantaged social groups were able to climb the social ladder, while former high prestige groups (nomads, religious elite) experienced a social decline.

These changes led to social tensions that are visible in conflicts over land and water which are common in this region. Whereas in earlier times, local institutions were involved in regulating these conflicts, today modern formal institutions are responsible for solving the problems.

Water changed from a scarce gift from God to a commercial good, which can be bought and sold.

Workpackage B4-5: Local knowledge systems and socio-economic conditions of water use in the Drâa catchment

Water and agriculture

In villages neighbouring scientific test-sites, information about water availability and usage in the domestic and agricultural spheres was collected. This data enabled conducting a first survey of the social and economic environment of the population in the Drâa Catchment. In the whole region, irrigation agriculture in river oases is of decisive importance for food production. The recent drought not only affected the people living in the main Drâa valley, but also villages in the catchments and neighbouring mountainous regions. Annual crops like wheat, barley or henna often completely failed on those fields where water from rivers or springs is normally used for irrigation. Even motor pump-irrigation became impossible in many regions because of the declining ground water tables. In most cases, farmers were only able to sustain permanent crops like palm trees, nuts and almonds.

A certain exception are the communities in the Upper Atlas Mountains. Here farmers could cultivate cereals and other annual crops during the past years but, due to the lack of water from rain and melting snow, with a large decline in yield during the years 2001 and 2002. To enable poorer families with less access to land and water to irrigate at least a minimum acreage, the total cultivated and irrigated area was reduced by a socially controlled and accepted plan.

Migration and socio-economic changes in the Drâa valley

As a result of the recent drought, the migration of whole families from the research area to other rural regions or to urban centres in Morocco is evident. In addition, the number of young male labour migrants who seek employment in the urban centres in the north of Morocco, the West Sahara region, or in Europe is increasing.

The second working area of the workpackage B4-5, the village of Oulab Yaoub at the southern fringes of the second palm oasis, provides a good example of this situation. The drought forced many farmers to migrate to urban areas and seek employment as unskilled workers, mostly in the construction sector. Most of the migrants stay in Morocco. In each family, between one and three family members are temporary or permanent migrants within the country. International migration is limited to a few individuals who are working in France or Saudi Arabia.

Labour migration as a way to improve living conditions is a long-standing tradition for those families that owned less land or were otherwise underprivileged. Nowadays migrant households are better off than the average family because of the influx of cash. This leads to a modification of local water- and land- use patterns and to frequent conflicts about scarce resources (cf. Ait Hamza, 1997; Bencherifa, 1996; Lazaar, 1997; Mter, 1997). The distribution and allocation of water are controlled by complex social networks and local political institutions (cf. Hammoudi, 1985:29; Ilahiane, 1999; Lefébure, 1979). Social and economic inequalities cause conflicting interests between individuals and groups (cf. Leveau, 1985). These preliminary findings point to a considerable change in the socio-political hierarchies and gender relationships (cf. Ait Hamza, 1997; Bencherifa, 1996; Mter, 1997). These dynamics will be further analysed during the next field campaigns.

In addition, samples of household economies and water consumption in selected households were taken. A GPS-mapping of all the wells in the village in addition to the “Etat Parcellaire” of the oasis gardens provided by the ORMVAO was completed. Additional user information about water quantity and quality together with background information about family, kinship, and social structures were collected by semi-standardised and standardised questionnaires.

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<u>Part C</u>

Project infrastructure

Subproject C2

Data Management / Internet

Participants
Prof. Dr. P. Speth Institute of Geophysics und Meteorology, University of Cologne
Prof. Dr. B. Diekkrüger Geographical Institute, University of Bonn

Summary

IMPETUS as an interdisciplinary research project depends on a vivid knowledge exchange between all staff members, institutes and the public. An important part of this knowledge and data exchange can be managed by using the internet. Subproject C2 coordinates the data management and the IMPETUS websites as internal and external communication platform. During the first project phase, a complex meta-database was developed to catalogue information on all data that are collected or acquired. At the moment the database is in a test stage.

The IMPETUS websites contain extensive descriptions of IMPETUS and its subprojects, lists of staff, institutes, publications, web links, events, documents for download, mailing lists and actual weather reports from Northwest and West Africa.

State of data acquisition

During the first project phase a huge amount of different datasets was acquired within IMPETUS. Partly these data were collected during field campaigns (up to several months), partly they were collected automatically by different measuring stations. At the beginning of the first phase a total of 15 climate stations were installed in Benin and Morocco. Each station records up to 15 different parameters with a temporal resolution of 10 minutes. In Morocco 12 stations were installed along an elevation and aridity transect (Fig. C2-1) within the upper and middle Drâa catchment. In the southern part of the Upper Ouémé Valley in Central Benin, a high-resolution hydrological monitoring network was installed in the Aguima catchment (Fig. C2-2).

During regular field campaigns over 100 different projects for acquiring hydrological, meteorological, geological, botanical, microbiological, ethnological data etc. were started. For example, vegetation was monitored regularly on 36 test sites in the Drâa catchment in Morocco and about 600 vegetation censuses were carried out to classify the vegetation types of the Moroccan area of investigation. In Benin locations of nearly 1000 drinking water sources were catalogued. At about 140 wells water samples were taken and analysed microbiologically. More details concerning data acquisition can be found in the subproject chapters of this report.

