Towards Applied Modeling of the Human-Eco-System

an approach of hydrology based integrated modeling of a semi-arid subcatchment in rural north-west India

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Acknowledgments

This study shall help to find ways towards sustainable development of forgotten places and communities which are excluded from participating in the big global economics but still forced to favor profits over sustainability.

ऋण निर्देश

झाबुआ के लोगों के मदद बिना यह ही मेरि जाँच खेती बारी, पानी और सेमी-अरिड झाबुआ जिला के विकास के सम्भन्ध के बारे में सम्भाव न होता.
मैं जिस लोगों को मेरा विशेष धन्यवाद देना चाहता हूँ जो मेरी मदद की – खोदने में व मुझे पानी और खाना देने के द्वारा.
इसके सिवाय मैं सब झाबुआ के ग्रामीण विकास ट्रस्ट के सदस्यों और द्विवेदी जी को शुक्र करना चाहता हूँ.
झाबुआ, भोपाल और दिल्ली के GOs और NGOs के सम्पर्क में आने में मुझे बहुत ही ख़ुश किया.
इसके अलावा मैं पसिंग और चेतना हाईस्कूल उनके मेहमानदारी के लिए धन्यवाद देता हूँ.
मैं कृषि महाविद्यालय इन्दौर के Dryland Agriculture Project क सब सदस्यों को भी शुक्र करता हूँ.
आखिर मेरी विशेष धन्यवाद ड॰ अनुपम के॰ सिंघ को है – उनके मदद और मित्रता के लिए.

I would like to thank everybody who supported this project. I like to express my gratitudes to all the people in Jhabua who helped me during the fieldwork and research for data. It was overwhelming to get support from so many sides and I hope this study can return some arguments and insights for a just and free world we all dream of.
I like to express my thank to my guides Prof. Erwin Zehe, Dr. Anupam K. Singh and Dr. Luis E. Samaniego and all colleagues at the Institute for Geoecology. Without your openness for inspirations and discussions as well the provided possibilities and facilities this work had never been possible. Moreover I thank my family and friends for your constant encouragement.

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This work is submitted to the University of Potsdam as thesis for the diploma (master) degree in Geoecology. It has been compiled using LaTeX. During the study mainly Public Software has been used for data and GIS processing. Please refer to the projects for further description:

GRASS GIS: http://grass.itc.it	Quantum Gis: http://www.qgis.org
R-Project: http://www.r-project.org	Octave: http://www.octave.org
OpenOffice: http://www.openoffice.org	php: http://www.php.net
gfortran and other compilers: http://hpc.sourceforge.net	LaTeX: http://ctan.org

The calculations have been run on Linux, Mac OS X and Windows Systems. For programming and satellite image analysis proprietary software was used, too.

MATLAB®	Compaq®Visual Fortran
ENVI	TextWrangler

Nevertheless everybody shall be encouraged to use and contribute to public domain projects.

Abstract

The development of rural areas concerning food security, sustainability and social-economic stability is key issue to the globalized community. Regarding the current state of climatic change, especially semi-arid regions influenced by monsoon or El Niño are prone to extreme weather events. Droughts, flooding, erosion, degradation of soils and water quality and desertification are some of the common impacts.
State of the art in hydrologic environmental modeling is generally operating under a reductionist paradigm (Sivapalan 2005). Even an enormous quantity of process-oriented models exists, we fail in due reproduction of complexly interacting processes in their effective scale in the space-time-continuum, as they are described through deterministic small-scale process theories (e.g. Beven 2002). Yet large amounts of parameters - with partly doubtful physical expression - and input data are needed. In contradiction to that most *soft* information about patterns and organizing principles cannot be employed (Seibert and McDonnell 2002).

For an analysis of possible strategies on the one hand towards integrated hydrologic modeling as decision support and on the other hand for sustainable land use development the 512 km^2 large catchment of the Mod river in Jhabua, Madhya Pradesh, India has been chosen. It is characterized by a setting of common problems of peripheral rural semi-arid human-eco-systems with intensive agriculture, deforestation, droughts and general hardship for the people. Scarce data and missing gauges are adding to the requirements of data acquisition and process description.
The study at hand presents a methodical framework to combine field scale data analysis and remote sensing for the setup of a database focusing plausibility over strict data accuracy. The catena-based hydrologic model WASA (Güntner 2002) employes this database. It is expanded by a routine for crop development simulation after the de Wit approach (e.g. in Bouman et al. 1996). For its application as decision support system an agent-based land use algorithm is developed which decides on base of site specifications and certain constraints (like maximum profit or best local adaptation) about the cropping. The new model is employed to analyze (some) land use strategies. Not anticipated and a priori defined scenarios will account for the realization of the model but the interactions within the system.

This study points out possible approaches to enhance the situation in the catchment. It also approaches central questions of ways towards due integrated hydrological modeling on catchment scale for ungauged conditions and to overcome current paradigms.

Zusammenfassung

Die Entwicklung ländlicher Regionen hinsichtlich von Ernährungssicherheit, Nachhaltigkeit und sozio-ökonomischer Stabilität ist eine der wichtigsten Aufgaben unserer globalisierten Gemeinschaft. In Hinblick auf den Klimawandel sind insbesondere semi-aride Gebiete im Einfluss von Monsun oder El Niño von extremen Wetterereignissen betroffen. Tockenheiten, Überschwemmungen, Erosion, Bodendegradation, Verschlechterung der Wasserqualität und Versteppung sind nur einige, oft beobachtete Folgen.
Der Stand der Forschung in Sachen hydrologischer Umweltmodellierung ist insbesondere einem reduktionistischen Paradigma verhaftet (Sivapalan 2005). Obwohl eine enorme Menge verschiedenster Prozessmodelle existiert können auf Grundlage kleinskaliger Prozessapproximationen die komplex interagierenden Prozesse in ihren wirkenden Skalen im Raum-Zeit-Kontinuum nur begrenzt beschreiben werden (z.B. Beven 2002). Während die verwendeten Modelle große Mengen an Parametern und Daten benötigen, können wichtige Informationen über Muster und Organisationsprinzipien nicht in die Simulationen einfließen.

Für eine Analyse möglicher Wege und Restriktionen der integrierten hydrologischen Modellierung als Mittel in der Entscheidungsunterstützung wurde das 512 km^2 große Einzugsgebiet des Mod Flusses in Jhabua, Madhya Pradesh, Indien ausgewählt. Es ist gekennzeichnet von charakteristischen Problemen der *Neuen Peripherie* (z.B. Scholz 2004) (im human-geographischen Kontext) und intensiv anthropogen beeinflusster Agrar-Öko-Systeme der semi-ariden Tropen. Die dünne Datengrundlage des nichtbepegelten Einzugsgebiets stellt dabei eine besondere Anforderung an die Datenakquise.
In der vorliegenden Arbeit wird ein methodischer Ansatz vorgestellt, der Feld- und Fernerkundungstechniken zur Landschaftsanalyse verbindet. Mit dem Fokus auf Plausibilität statt strenger "Datengenauigkeit" wird eine Datenbank zur hydrologischen Modellierung des Gebiets entwickelt. Das Catena-basierte hydrologische Prozessmodell WASA (Güntner 2002) wird um eine Routine zur Simulation der Entwicklung von Nutzpflanzen nach de Wit (z.B. in Bouman et al. 1996) erweitert. Zur Anwendung des Modells als Entscheidungsunterstützungssystem ist ein agentenbasierter Landnutzungsalgorithmus entwickelt worden, welcher auf Grundlage von Standorteigenschaften und politischen Vorgaben wie Profitmaximierung oder Standortanpassung über die Landnutzung entscheidet. Das neue Modellsystem wird zur Untersuchung von einigen Landnutzungstrategien so verwendet, dass nicht antizipierte Szenarien sondern die Wechselwirkung des Systems selbst die Realisation des Modells bestimmen.
Die Umsetzung zeigt einerseits mögliche Ansätze zur Verbesserung der Situation im Untersuchungsgebiet auf. Anderseits gibt sie konkrete Vorschläge zu zentralen Fragen hydrologischer Umweltmodellierung und zur Überwindung bestehender Paradigmen.

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Part I

Introduction

1 Outline - Motivation of integrated hydrology based modeling towards a decision support system

1.1 General Motivation

The development of rural areas concerning food security, sustainability and economic stabilization is key issue to the globalized community. It has been adopted into the policy goals of all development agencies and the UN (UN 2006). It is known that 75% of the world's population live in areas affected at least once by earthquake, tropical cyclone, flood or drought between 1980 and 2000 (UNDP 2004).
Regarding the current state of climatic change, especially areas influenced by monsoon or El Niño experience extreme weather conditions. Semiarid ecosystems are very sensitive to changes induced naturally or by human activities. In particular, these regions increasingly face water shortage, degradation of water quality and erosion. Additionally growing food demand but decreasing soil fertility raises fundamental questions towards cropping strategies, which on the one hand preserve the productive capacity of the land and on the other hand resist as much as possible weather extremes.