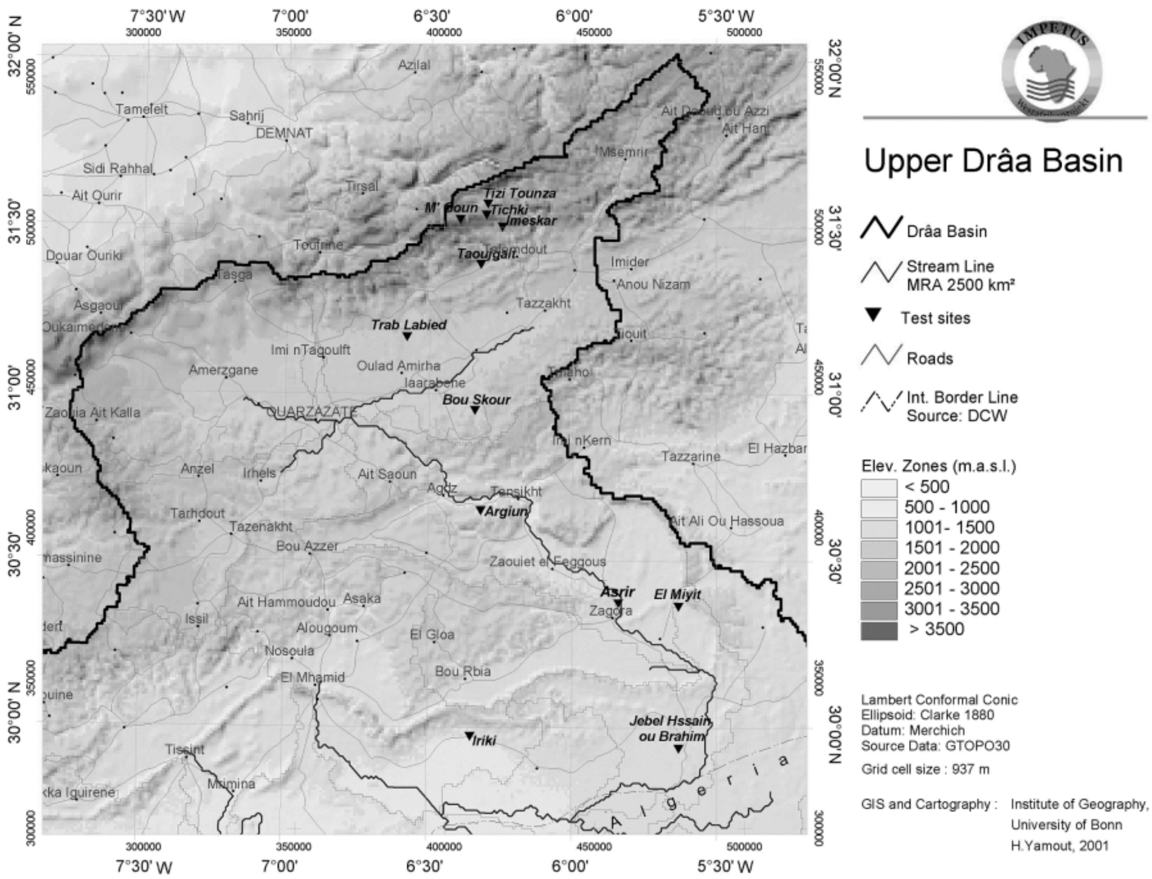

Fig. C2-1: IMPETUS test sites and measuring stations in the upper and middle Drâa catchment, Morocco

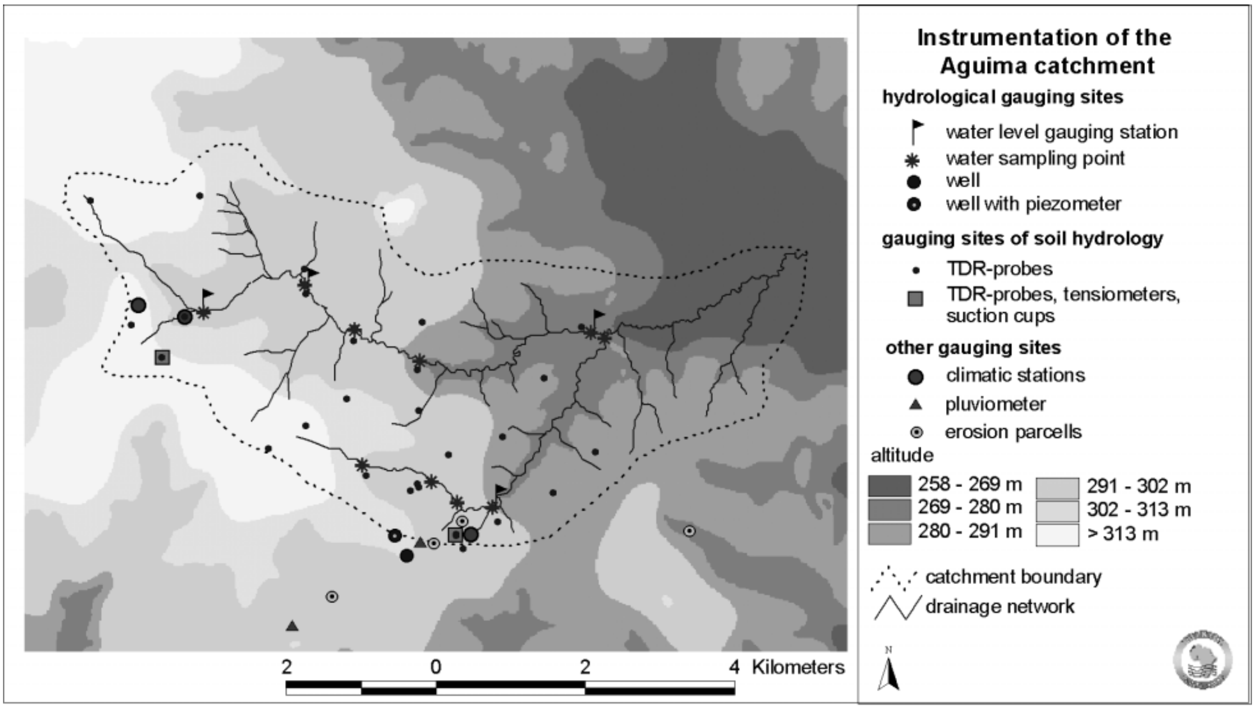

Fig. C2-2: Instrumentation of the Aguima catchment, Benin

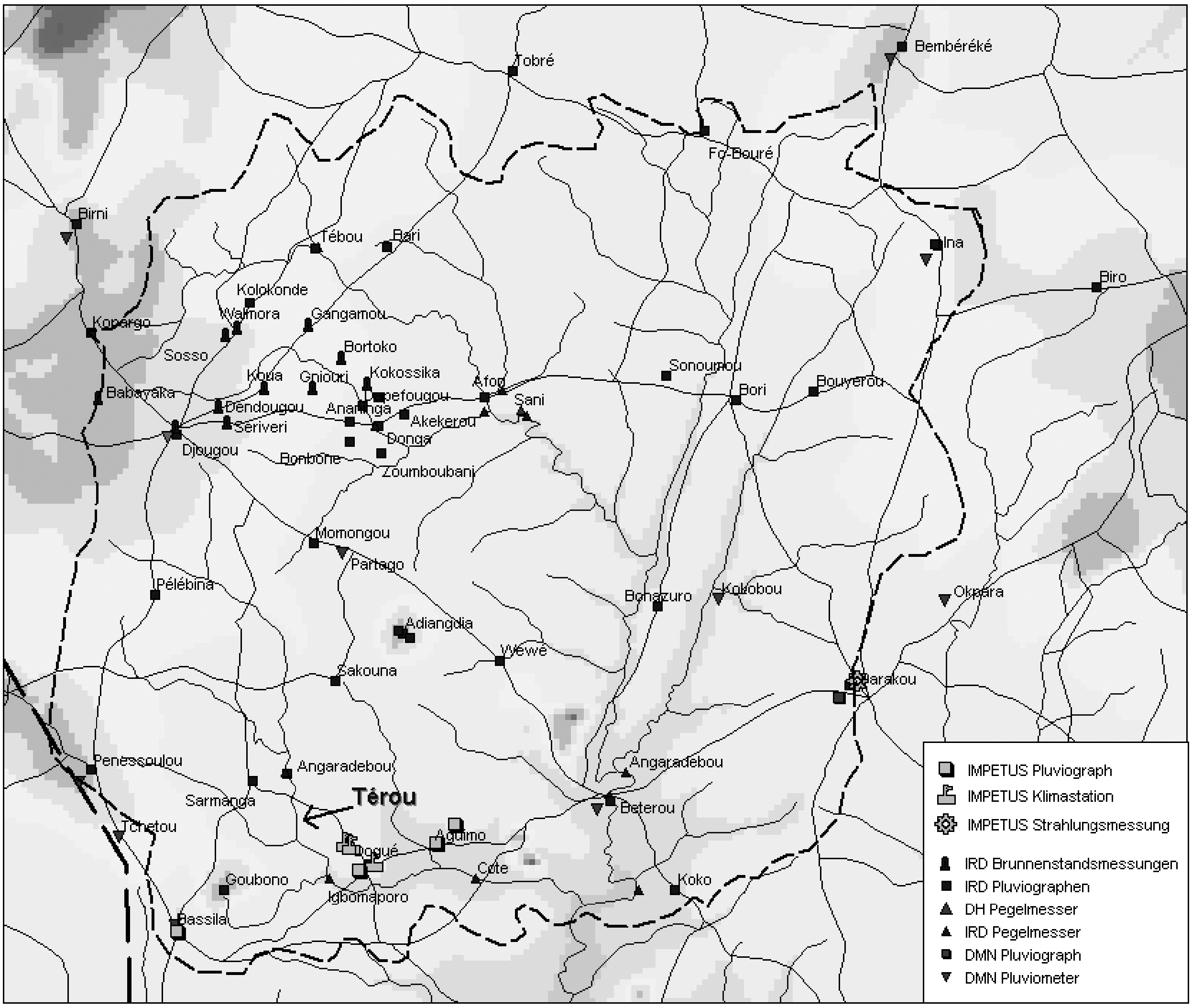

Fig. C2-3: Hydro-meteorological monitoring network in the Upper Ouémé Valley, Benin

In addition to these data directly collected by IMPETUS members, different datasets from other organisations were obtained and analysed. IMPETUS has access to a large hydrological and meteorological monitoring network comprising nearly 100 measuring stations in the Upper Ouémé Valley in Central Benin (fig. C2-3). These stations are operated by the Direction Météorologique Nationale (DMN, Benin), the Direction de l’Hydraulique (DH, Benin) and the Institut de Recherche pour le Développement (IRD, France). The remote sensing working group has acquired, georeferenced, corrected and analysed about 600 satellite images from different platforms (NOAA, SPOT, Landsat, ASTER). These data are covering the IMPETUS investigation areas in Benin and Morocco and are used e.g. for land use classification, investigation of seasonal vegetation dynamics or generation of DEMs.

Meta-database

Metadata provide information about data. The aim of the metadata concept is answering the following question:

> "Which data can be found where, in which quality, who can give me more information and how do I get access to the data?"

Metadata contain information about

- identification,
- content,
- quality,
- spatial reference, and
- availability

of the data, but do <u>not</u> contain the data itself.

To provide an informative catalogue of all data collected or acquired within IMPETUS, a complex database was developed using DBMS Microsoft Access. In this database all data are being documented and managed in the form of a metadata catalogue. The relationships within the database are shown in Fig. C2-4. The structure of the metadata is oriented at international standards like FGDC-STD-001-1998 (FEDERAL GEOGRAPHIC DATA COMMITEE 2000) and ISO/TC211 19115. These standards were principally developed for geographical data. Because IMPETUS data also cover spatially independent data, these structures had to be partly modified. The new metadata structure is being intensively tested by the different disciplines of IMPETUS at the moment. Table C2.1 gives an overview of the structure and contents of the meta-database.