1.1.1 Jhabua in need for wise decisions

The situation in Jhabua and the Mod catchment shall be exemplary for the semi-arid rural world of the 21st century. As described in chapter 2.1.1 the global development in singular economic centers and mega cities creates a vast periphery. Like in Jhabua many regions of the planet face structural deficiency, dependency on external support and high vulnerability of the already very low living standards. The recent history showed how quickly dry monsoon spells can cause severe famines. As matter of fact, especially these regions are sparsely studied. Information about processes and data of the human-eco-system is very scarce and often of very doubtful quality.
Within this rural periphery still major source of the world's agricultural products is located and almost 50% of the people are living here. Hence the need for a sustainability in these regions is of general concern. It is not a question of development support of any community somewhere, but central task to shape a future of justness and peace for humans on this planet.

1.1.2 Environmental science apart from hard data

This social and political setting meets environmental science which was until recently completely following the Laplacian determinism[1]. The aspiration for even more precise data, even better data resolution, even less uncertainty is part of this development. At the same time, environmental science has to admit not even to be able to completely theoretically reproduce the status quo, which is determined by the past.
The Mod catchment is no white spot on the map. Neither are surveys of local institutions lacking. But on a closer look the few reports and scattered records disperse to a rather weak basis for a system analysis based on tomographical comprehension of the processes. The study at hand thus would like to question the absolute validity of a functional representation of the ecosystem in highly idealistic concepts. Yet it is beyond the scope for this work to develop general methodological principles for system understanding and modeling.
The challenge of dealing with uncertainty in parameter determination, process representation, model performance and scenario anticipation shall be addressed with a landscape approach to plausible system depiction through functional entities and a multi-perspective assessment of the needed parameters. General plausibility shall be of more importance than any best fit of discharge curves.

1.2 State of the Art

Currently integrated modeling is a popular tool to develop decision support systems based on scenarios assuming certain conditions the system might be faced with (McCarthy et al. 2001). A vast number of process oriented mechanistic hydrologic models, probabilistic system oriented models or rather descriptive conceptual models exist.
All models show a considerable degree of uncertainty in their process representation and regional adaptation. Most models are not even applicable to situations different to the setting they have been developed for. As Sivapalan puts it: *"Catchment hydrology is presently operating under an essentially reductionist paradigm, dominated by small-scale process theories. Yet, hydrology is full of examples of highly complex behavior, including strong nonlinearities and thresholds, and paradoxes that defy causal explanation through these small-scale process theories."* Although models might be able to represent several systems' compartments in defined boundary conditions, one still lacks knowledge about rules by which systems rearrange themselves regarding the interaction of their state variables (Beck 2005). Moreover the need of vast amounts of consistent quantitative data and a very vague integration of qualitative data trouble all physical models. Furthermore, calibrated models still do not employ all infor-

[1]Pierre-Simon Laplace 1749-1827: *We may regard the present state of the universe as the effect of its past and the cause of its future. An intellect which at a certain moment would know all forces that set nature in motion, and all positions of all items of which nature is composed, if this intellect were also vast enough to submit these data to analysis, it would embrace in a single formula the movements of the greatest bodies of the universe and those of the tiniest atom; for such an intellect nothing would be uncertain and the future just like the past would be present before its eyes.*

mation available (Seibert and McDonnell 2002) and fall in the trap of equifinality. Conceptual models in contrary mostly lack due integration into the specific problem setting, as they provide a rigid structure of highly aggregated and simplified processes.[2]

Aside the question of assumptions about the systems characteristics and employed abstractions, the very rigid nature of modeled scenarios itself does not match the way policies are realized and how people act in an environment with changing boundary conditions. Complexity of natural systems and the overwhelming number of possible futures have made the scenario approach to a widely accepted mean of impact assessment for policies and decision support. Scenario planning, however, does not lead to a substantial analysis of possible policies as it already anticipates a determined behavior of the system (Thompson 1997), (Samaniego and Bardossy 2006).

The description of the system will always be based on the little knowledge we have and which perhaps is not true. It will remain biased by our observations, which cannot take place at every instant in the space-time-domain. Still we are persisting with reality descriptions out of Laplacian determinism. But how shall this serve to find a robust strategy that succeeds under thousands of possible futures where parameters, structure and reality itself changes?

1.3 Research Goals

A set of methods shall be developed to gain comprehensive data from the scratch, simulate hydrology- and human-eco-system-interactions on field scale through land use and to stress test land use policies for decision support.

The study at hand can not entirely exhaust the restrictions of consolidative modeling[3], perceptual model uncertainty[4] or the restrictions of future anticipation in scenario approaches[5]. Yet it is aimed to practically realize an integrated simulation which serves as decision support tool and exploratory method application. A combined approach of in situ and remote data acquisition and preparation, sound physical hydrologic modeling including dynamic soil-water-plant-interactions and a rule and knowledge based agent for strategy analysis shall be realized. Hence this research needs to address several parallel tasks:

- set up a comprehensive data base of environmental and social-economic conditions and properties of the almost ungauged catchment using hard and soft data,

[2]For further discussion of the state of the art in hydrologic modeling see (e.g. Sivapalan 2005), (Sivapalan et al. 2003), (Wagener et al. 2003), (Bloeschl 2005), (Beven 2002), (Beven 2006), (Lempert et al. 2003)

[3]See (e.g. Bankes 1993), where Bankes discussed *consolidative modeling* as counterpart to *exploratory modeling*, where the former comprises most current models which base on a priori knowledge and theories which are somehow calibrated to synchronize model result and observation.

[4]See (e.g. Wagener and Gupta 2005), (Sivapalan 2005) or (Bloeschl 2005) for an overview about the discussion of model uncertainty in hydrology.

[5]See (Samaniego and Bardossy 2006) or (Lempert et al. 2003) for discussion about possible simulations of land use impacts and alternatives to scenario analysis.

- introduce a dynamic cropping routine into a hydrological model,
- develop a weather generator and an cropping decision agent for exploratory application of the combined model,
- establish a knowledge base for the agent on which its decisions are based on,
- apply the combined model for strategy analysis

1.4 Research Sketch

Figure 1.1 gives an overview about the research outline.

The medium sized Mod River catchment of about 500 km^2 was identified within the

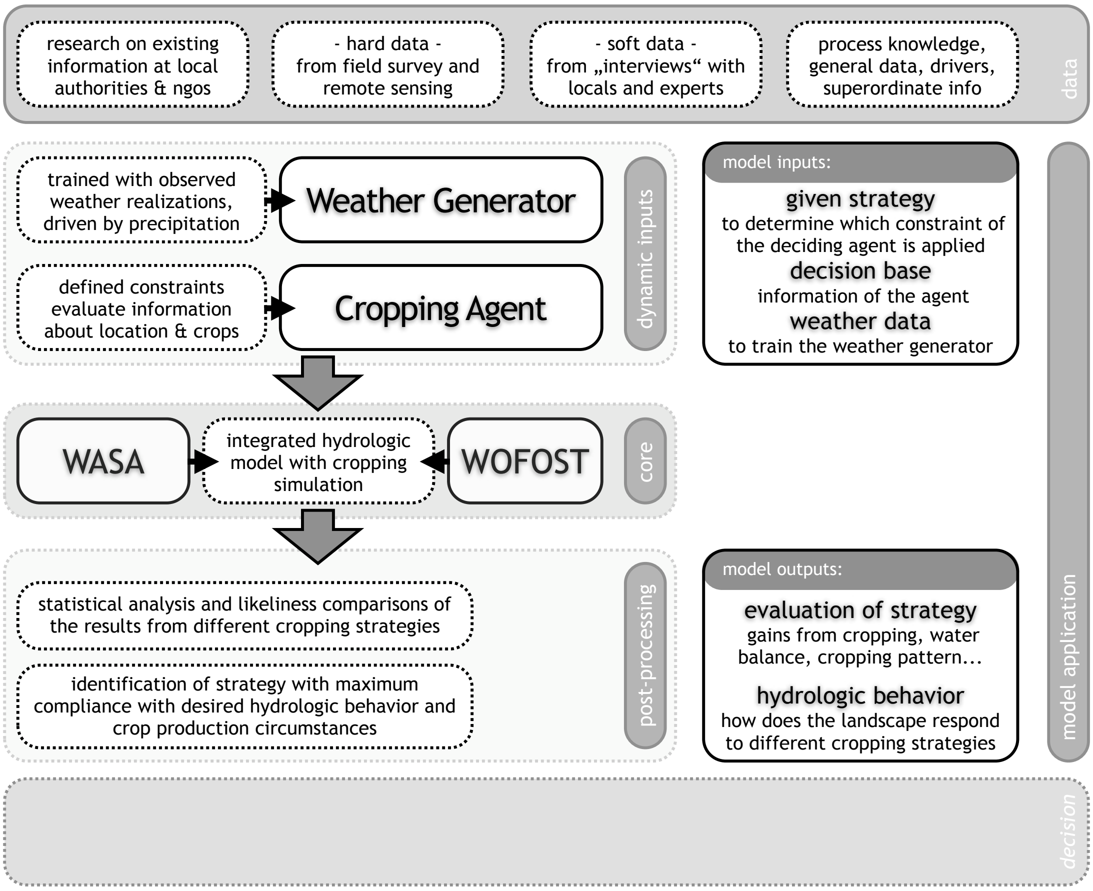


Figure 1.1: General Structure of the Approach of this Study

Anas basin (Singh 2004) in Central West India as study area, which provides the targeted setting of semi-arid climate and a high degree of human-ecosystem-interactions by land use (see chapter 2 and 2.2 for a detailed description of the setting).