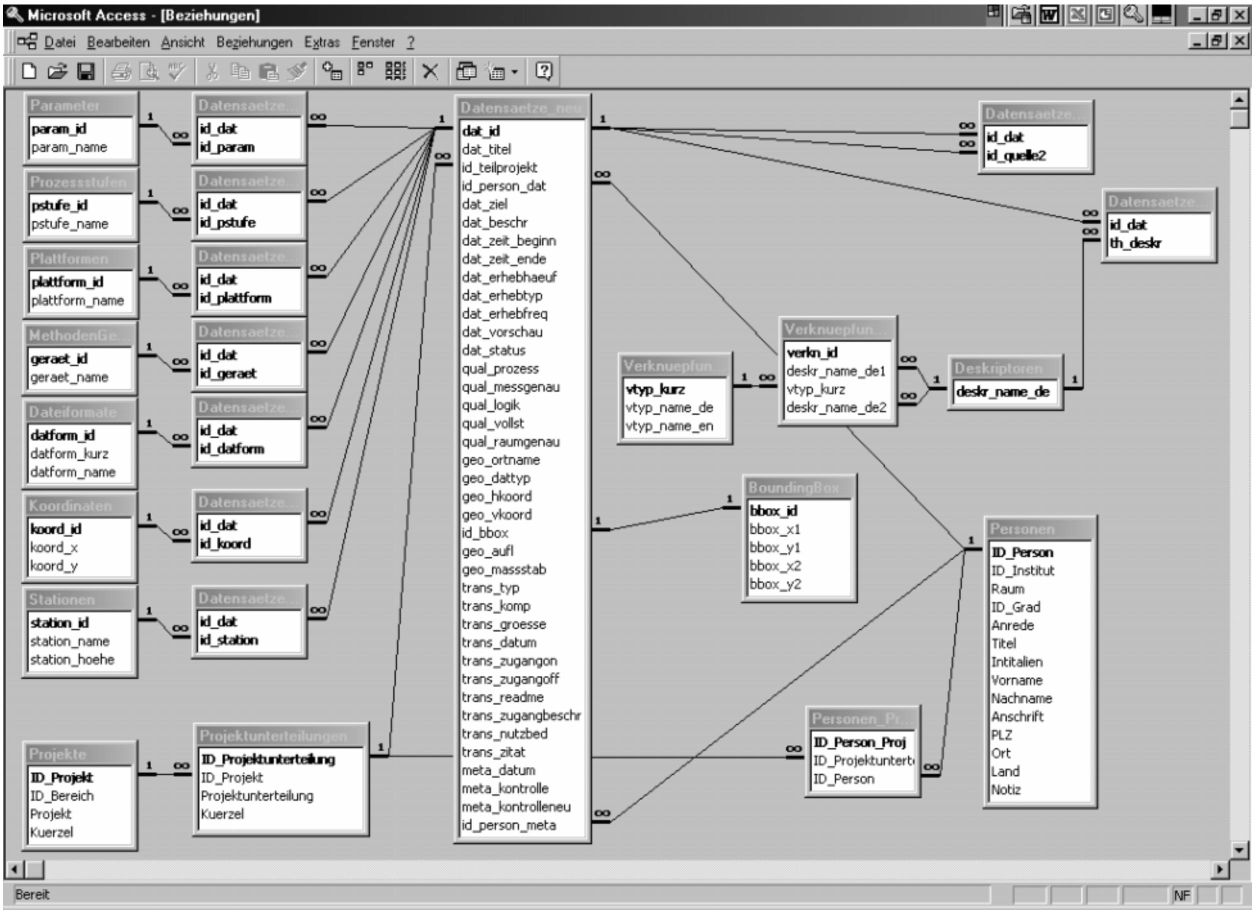

Fig. C2-4: Entity-relationship model of the IMPETUS meta-database

Tab. C2.1: Contents of the IMPETUS meta-database

Meta-data – Identification	
ID	
Subproject	
Contact Person	
Meta-data – Content	
Aim / Purpose	
Description	
Parameter / Attribute List	
Beginning Date	
Ending Date	
Acquisition Frequency	single, multiple
Acquisition Regularity	regular, irregular
Acquisition Frequency Description	
Preview Image	
Status	finished, in progress, planned
Keyword List	
Meta-data – Data Quality	
Method / Instrument List	
Processing Levels	raw data, derived data, modelling results / simulated data, report / description
Source Data / Related Data	
Data Provenance	
Platforms	satellite, airplane, balloon, tower, vehicle, person, ground, ship
Processing Description	
Parameter Accuracy Report	
Logical Consistency Report	
Completeness Report	
Spatial Accuracy Report	
Meta-data – Spatial Reference	
Spatial Reference Description	
Station List	
Geodata Type	point, vector, raster
Planar Coordinate System	
Vertical Coordinate System	
Coordinate List	
Bounding Box	
Resolution	
Scale	
Meta-data – Transfer Information	
Data Character	text, table, map, image
Data Form	digital, non digital
File Format List	
Compression	not compressed, ZIP, TGZ/GZ, ARJ, LZH, …
File Size uncompressed	
File Size compressed	
File Creation Date	
Online Access	
Offline Access	
Readme File	
Access Constraints	public, IMPETUS internal, no access
Use Constraints	
Citation Information	

The meta-database is connected to the IMPETUS web server. All staff members can search the meta-database via internet and can submit relevant information about their own datasets to the data management using a HTML-based form (Fig. C2-5). Before adding the meta-information to the meta-database, a careful quality check is carried out by the data management.

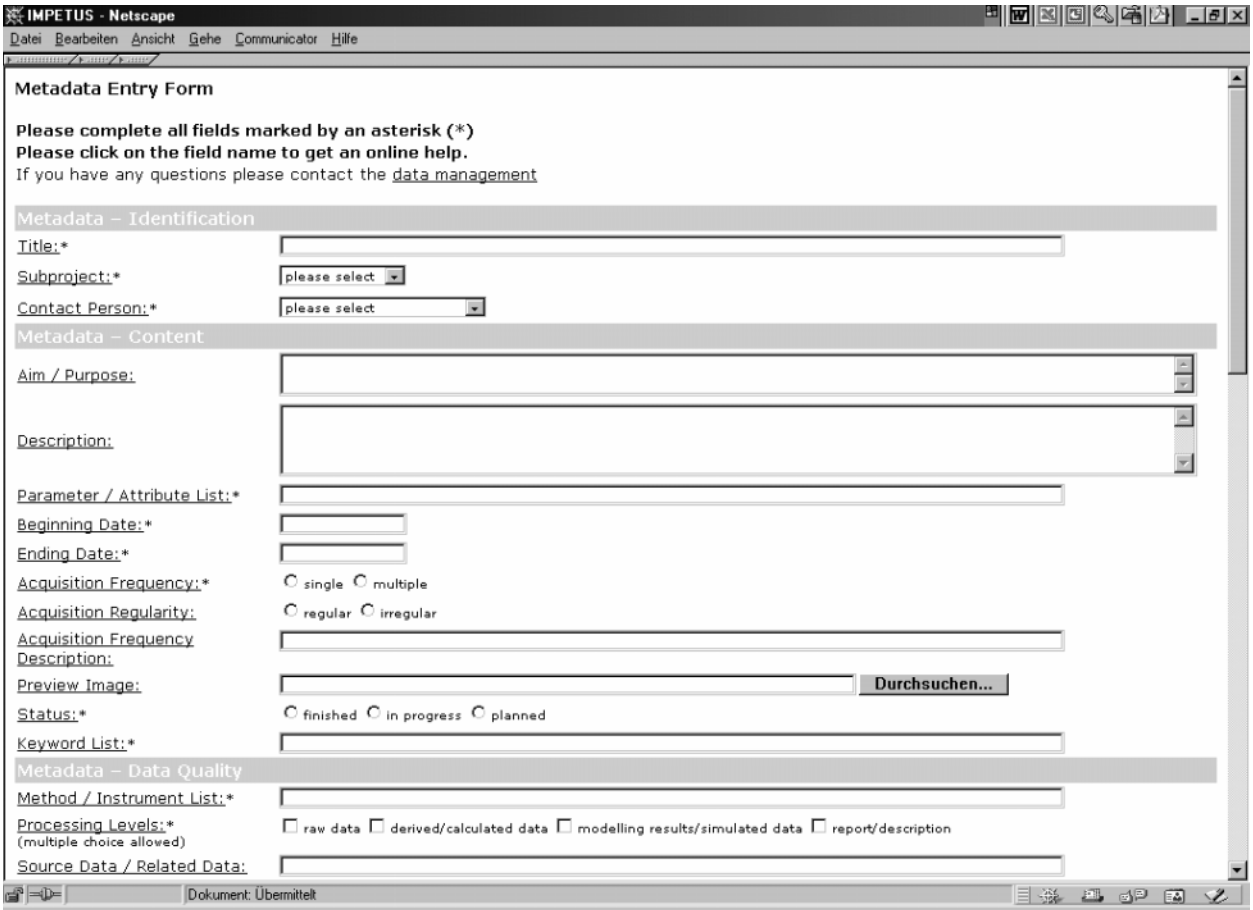

Fig. C2-5: Entry form for meta-information

For using the web based meta-database two user groups are distinguished: IMPETUS staff members and public users. The meta-information itself is accessible to all users. Staff members get additional access to the data itself, if these are available on Internet servers of the involved institutes. Authorized users do not have to know the exact storage location. The meta-database result provides a direct download link (Fig C2-6). Public users primarily do not have download access. For each dataset access constraints can be assigned individually, so each dataset can be made available to public users at any time. All relevant data shall be made accessible to the public during the next project phase.

Searching the meta-database is feasible by using different possibilities: by systematic or alphabetical browsing a hierarchical thesaurus, searching by subprojects, contact persons (only internal) and coordinates or by using a full-text search. Fig. C2-7 shows the search form.