As hydrologic model WASA (*Model of Water Availability in Semi-Arid Environments*) (Güntner 2002) was chosen (see chapter 7 for an introduction) because of

its ability for a detailed hydrologic process representation in semi-arid environments and the structural options of an integration of a soil-atmosphere-plant module. This latter module will be based on the theory of WOFOST (*World Food Studies*) and SWAP (*Soil-Water-Atmosphere-Plant*) (e.g. Bouman et al. 1996), (Dam et al. 1997) and (Boogaard et al. 1998) which are applications of the 'School of de Wit' crop growth simulations (see chapter 7.2 for an introduction).
WASA employs a catena based approach for which a relatively high amount of data needs to be prepared (see part II). As the model can be regarded as more or less classical mechanistic approach of a complex utilization of rather small scale process theories (compare e.g. Sivapalan 2005) the catchment will be described through a large set of parameters for all compartments like catenas' shape, drainage system, channel network, soil properties and its spatial distribution (which needs also to account for its heterogeneity), land cover and general topography and climate. Additionally data availability is rather scarce in terms of maps and studies about its compartments. As Singh argues: The Anas catchment can be regarded as ungauged.
The application of WASA in a remote and few-explored basin might sound contradictory in first place if one intends to set up the model based on a enormous number of samples and field experiments. The study at hand does not allow such detailed data gathering, as it is impossible to be accomplished for most of the earth's catchments, will not allow to fully dissolve restrictions set by heterogeneity and subsurface inconsistency and cannot overcome the Heisenberg uncertainty principle[6]. At the same time modeling without specific parameterization will fail to simulate and understand driving processes and local specifications. Hence an approach to identify a set of (internally and externally) plausible parameters from field and laboratory analysis, existing statistics and studies (*hard data*), remote sensing and information from local experiences and geomorphological and landscape analysis (*soft data*) will be presented here.

Based on this setting with static catena properties (although this might be arguable as we regard landscapes as evolving systems of biotic and abiotic compartments) in a second phase realizations of different cropping strategies will be simulated. As a single scenario cannot account for any likelihood of the millions of possible futures and remains restricted to anticipated bounds, the implementation of an agent (e.g. Wooldridge 2000, Russell and Norvig 2003) deciding on knowledge and policy specifications will be used to analyze the model's predictions for different weather scenarios (see section 8.2 for the weather generator description) and different agent's constraints (see section 8.1 for an overview of the agent).

[6]Werner Heisenberg 1901-1976: *"The more precisely the position is determined, the less precisely the momentum is known"* [Heisenberg 1927, Paper on uncertainty principle]

2 Jhabua: one example of a semi-arid rural human-ecosystem of the 21st century

This chapter shall introduce the project area as rather typical setting in the (tropical) rural world of the 21st century. It will be pointed out how natural dynamics and landscape development interact with the economic and social situation. Moreover it will be indicated what urgent tasks exist and persist and where system understanding is needed for decision support.

2.1 Location

The District of Jhabua is the most western part of Madhya Pradesh Province in central north-western India. Exemplarily the Mod River sub-catchment of the Anas River (Singh 2004), which itself is part of the Mahi Basin, has been chosen as project site for this analysis. It is situated in the Tahsils of Jhabua, Ranapur and Udaighar between 22°46' and 22°30' northern latitude and 74°20' and 74°35' eastern longitude. The location is also introduced in figure 2.1.
Following (Sharma et al. 2005) and (Tomar et al. 1995) the Mod catchment falls into the Western plateau and hills region of Madhya Pradesh and is further identified as subregion Jhabua hills by the National Agricultural Research Project (NARP), India. Its topography undulates between 500 and 300 meter altitude (above mean sea level).

2.1.1 Periphery in Many Aspects

Jhabua at the first glance is situated right at the major infrastructure between the centers of NW India. There are the national road from Ahmedabad to Bhopal and the railway line Delhi-Mumbai with a station in Meghnagar. The industrial area of Indore is only some 100 km away. Moreover a major gas pipeline is running through the district. If the development of a region depended on such infrastructural factors only, Jhabua should not be periphery. But it is in many aspects. In the given centralistic organization of India it still is remote to any of the developing centers of the country. While Madhya Pradesh alone is one of the most poor provinces, Jhabua without noticeable industries is considered to be one of the ten most desperate districts in India. 97% of the people depend on agriculture as primary source of subsistence (Agrawal 2006). As modern India's society is dominated by mainstream casts and principally the Brahmin Cast, Jhabua as central area of Bhil communities

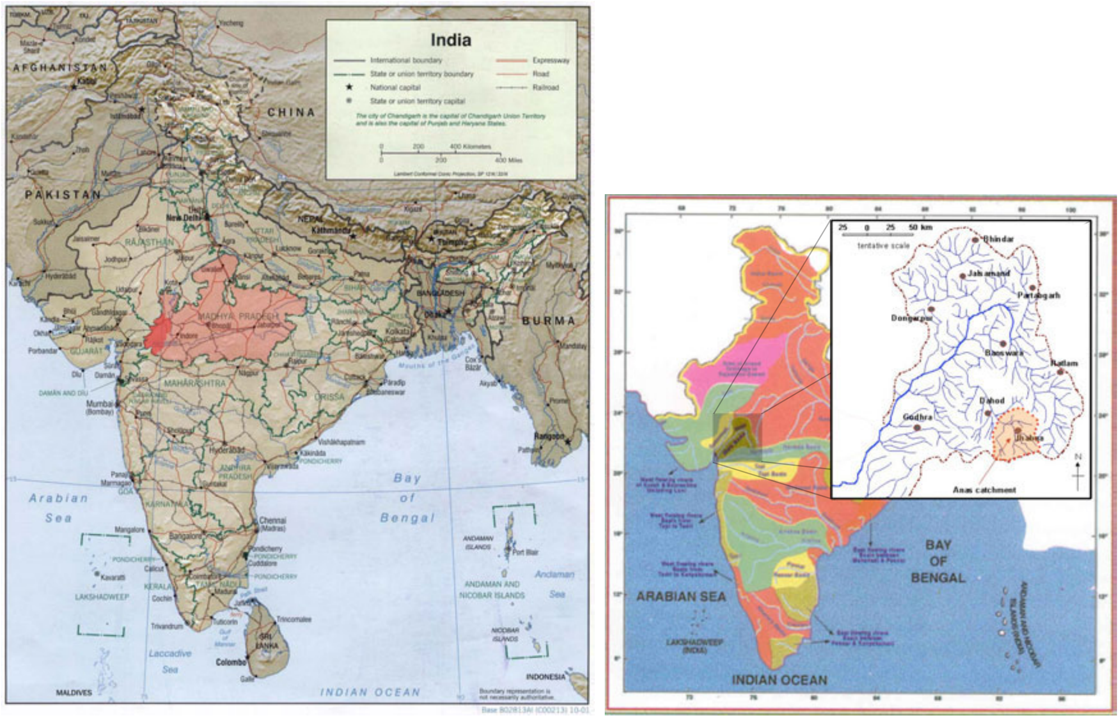


Figure 2.1: (a) Map of India, Location of Madhya Pradesh Province and Jhabua District and (b) Major River Basins of India with Mahi Basin and Anas Catchment, source: Ministry of Water Resources, (Singh 2004)

- one Adivasi group an thus Scheduled Tribe - has high barriers to take part in national transactions. Due to centuries of structural oppression during the colonial era and in current patriarchal and neoliberal tendencies still illiteracy is very high, families are large and the risk of diseases persists. Additionally the pressure for temporal or seasonal migration to financially sustain their living forces about 60% of the households to leave the region during dry season. Although lots of NGOs are actively working to help the communities' development since centuries, the problems still outbalance the small successes.

Fragmented Society

Following the theory of Senghaas (1974, 1979) (in Scholz 2004) of the Periphery Capitalism, the so called "backwardness" of Jhabua is not to be seen as prior to any upcoming development. Both, development and underdevelopment, are functional interrelated sides of the same process of the capitalistic system. Hence former external factors have initiated an internally operative system of insufficiencies and perpetuating social structures. Even more applicable appears the theory of Fragmenting Development (e.g. Scholz 2004) to analyze the current status and development perspectives of the region. It does allow to approach a geographic region not as homogenous "container" but as network of agents and institutions. Global fragmentation in times of economical globalization is unsurprising. Local fragmentation continues to smaller scale where the same structures persist: A facade of offices and mansions of the very few, mostly external agents or managers (compare Albert 2004) suggests worth and development while the vast majority of the population forms a work force or - even worse and much more prevailing here - the underclass or working poor. Kronauer (1996) (in Scholz 2004). These people are excluded from the mainstream society because they are not needed as laborers, they have no relevance as consumers and their products are not valued.