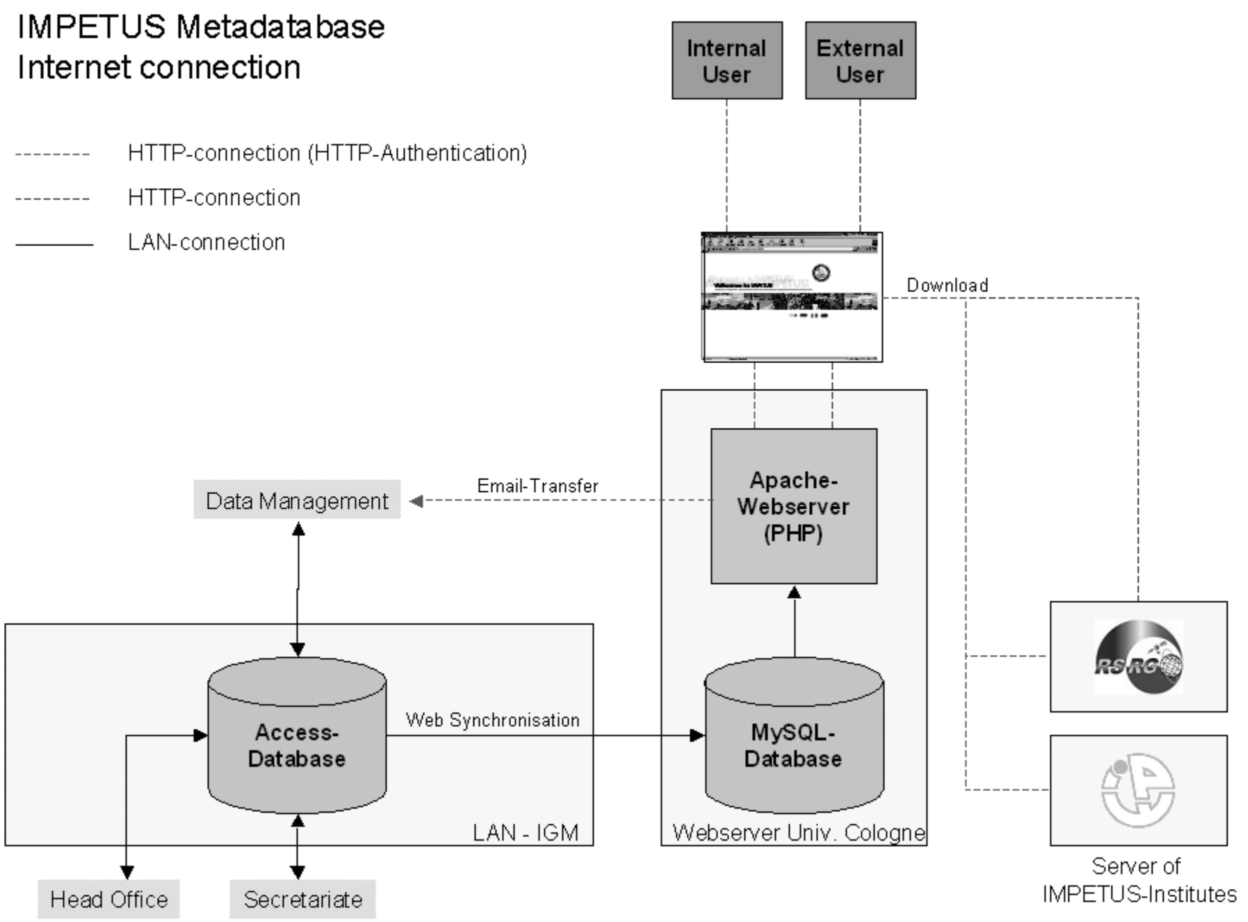

Fig. C2-6: Connection scheme of the IMPETUS meta-database

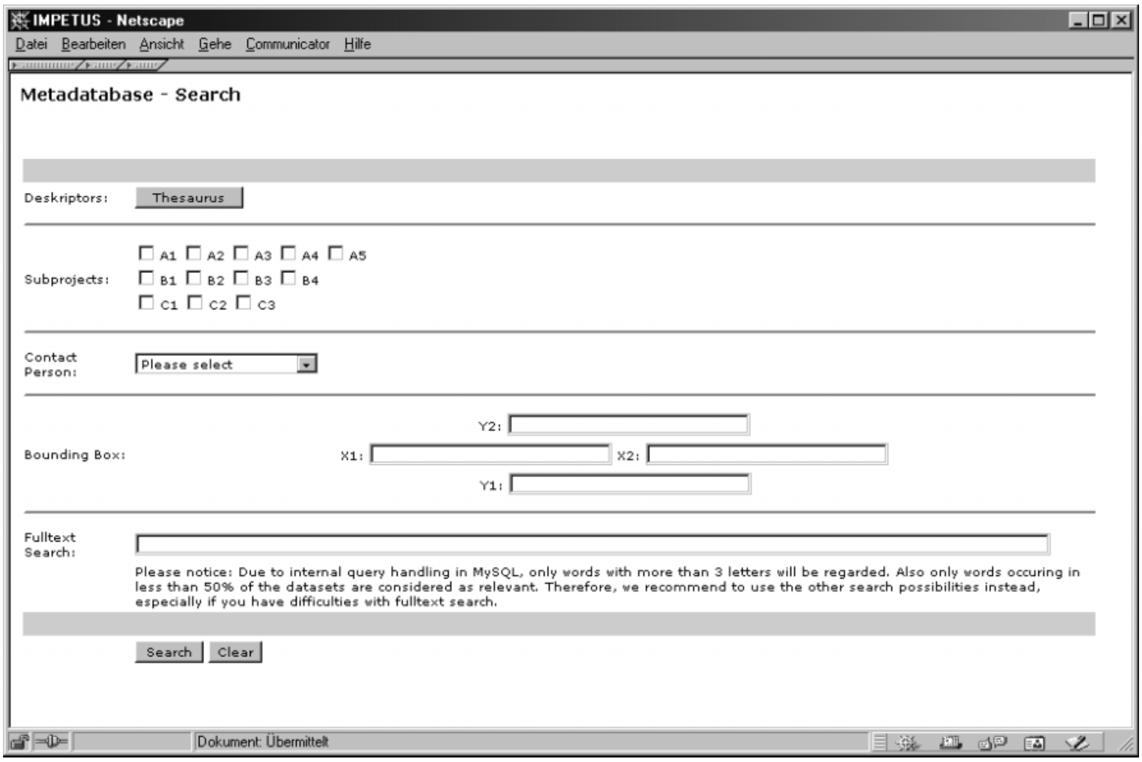

Fig. C2-7: Meta-database search form (internal version)

Internet

The internet presentation of the IMPETUS project is realized at the University of Cologne. On the one hand the IMPETUS websites are used as communication platform for all IMPETUS members, on the other hand they are used for public presentation of the whole project. The websites were developed using a content management system based on PHP and MySQL. Maintenance of the sites is being facilitated by this system. To permit all project partners to participate in this communication platform, most parts were translated into English and French.

Important public parts of the IMPETUS websites are

- general presentation of IMPETUS with its subprojects including first scientific results,
- list of all participating institutes and staff members including contact information,
- list of publications resulting from IMPETUS,
- central mailing lists for contacting selected project groups,
- download of IMPETUS publications (reports, posters),
- meta-information on collected data (see previous chapter),
- list of relevant scientific events (e.g. meetings, conferences) ,
- daily updated weather reports from West Africa,
- selected internet links (Africa, Global Change, Development Policy, Water Aspects, etc.).

Beside the public area of the IMPETUS websites, an internal password protected area was created, mainly for communication between IMPETUS members and partnership organisations. Important contents are:

- general directives for staff members (standing orders, travel expense accounting, etc.),
- protocols, travel reports,
- forms, and
- intermediate results of the subprojects (not yet published).

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Subproject C3

Atmospheric Circulation Models

Participants	Discipline
Dr. Mojib Latif Max-Planck-Institute for Meteorology, Hamburg	Meteorology

Summary

The main goal of this subproject was to gain a better understanding of the rainfall variability over West Africa on interannual to decadal time scales based on the global atmospheric general circulation model ECHAM4.5 (Roeckner et al., 1996). The focus was set on the impact of sea surface temperature anomalies (SSTAs) on the one hand and dynamic vegetation on the other hand.

The warming of the tropical Indian Ocean appears to be the most important factor in the recent decadal drying trend in West Sahel rainfall. SST-forcing alone, however, failed to simulate the magnitude of the observed rainfall anomalies in that region. Introducing dynamic vegetation led to a much better reproduction of the amplitudes of the Sahelian rainfall anomalies.

ECHAM4-T106 (horizontal resolution) global forcing fields for climate change simulations with the continental-scale model REMO (cf. subprojects A1 and B1) were provided for three different time sclices: the past (1960–1989), the present (1990–2000), and the future (2070–2099).