Economic Dependencies

The people of Jhabua - regardless if living in the towns or villages - try to maneuver to take part as work force and even migrate into rather remote centers where they become exploitable, unskilled workers dumping the labor market due to their desperate situation in extreme poverty.
To come back to the impact on the local land use practices and development perspectives one has to realize that labor intensive agricultural work for subsistence today does not reward any surplus which is needed in the capitalistic economics. Hence farmers need to grow crops and products to be sold on regional and supraregional markets. But this implies the use of hybrid seeds and cash crops, an increase in the use of fertilizers and other agro-chemicals, an increase in the need for irrigation not to lose the investment of seeds and chemicals, intensified cultivation and higher expenses for market access. Since water is scarce, soils are meager and regional market gains are low or even below production costs, the "miracle of the green revolution" did not help the needs of the poor.
Nearly every household is unable to repay loans for seeds and agro-chemicals (which is also due to extreme interest rates). Examples of micro-credits and self-help-groups show positive impulses but cannot overcome the structural dependencies.

Patriarchy

As introduced, internal social structures are responsible for the miserable situation. The focus of an economics dominated society obviously lies on markets; but the role of hierarchies and dependencies in the smallest units of society might have much more relevance. In the framework of hard field labor, poor health care and health awareness, male dominated migration and a transition between traditional and "modern" living a strong patriarchy in decisions about family concerns, the ignorance of women-specific health necessities at home and in hospitals and general prude in all concerns of sexuality and fertility persists (Pande 2003). Without going into detail here and referring to the cited book it shall be pointed out, that decisions about rural development cannot neglect the strong impact of such fundamental and resolute structures. Many assays point to overpopulation as reason for environmental and social distress ignoring that this is not reason but symptom. Furthermore health care and even anti-HIV campaigns disregard the deprived status of 50% of the population. The study at hand will not be able to propose profound strategies, but it urges for an integration of such gender-related aspects in any development considerations.

2.2 Natural Setting

2.2.1 Climate

The Mod catchment falls into the agroclimatic zone of Jhabua Hills which is part of the western plateau and hills region. It is classified as hot semi-arid ecoregion. It receives between 350 and 1600 mm of rain per year, which almost entirely falls in the monsoon season between june and september. The gross water balance is negative with a water deficit of 800 to 1200 mm/a and above. The agricultural growing period is limited to 90 to 150 days. The prevailing soil moisture regime is Ustic and the soil temperature is hyperthermic (Tomar et al. 1995). The region is marked as drought prone. As overview the climate diagrams of Indore and Udaipur, which are the closest long-term weather stations are given in figure 2.2.

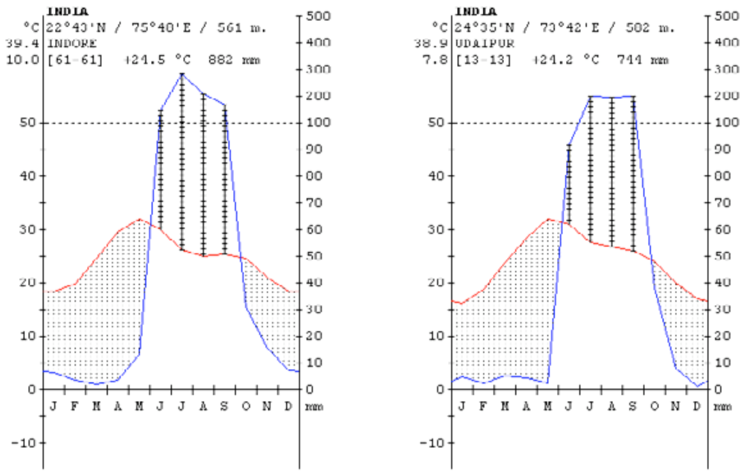


Figure 2.2: Climate Diagrams (a) Indore, Madhya Pradesh, (b) Udaipur, Rajasthan, India; Source: S.Rivas-Martinez, Phytosociological Research Center, Spain

One year is divided into four seasons (H.K. Jain et al. 1993): the south-west-monsoon season from june to september, which is considered as natural growth period; the post-monsoon season as clear wether spell as high pressure follows the retreating monsoon lasting from october to december; the winter season which is characterized by low humidity and low temperatures, extra-tropical low-pressure systems usually bring some small yet important winter rains; the summer season from march to may when temperature rises and pressure decreases over the Indian subcontinent, heavy dust storms are typical and natural vegetation is dormant.
There are two cropping seasons though: *kharif*, which starts with the monsoon onset and last until the maturity of most crops until december; and *rabi*, which is the second cropping period until the beginning of summer.

2.2.2 Monsoon over India and Madhya Pradesh

The period of *kharif* season from June to September is the summer cropping spell during which most of the subcontinent receives 85% of its annual rainfall (Singh 2001). Certainly in semi-arid Jhabua but all over India the annual crop production in *kharif* and *rabi* (winter) season are strongly correlated to the summer monsoon rainfall (Krishna Kumar et al. 2004). At the same time the considerable year to year variability of the monsoon is major field of interest of the meteorological community and part of the Indian life and cultures (e.g. Frater 1990). Singh explains the daily spatial and temporal rainfall variation to depend on the intensity of the monsoon current which itself is dependent upon a complex system of depressions in the Bay, oscillation of the monsoon trough, movement of the westerly systems across the Himalayas and local topography and boundary layer dynamics (Keshavamurty and Rao 1992). Plenty of studies deal with monsoon prediction and even successfully prove relationship to the El Niño Southern Oscillation (ENSO) (Shukla and Mooley, 1987 in Zehe et al. 2006), (Rahmstorf 2002) and to anomalies of the sea surface temperature (Gowarikar et al., 1991 in Zehe et al. 2006).

Figure 2.3 gives a first picture of the situation in different monsoon occurrences over India based on observations from 68 stations between 1940 and 1980 in (Singh 2001). Despite the low local accuracy on this scale, the influence of the Thar Desert drought stretching south in dry years and the proximity to the west coast with precipitation exceeding 200 cm/a has to be pointed out.

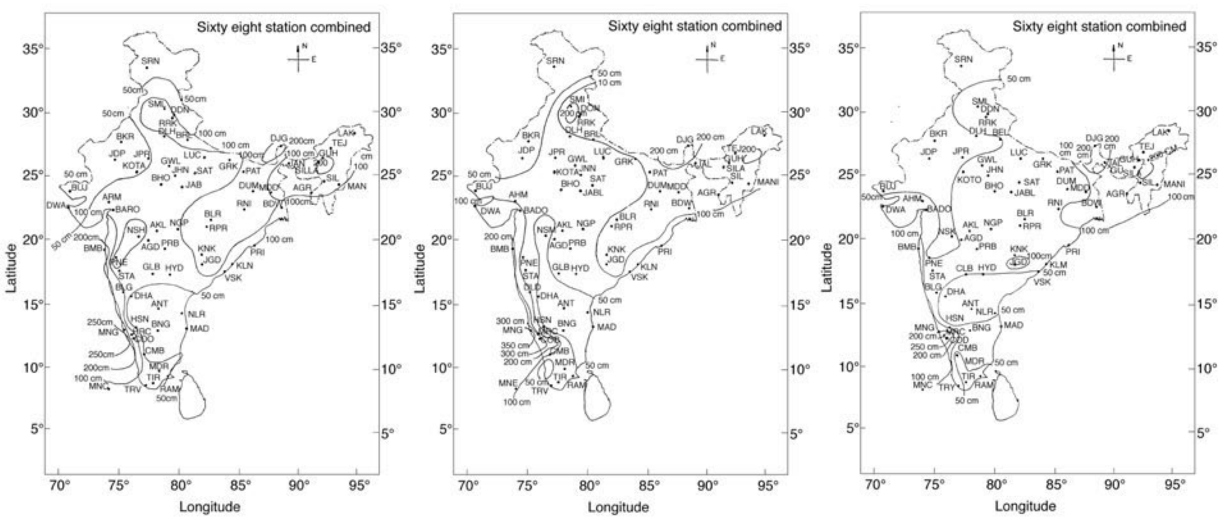


Figure 2.3: Average Rainfall [cm] Isohyets of India in (a) normal, (b) flood, (c) drought years. Taken from (Singh 2001)

Precipitation Variability and Auto-correlation

Monsoon rainfall varies on all time scales. An embracing overview is given in (Keshavamurty and Rao 1992). One difficulty in addressing monsoon variability is the vast size of the country. It is not uncommon, that one part is suffering from droughts while other parts are flooded. Hence indices like Monsoon Excess Index (MEI) and Coefficient of Variation of Monsoon (CVM) have been applied. Still all indices prove high variability and rather random distributions. E.g. (Mooley et al. 1982) calculate an interannual autocorrelation coefficient for the all Indian MEI for the period 1871 - 1978 as -0.058 and a coefficient of variation of 82.2%. Figure 2.4 taken from (Keshavamurty and Rao 1992) shows the interannual variability as $CVM = 100\frac{\dot{s_0}}{m}$. It shall be acknowledged that the highest year to year variability is in north-west India - in Rajasthan, Gujarat and adjoining regions.

E.g. (Singh 2004) describes typically 30 to 50 rainfall events to be responsible for

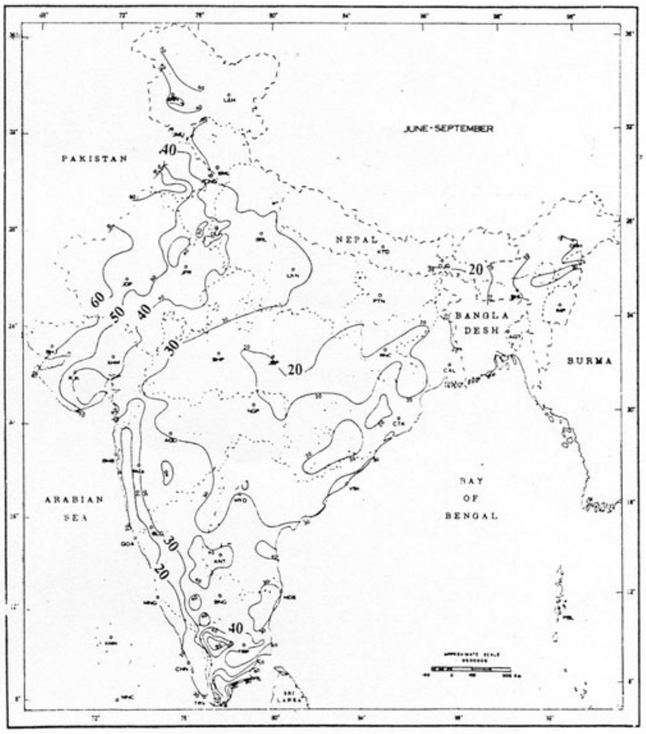


Figure 2.4: Coefficient of variation of interannual monsoon rainfall after India Meteorological Department. Taken from (Keshavamurty and Rao 1992)

almost 90% of the annual rain. (Zehe et al. 2006) refer to (Webster and Hoyos, 2004) to characterize the monsoon as sequence of rainy periods (monsoon bursts) and dry periods (monsoon breaks) of 10-20 days duration, while an average monsoon period here lasts 122 days (H.K. Jain et al. 1993). For a more detailed understanding of the 30-50 day oscillation of east-west overturnings in the equatorial region, the eastward propagation there and the northward propagation in the Indian region please see (Keshavamurty and Rao 1992).

For a more local scale figure 2.5 shows annual precipitation at three stations in and near the Mod Catchment. It receives a mean annual rainfall of 750 mm fluctuating between 350 and 1300 mm. An analysis of weekly distribution of rainfall in (H.K. Jain et al. 1993) points out, that erratic rainfalls are prevalent reason for drought conditions while an even distribution of rains through the monsoon period would result in

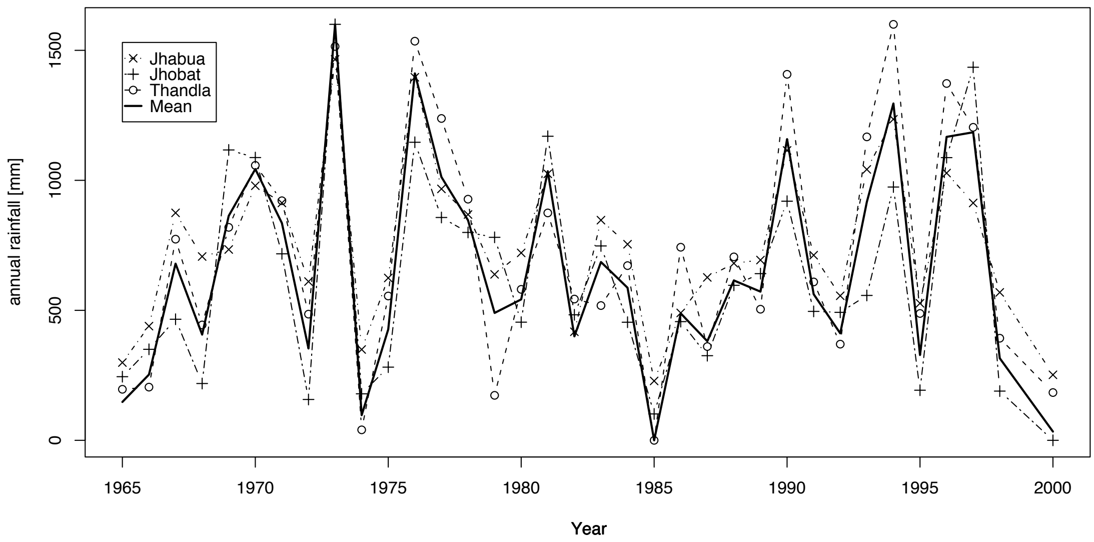


Figure 2.5: Annual Rainfall of the Tahsils Jhabua, Thandla and Jobat 1965 - 2000; Data from (H.K. Jain et al. 1993) and (Singh 2004)

rich crop production. Thus although the amount of precipitation might exceed the annual average, droughts with massive impact on the lives of the communities can occur. For the tahsils mentioned in figure 2.5 droughts were suffered from between 1974 and 1991, in Jhabua during 1974, 1979, 1982, 1984, 1985, 1986, 1987 and 1991; in Jhobat 1974, 1975, 1979, 1984, 1985, 1986, 1987 and 1991; and in Thandla in all years but 1976, 1977, 1978, 1981, 1983, 1988 and 1990. Thus out of 18 years in Jhabua and Jhobat only 10 and in Thandla only during 7 years "normal" or sufficient rainfall was observed.

2.2.3 Geology

The geology of India is highly variable and witness of various geologic eras. Figure 2.6 gives an overview about the situation of the subcontinent. To point out the location of the Mod Catchment one finds the Deccan Trap, covering all central west India, Precambrian formations of the Aravalli and Cretaceous sedimentary rocks. This turbulent situation imposes remarkable heterogeneity to the catchment.

The Deccan Trap

Due to the location of the Mod catchment at the boundary of the three provinces Madhya Pradesh, Gujarat and Rajasthan, and due to the centralistic hierarchy in the Indian administration, many descriptions of the geology of Jhabua focus mainly the Deccan Trap - or locally Malwa Plateau - as prevalent formation in western Madhya Pradesh and Maharashtra. The Deccan Trap was formed some 65 million years ago with the breakup of India from the Seychelles microcontinent as mighty basaltic

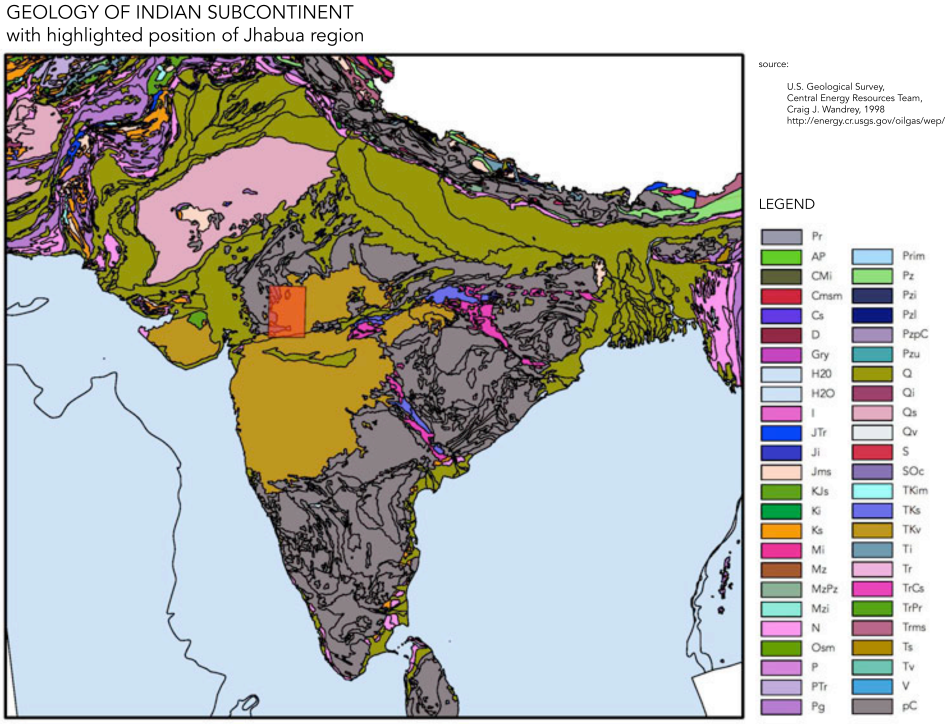


Figure 2.6: Geology of India with highlighted position of Jhabua District, source: U.S. Geological Survey, 1998

plume (e.g. Mahoney, 1988 in Sheth 2005). It is a formation of Pahoehoe, which is basaltic lava with relatively high and smooth viscosity. The flow typically advances as a series of small lobes and toes that continually break out from a cooled crust. Therefore the surface texture varies widely [Definitions USGS Volcano Hazards Program, *http://volcanoes.usgs.gov/Products/Pglossary/*]. E.g. Sheth discusses the role of eclogite as recycled oceanic crust preseved within the plume formation. He argues that rather high pressure has been force than high temperature, which would have resulted in a much more homogenous structure and cannot explain the richness in iron. The plume can reach a thickness of 1000 meters, while in northern Jhabua district the trap consists of a maximum of 165 m thick pile of seven flows. Here its base can be found at about 360 m (aMSL) (GSI 1976). Map 2.6 presents Jhabua on the edge of the Malwa Plateau - which actually forms the eastern watershed of the Anas catchment - and fringes and several singular hills of pahoehoe. In the Mod catchment the Deccan Trap extensions define the hills and the southern watershed.
Regarding pedogenesis, erosion and deep percolation or ground water recharge, pahoehoe is rather ambivalent. (Tomar et al. 1996) and (Sharma et al. 2005) introduce the deep black soils of the Jhabua Hills to origin from volcanic ash and point out, that the dark color is not a sign of elevated content of humus. During the fieldwork sites with highly weathered bedrock, decomposing easily in thin layers and showing intricate formations of lava, ash and metamorphic inclusions could be found very often. Yet also plateaus of shield-like basalts and rather resistant pahoehoe are not

uncommon. Due to the admixed form and due to disruption during the cooling of the lava cracks might be very prominent. In contrast the bedding in several layers does not speak for deep cracks and suggest a more confined groundwater.