Simulation of precipitation in West Africa with ECHAM

It is well known that the decadal rainfall variability of the Sahel (area south of the Sahara desert) is among the most pronounced so far identified in the historical climate records of the 20th Century. The rainfall over the West Sahel shows a multidecadal drying trend from the 1950s (wet-mode) to the beginning of the 1990s (dry-mode) with a slight recovery in the recent years. We investigated the impact of tropical decadal-scale SST forcing on West Sahelian rainfall. We examined the response of ECHAM4.5 to an observed tropical composite SST anomaly field between a period of the wet- (1951-1960) and dry-mode (1979-1995) in the Sahel. The model response to individual components and combinations of this tropical composite SST field in the Atlantic, Pacific, and Indian Ocean is analysed. The decadal changes in tropical SSTs force a dry- and wet-mode in the Sahel. The tropical Atlantic is not responsible for the recent decadal change in West Sahel rainfall; in particular the inter-hemispheric Atlantic SST gradient is not the cause of the decadal drying trend over the West Sahel. The western tropical Pacific decadal SSTAs are more important for the eastern Sahel. Since the decadal change in the Indian Ocean is mostly characterised by a warming, an additional experiment was performed in which the tropical Indian Ocean SSTs of the control run (covering the dry mode in the Sahel) are simply reduced by one Kelvin. Our experiments indicate that the warming of the tropical Indian Ocean seems to be the most important factor in the recent decadal drying trend in West Sahel rainfall. A large-scale atmospheric east-west pattern is associated with the warming of the Indian Ocean. As a result a large-scale divergence response (accompanied by an intensified subsidence) occurs over West Africa in the dry-mode. Our model results are confirmed by observational studies (e.g. Shinoda and Kawamura, 1994). The experiments also show that the tropical SST warming - especially of the Indian Ocean - might have contributed to the recent decadal change of the North Atlantic Oscillation (NAO).

One of the leading modes of rainfall variability over West Africa is a dipole between Sahel and Guinea Coast rainfall. An experiment shows that this Guinea-Sahel rainfall dipole can be induced by simultaneous SSTAs in the tropical Indian Ocean and in the eastern tropical Atlantic. This mechanism can also explain why there is not always a dipole between Guinea Coast and West Sahel rainfall (Fig. C3-1). The SSTs in the tropical Indian Ocean and in the eastern tropical Atlantic evolve more or less independently.

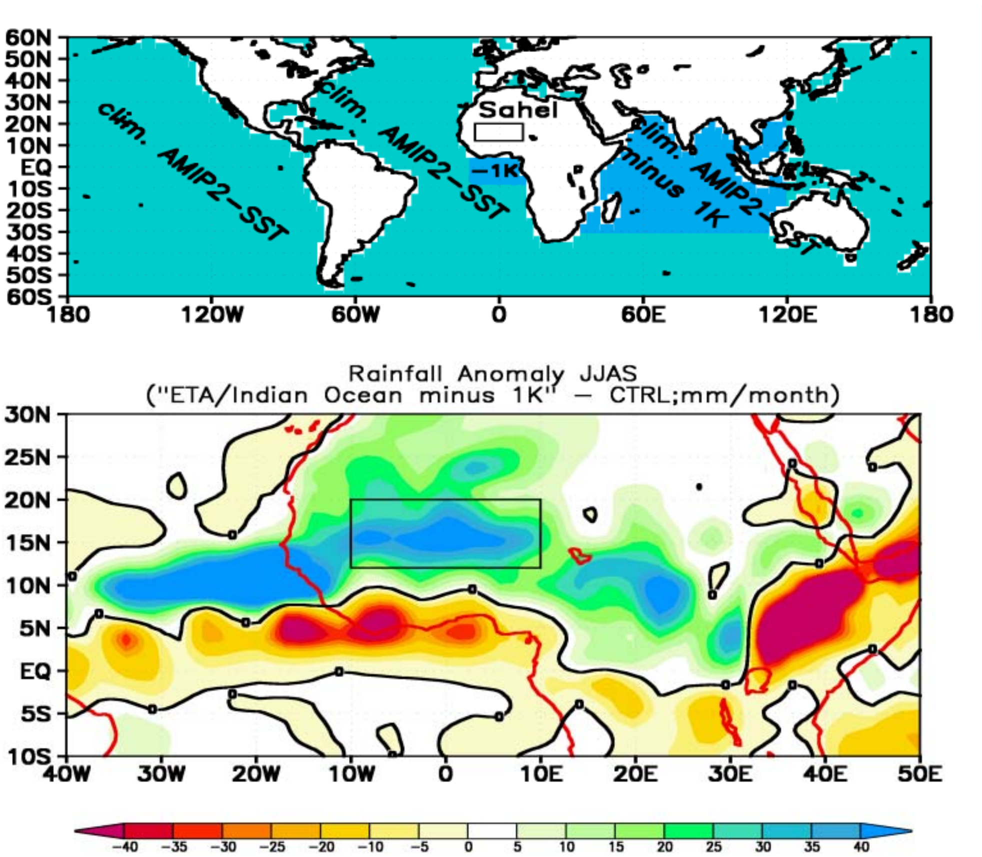

Fig. C3-1: Combined effect of warming Indian Ocean and eastern tropical Atlantic SST on West African rainfall. A decrease of the climatological AMIP2 SST (1979-1995, representing the "dry" mode) by 1 K in these two regions (top panel) leads to a significant increase in West Sahel rainfall and is able to produce the dipole between Guinea Coast and Sahelian rainfall (bottom panel).

Additional experiments were performed where the climatological SST was enhanced or decreased by one Kelvin in certain parts of the Atlantic Ocean. Changing SST in the eastern tropical Atlantic only caused significant changes along the Guinea Coast, with a positive SSTA increasing rainfall and a negative reducing it. The response was nearly linear. Changing SST in other parts of the Atlantic Ocean caused significant changes over West Africa, especially in the Sahel area. The response is found to be non linear, with only negative SSTA leading to significant reduction in Sahel rainfall. Furthermore, the impact of the SSTAs from the different Atlantic Ocean regions was not additive with respect to the rainfall.