The Aravalli Supergroup

The Aravalli generally is represented by a thick sequence of paleoproterozoic sediments with interlayed basic volcanites, showing imprints of complex deformation and change of the depositional environment (C. Chakrabarti et al. 2004). It overlies banded gneissic complexes and shows profound erosional unconformity (Heron, 1936 in C. Chakrabarti et al. 2004). Towards southeast - thus in Jhabua - the Aravalli Supergroup is covered either by the Deccan Trap or cretaceous sand- and limestones. Map 3.2 unveils the large area of feldspar-quartzite formations in the north-eastern part of the catchment. During the field work at virtually any place of the catchment these formations could be found - either as uncovered bedrock or as rock base (see chapter 3). Additionally other phyllites and granites could be found rather randomly. The proposed phyllite base of the catchment suggests a rather low permeability for ground water recharge and could mean, that the ground water system is inconsistent with the catchment's boundary. This is of further importance knowing that wells commonly reach down 70 meters or more from surface.

Cretaceous Sediments

Additional to the complex system of paleoproterozoic sediments and paleocene pahoehoe some minor occurrence of cretaceous lime- and sandstones exists. It is dated as upper cretaceous and hence with relative proximity to the paleocene lava flows. Although the mapped nodular limestones and nimar sandstones could not be further identified during the field survey, again there were several founds of both rocks in the western and southern pits and outcrops as dispersed gravel and parent material of pedogenesis. In a well in Chagola also a relatively mighty band of very soft and porous red sandstone could be found suggesting few compression and the baking of the young sand stone by the lava heat and the oxidation of all iron to give it the very red color (see appendix 12.1). In Kermal limestone could be found as bedrock at 70 cm. While limestone in Kermal is consistent with the geological map of the GSI (Geological Survey of India 1988) to show this geology, the Chagola sandstone once more points out the high diversity and many traces of the catchment's formation history.

2.2.4 Geohydrology

Map 3.2 introduces the geohydrologic situation of Jhabua. In (H.K. Jain et al. 1993) a survey of the Ground Water Department of Madhya Pradesh is cited but cannot be downscaled to a single catchment. The total annual ground water recharge for Jhabua district is given there as 415.21 Mm^3. With an area of 6,757 km^2 this means 61.4 mm recharge per square meter. In the same report block-wise data about water

Figure 2.7: Rocks in the Mod catchment; (a) on the plateau near Mod river at Matasula, (b) rocks as outcrops from pahoehoe near Chagola, (c) feldspar-quartzite near Uberao

resources and ground water irrigated area is given in table 2.1. Further ground water data is to be found in appendix 12.2.

Table 2.1: Block-wise annual ground water resources and ground water irrigated area in Blocks of Jhabua district during 1986; whole district data of 1990; after Irrigation Department, Govt. of Madhya Pradesh, 1990 (in H.K. Jain et al. 1993), Total Block Area after Statistical Year Book Jhabua District 1991

Block-wise annual ground water ressources (Mm^3) and irrigated area (ha)							
Block	recharge	net draft	GW bal.	no. wells	irr. area	tot. block area	recharge mm
Jhabua	26.23	1.36	24.87	490	102	43700	60.0
Ranapur	31.76	2.66	29.10	957	80	40000	79.4
Udaighar	41.20	2.50	38.70	894	189	36800	111.9
J. District	415.2	116.7	298.5	NaN	NaN	6,757km2	61.4

Comparing this data to the mean annual precipitation of 750 mm, in 1986 only 668 mm, almost 10% of the precipitation are assumed to attain to groundwater recharge. Under humid conditions (e.g. Zehe et al. 2001) some 30% of the precipitation have been determined as ground water recharge, without erratic rain bursts and completely parched top soil. At the same time during the field work dried and salted pump wells have been found at many places. None of the farmers with irrigation facilities can irrigate all the dry season - sometimes not even the whole rabi season. But the officials still speak of large development potential of the use of ground water which is already taken from depth down to 70 or more meters. Hence the study at hand needs to address the plausibility of the assumption of a 10% ground water recharge (see section 9.2).

Additionally insightful are the fluctuations in pre- and post-monsoon ground water levels at several wells of the basin. The State Water Data Centre Bhopal observed the pre- and post-monsoon water levels in several wells (H.K. Jain et al. 1993) (see appendix 12.3). It can be noticed, that the water table in the wells have considerable fluctuations of up to some eight meters (Kundanpur, Ranapur Block, 1986). While the water table reaction is very different from well to well even within a block also no proportional reaction to precipitation can be established. In (H.K. Jain et al. 1993) a general decrease in pre-monsoon water tables between 1974 to 1991 is mentioned.

2.2.5 Forests

Jhabua today, even barren land with the character of some desert dominates, is widely known as forestal area. Rock-exposed hillocks and extensive erosion sites prevail the villages, where people still report of inaccessible places and roaming tigers (see fig.2.8). The *Jhabua State Gazetteer* 1908 (in H.K. Jain et al. 1993) recorded: *"The state consists of hilly forest-clad tract comprising numerous ranges rising to about 1800 feet above sea level and covered for the part with thick jungle of small but valuable timber trees, chiefly, teak and blackwood. Other important species like mango, mahua, aaonla, bahera, babool, dhawda, imli, khair and palas also occur."*
Between 1963 and 1993 alone, dense forest cover declined from 33.3% to 4.9% of its geographic area (Agarwal and Narain 1999). The reason lies in a rapid change in the traditional way of living of the Bhil communities, the entry of concessioners and timber merchants after the fall of the British Raj, and a shift in livelihood dependencies. While the Bhil subsistence relied on the forest ecosystem, a shift of ownership of the forests and a pressure arising from growing population plus the "modernization" of agriculture in India's Green Revolution pushed for forest degradation (Foster et al. 2002).
The Mod-River catchment has almost no registered forested patches. The few existing are defined as scrub or degraded forests and are hardly more than single trees and of meager size. This could also be proven by satellite images in chapter 5. Deeply connected with deforestation is desertification and a drastic shift in the whole water-, energy- and nutrient-household.

Figure 2.8: (a) Dense Forests as probable native vegetation (b) Current Situation within Mod Catchment

2.2.6 Hysteresis of the Soil-Water-Atmosphere-Plant-System

Reports from the local people and the statistical records of agricultural productivity show the impact of the monsoon also for rabi season. Despite the facts that potential evapotranspiration in Jhabua is about 2000 mm/a and almost all precipitation takes place between june and september, still the amount of the monsoon rainfall highly influences the catchment's water content in rabi season. During the field work most clayey soils showed considerable moisture below the parched top soil, which is accessible to deep routed plants.

An analysis of satellite images could shed light into this behavior of the catchment but fall beyond the scope of this project, mainly because only one Landsat ETM+ image of this period has been openly accessible (see also chapter 5). For the modeling of the semi-arid basin this hysteresis is a quite important property to judge about the plausibility of the modeled dynamics. A dynamic graphical interpretation of the modeled soil moisture will also address this aspect (see appendix 12.11)

Part II

Analysis and Data Acquisition from the Scratch

As already introduced in chapter 1 science and particular natural science traditionally depends on data. Although surpassing the Laplacian determinism, there is no modeling without data about the system's setting and dynamics.
As Sivapalan et al. [2003] describe: "*A general hydrological prediction system contains three components: (a) a model that describes the key processes of interest, (b) a set of parameters that represent those landscape properties that govern critical processes, and (c) appropriate meteorological inputs (where needed) that drive the basin response. Each of these three components of the prediction system, is either not known at all, or at best known imperfectly, due to the inherent multi-scale space-time heterogeneity of the hydrological system, especially in ungauged basins.*" At the same time the nature of hydrologic modeling is of perceptual model uncertainty, parameter estimation uncertainty and the structural uncertainty of the model itself (e.g. Wagener and Gupta 2005).
Hence this research needs to address the question about what data might best represent the catchment's behavior in reality, what data can be gathered with reasonable effort and what data is needed by the utilized models.
In regard of very scarce data, limited knowledge about the processes and the urgent obligation to save the potentials of the landscape for a sustainable development meeting the people's needs the topic of data quality, uncertainty and what can be represented by available data becomes even more compelling. At the one hand all existing knowledge about the Mod catchment is very much dispersed in administrative offices and concerned institutions. Sources of the data can often not be traced back. No common convention about spatial entities the data refers to exists. Even data of the same kind, e.g. like weather records, have no consistent method of acquisition. On the other hand there actually is lots of information about many aspects to describe the system. People face the phenomena of droughts and erosion ever-since. Administrations and NGOs are recording data over centuries. But the data is not easily translatable into physical or probabilistic functions.