In a second type of experiments we investigated the impact of vegetation on rainfall over West Africa. Four simulations with the simple dynamic vegetation model (SVEGE) by Zeng et al., 1999, was coupled to the ECHAM4.5 were performed, driven with observed SSTs from 1945 to 1998. The standard ECHAM-AGCM -forced by the same observed SSTs- was able to reproduce the drying trend from the 50s to the mid-80s in the Sahel, but failed to simulate the magnitude of the rainfall anomalies. The coupled model was not only able to reproduce this drying trend, but was also able to better reproduce the amplitudes of the rainfall anomalies. The dynamic vegetation acted like an amplifier, increasing the SST-induced rainfall anomalies (Schnitzler et al., 2001).

Computation of global forcing fields for climate change simulations with REMO

The atmospheric general circulation model ECHAM-4 with 19 spaced levels (Roeckner et al., 1996) was used to simulate initial and boundary conditions for the regional climate model REMO. The T106 horizontal resolution Gaussian grid (~ 1.1^0) was chosen for the model simulations. The global datasets for surface temperatures, sea ice concentration and sea ice depth were bi-linearly interpolated from low-resolution horizontal grid (T42, ~2.8^0) and used as input datasets. These surface layer parameters were previously simulated with the coupled atmosphere-ocean model ECHAM4-OPYC3 at the Max-Planck Institute for Meteorology in Hamburg (Roeckner et al., 1999). The global fields simulated in the model experiments reflect climate changes in the past (1960-1989), present (1990-2000), and future (2070-2099).

Changing concentrations of greenhouse gases, total ozone and anthropogenic sulfur emissions were considered as radiative forcing. Both direct and indirect sulfate aerosol effects were taken into account. In the model run for the period 1960-1989, the greenhouse gases, as well as the anthropogenic sulfur emission concentrations were prescribed according to observations. Model climate simulations for “present-day” and “future” followed the International Panel on Climate Changes (IPCC) B2 emission scenario. This scenario is based on the more realistic (comparing to other IPCC scenarios) description of the concentrations of greenhouse gases and sulfate aerosols according to the rate of socio-economic development and ecological sustainability (IPCC, 2000). All output variables were written out in a 6-hour time-step interval and stored in GRIB format. Monthly means were computed for each parameter. Fig. C3-2 shows ECHAM4-simulated 2 m-temperature and total precipitation (large scale and convective) over North Africa for the period 2070-2099, as well as the changes in these variables for the B2 scenario run and past-day (1960-1989) conditions.

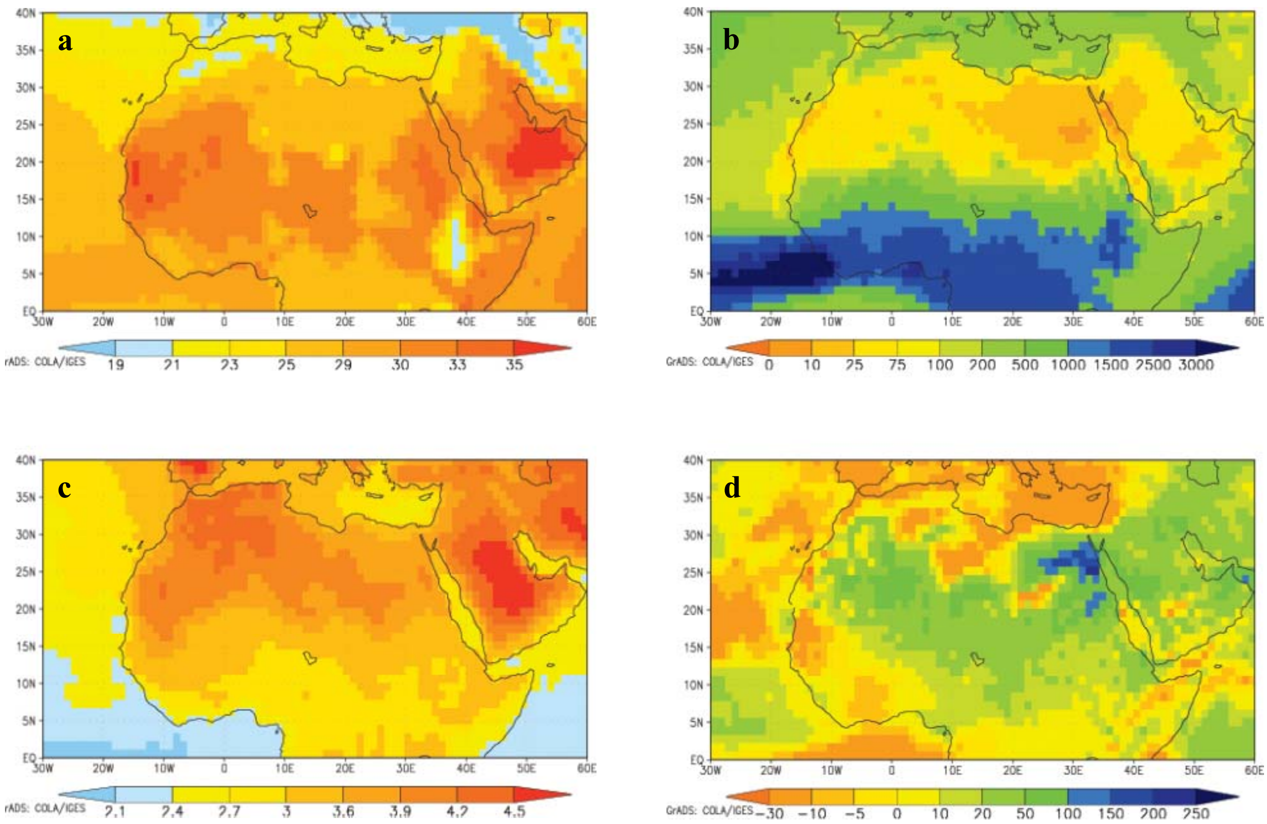

Fig. C3-2: ECHAM4 simulated **(a)** 2 m-temperature, [°C]; **(b)** total precipitation, [mm/yr] for the period 2070-2099; **(c)** changes in 2 m-temperature for the period 2070-2099 compared with the period 1960-1989, [°C]; **(d)** precipitation for the period 2070-2099 expressed as percentage of the precipitation amount in 1960-1989.

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