This part will present the conducted field survey, where major concern was given to ascertain the landscape's characteristics and to identify leading soil formations and their properties. This is supplemented by a laboratory analysis of samples from the catchment. A second part will unveil remote sensing as analytical method to transpose single point investigations into spatially continuous and explicit information about the catchment's properties and patterns. Finally there is additionally acquired information presented which mainly is used to accomplish a set of highly plausible data in the face of very limited sample populations and arguable data quality.
It shall be pointed out that this methodical alliance of several means and beliefs of data acquisition is not only an approach to bridge the gap between the "data-hungry" hydrologic model WASA (see chapter 7) and the almost "unexplored" Mod catchment. It shall also present a possible framework on which new techniques[1] of catchment behavior analysis could take place.

[1] As it is presented in several publications of the PUB initiative of IAHS members (e.g. Sivapalan et al. 2003), (Beven 2002), (Lempert et al. 2003) or see *http://www.pub.iwmi.org/*

3 Field Survey

Due to absence of detailed pedo-hydrologic data the gathering of information about soil properties like infiltrability, layering, depth, grain size distribution etc. was considered to be key to a sound modeling approach. It soon became obvious, that a detailed sampling comprising all the catchment is not achievable. Thus it was decided to identify leading soils and landscape formations and to determine properties of those as preliminary study which is to be integrated in a remote sensing analysis.

3.1 Input Data for the Models

3.1.1 WASA

As introduced, there is no modeling without data. To apply WASA a rather large set of specific data about all catenas, the hydrologic properties of the soils, the channels and land cover has to be provided. For a more detailed introduction of WASA see chapter 7 or (Güntner 2002). The preprocessing employed the LUMP-algorithm (*Landscape Unit Mapping Program*) (Francke et al. 2007) for semi-automted delineating of representative hillslopes (or catenas) based on topography, soil formations and land cover patterns (see section 7.1.3 or (Francke et al. 2007) for details). Hence there is a requirement for distinguishable classification of soils and (potential) land cover in order to identify entities of quasi-uniform hydrological behavior and their distribution in the catchment plus a plausible physical parameterization of these entities for a process description on the appropriate scale.

The following descriptive units are to be assigned:

- Subbasin (SUB)
  - area
  - downstream subbasin (drains to)
  - stream order
  - lag time
  - retention
- Landscape Unit (LU)
  - kf (hydraulic conductivity) of bedrock
  - mean slope and length of LU class
  - mean maximal depth of soil on LU
  - maximal depth of alluvial horizon in LU
  - depth of river bed below LU outlet edge
- Terrain Component (TC)

  - slope
  - fraction with rocky surface

- Soil-Vegetation-Component (SVC)
  - soil and vegetation class ID
  - Manning roughness coefficient
  - MUSLE coefficient (optional)

- Vegetation Class
  - stomatal resistance
  - minimum/maximum suction
  - height of vegetation (at four instances in a year)
  - rooting depth, LAI, albedo (at four instances in a year)
  - MUSLE coefficient (optional)
  - Manning roughness coefficient (optional)

- Soil Class
  - bedrock/groundwater flag
  - organic matter
  - grain size distribution

- Horizon (in a soil class)
  - order in soil class
  - depth
  - residual vol. water content
  - theta at permanent wilting point
  - theta at field capacity
  - effective field capacity
  - theta at saturation
  - ks (hydraulic conductivity at saturation)
  - pore-size-index
  - suction
  - bubble pressure

- Meteorological Data in daily time step
  - mean temperature
  - precipitation
  - air humidity
  - solar radiation

For a more process oriented understanding of this paramertization it shall be referred to section 7.1.2 and figure 7.1, where in brief the modeling concepts are described. It shall also be pointed out, that the alternations of the model (see section 7.2) required additional meteorological data specifications and also shifted the lumped definitions of each SVC towards uniquely identified entities (see section 7.2.3).
Although the Mod catchment is considered as ungauged basin, a short series of discharge data exists to validate the model's performance.

3.1.2 WOFOST

As WOFOST or more generally the de Wit - algorithm (see section 7.2) was only used for a relocation of the crop development simulation approach the required data is crop specifically stored in some look up tables provided with SWAP and WOFOST (Kroes and van Dam 2003), (Boogaard et al. 1998) for pigeonpea, millet, sunflower, sorghum, chickpea, maize, cotton, groundnut, sugarcane, soybean, casawa, wheat and grass[1].
Yet there is the requirement to assign a certain crop or land cover to each SVC, if this algorithm is applied. Hence statistics about cropping patterns will be transfered into a look-up table about potential land use and crop-soil-suitability in the first phase of coupled modeling (see section 7.2.3) and harvest statistics will be used for validation of the model's performance.

3.1.3 Agent

The agent approach as simple form of artificial intelligence also requires information which is specific for the location. In contrast to the needs of WASA, this data is rather qualitative to enable decisions about preferences and credible realizations. For a detailed presentation refer to section 8.1.

3.2 Existing Data

Concerning the physical properties of the landscape in the Mod catchment there is data existing. The Geological Survey of India published a set of maps during the 80's. Namely these are a topographic map 1:50,000; a geological map 1:350,000; geohydrological, geomorphological and land use map 1:1,000,000; and a soil, forest and geohydrological map 1:350,000. Given the catchment of about 500 sqkm with high variability in all properties, these maps might mainly be some kind of starting point but no reliable basis of a physical model. Additionally there could several sets of statistical data be acquired, which have been provided by the local authorities. A detailed presentation is given in chapter 6. A major problem with these is, that all refer to administrative units like tahsils, blocks or villages but there is no explicit information about these entities given. Even the statistical year books have fluctuating figures about the areas. The tahsil maps name the villages and show the borders but also have considerable ambiguity.

3.3 Sampling Design

Based on maps of topography, geology and soils (Geological Survey of India 1988) and (Singh 2004) sampling sites have been identified to be able to a) verify this

[1]The files are disclosed in the WASA source code and bear meta information in each header. All files had to be ported to a readable format for Fortran F90. Some were adjusted to local specifications and is commented inside the code. A copy is provided with this report on file.

mapped data, b) describe characteristic slopes and toposequences[2], c) represent the catchment's diversity and returning structures and d) to cover all major formations. The following supplemental maps shall illustrate the identification process and the catchment's properties in Map 3.1 and 3.2.

3.3.1 Identification of Transects

It was decided not to use a random or a weighted-random sampling design. A random sampling design could consider biases like topography or any identified classes, but because of high variability of geology, soil, land use and degree of erosion etc. the needed amount of samples would exceed any reasonable number. Additionally there is no "certainty" about the landscape's structures and patterns before. The organization of a landscape is not a random process, thus a random sampling design could prove to be biased afterwards and is no warranty for impartial data.
Hence it is assumed, that a) topography does represent most of the bias of the landscape, b) that the needed data has to be representative for "common" catenas, c) sampling points are not independent (within a certain distance) and thus could represent sequences of the landscape and d) all qualitative maps might be of questionable accuracy. An intersection of topography, soil, geology and landuse resulted in identification of high diversity between Kanjawani and Ranapur and around Udaigarh. To cover most of the proposed soil classes from the given map, mainly five transects have been appointed (see Topographic Map 3.1).

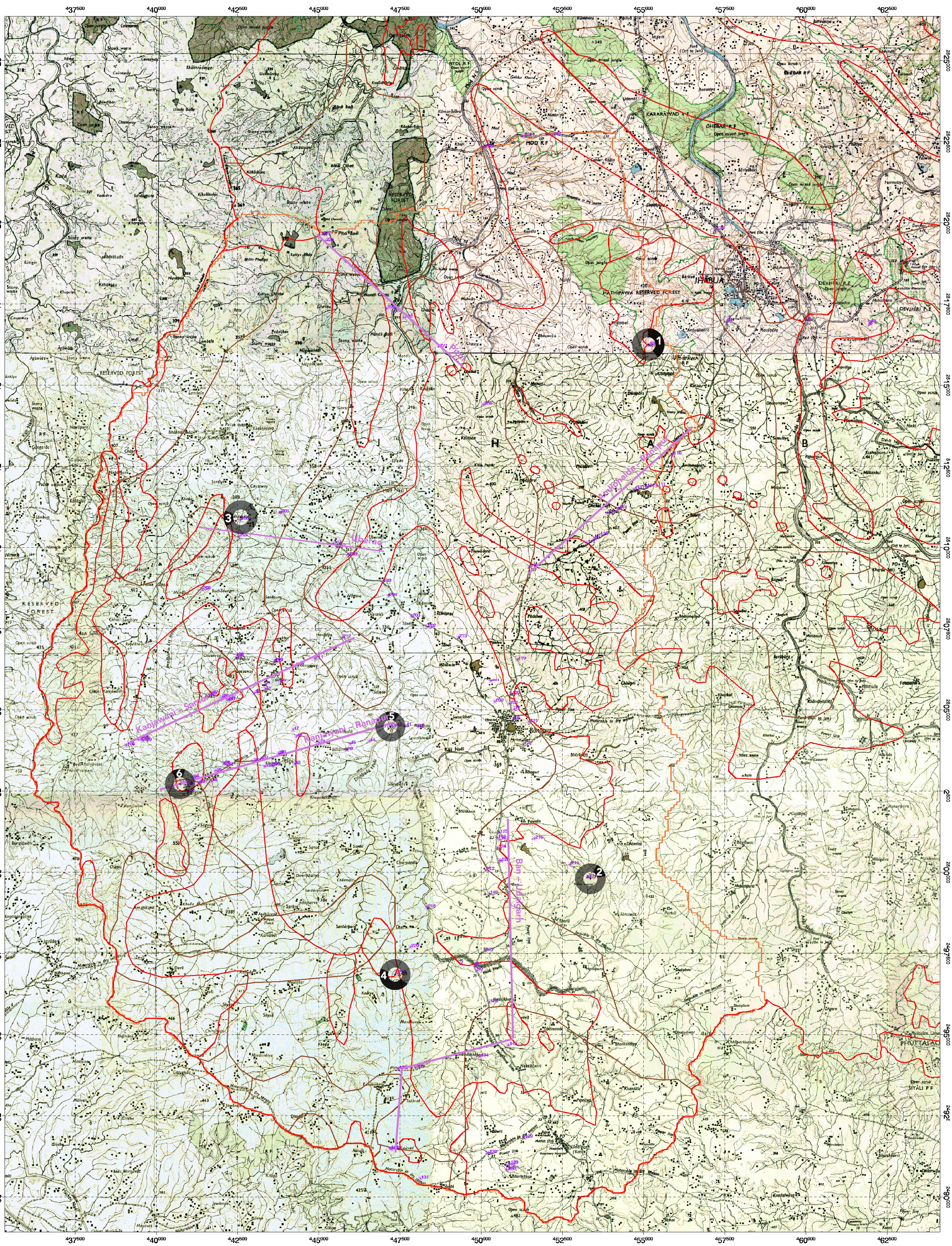
Kanjawani-Ranapur/Samoi Cutting through the central part of the catchment, comprising the main riverbed of the Mod river and its side-arm Bhamchi river and encompassing most of the topographic formations the two transects have been the main emphasis during the field work. In order to question the correlation of sampling points not only in direction of the slope but also transverse to it, two transects have been proposed in medium distance. They have been found representative for sequences of surface and subsurface conditions and land use practices in the basin. (See also figure 5.5 and appandix 12.1 for impressions from the field.)

Ban-Udaigarh The southern part of the catchment generally appears a little less heterogeneous. Rather large plateaus and slopes undulate up to the gentle watershed. The samples on this "transect" shall represent the conditions found in the southern part.

Uberao This stretch is somehow intermediate the central plateaus and the northern hills. It is dominated by highly skelettal soils and outcrops of feldspar-quartzite formations. Agricultural land use is very much restricted to the few arable fields and kharif season.

[2] As the study employs a catena based approach, a toposequence is understood as sequence of topologic entities defined by soil, slope, relative position etc.

Topographic Map Mod Catchment, Jhabua District, Madhya Pradesh, India
including soil classes, geology classes and sampling/observation points



Catchment's Boundary as Orange Line.
Soil Classes as Brown Boundaries.
Geology Classes as Red Lines.
Sampling/Observation Points as Purple Asterix.

0 1 2 3 4 Miles
0 1 2 3 4 5 6 7 Km

Map Scale 1:130,000

Based on Survey of India 1978, Topographic Map 1:50,000
Geology and Soil Map based on A.K. Singh, 2002

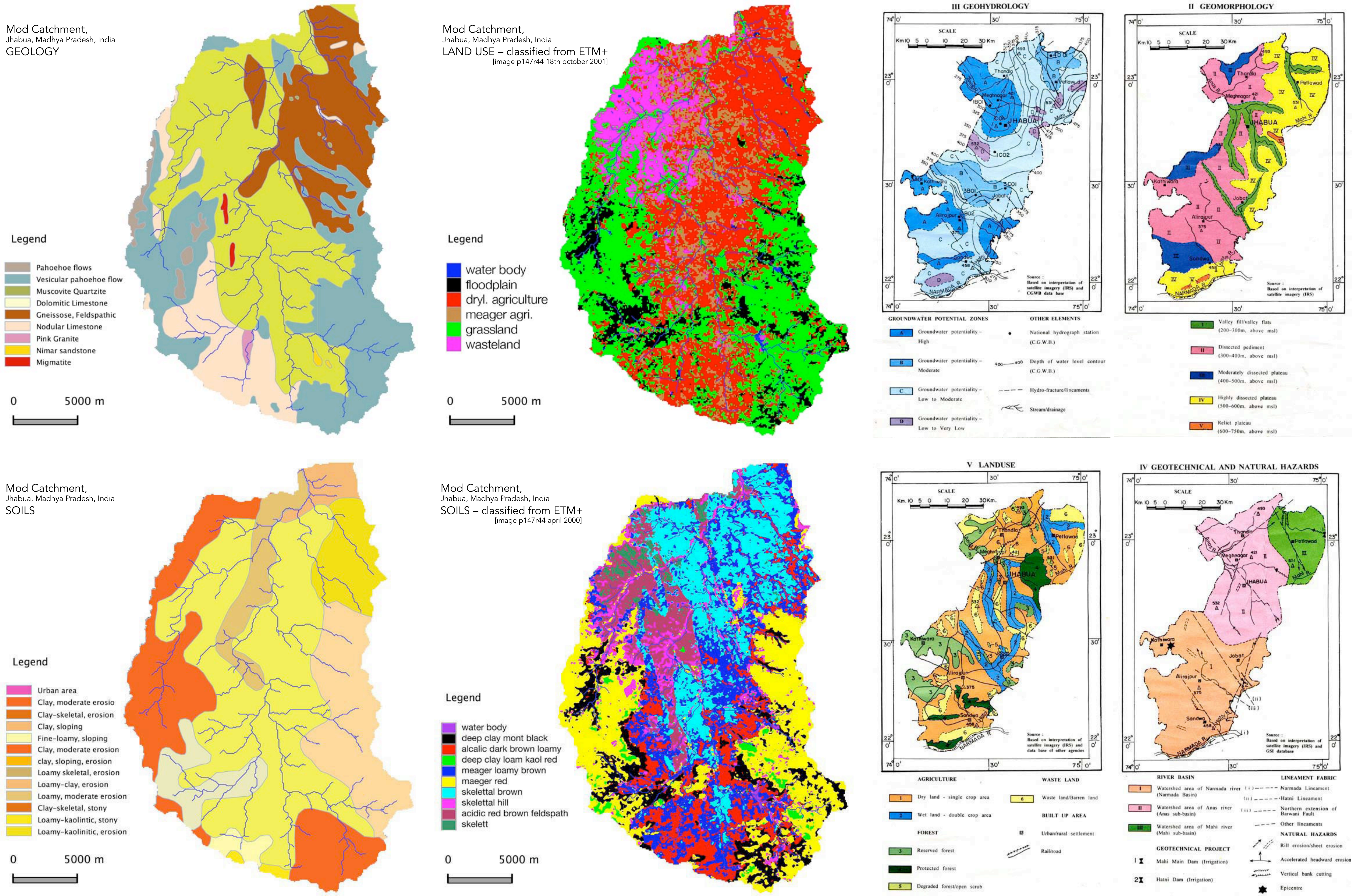


Figure 3.2: Thematic Maps of Mod Catchment and Jhabua District — Supplemental Material to "Towards Applied Modeling of the Human-Eco-System"
Maps GEOLOGY and SOIL: source A.K. Singh 2002; Maps II, III, IV and V: source Survey of India 1978

Pitol The northern area of the catchment shall be represented by this transect. Its undulation terrain and meager condition shows traces of more intensive land use in earlier times. The study at hand did not undertake extensive analysis in this part.

Amliphalda-Ranapur The landscape along the main connection of the local center Ranapur and the district's headquarters in Jhabua is considered representative for the eastern part of the catchment.

3.3.2 Sampling Objectives and Methods

To describe the landscape and in order to recognize leading soils and their hydrological properties soil pits shall serve to identify the profiles and to sample material for grain size distribution analysis, bulk density, color, organic carbon analysis. On the sites infiltrability is measured with a double ring infiltrometer.

Soil Profiles Since soils in Mod catchment are generally rather shallow, it was aimed to dig the soil pits down to the bedrock to also collect data about the lower boundary of the soil domain. Every pit was examined regarding the following aspects:

- Geographic and relative position,
- Surface structure, land cover and vegetation
- Erosion and preferential flow
- Drainage and geology
- Soil layers
- Matrix, pores and cracks
- Root depth

In appendix 12.1 the data sheets of all profiles are attached.

Outcrops In the undulating landscape of the Mod catchment with traces of erosion almost everywhere an abundant set of information can be gathered by the analysis of the land forms and outcrops. Although these samples are biased because they are always situated at edges of entities, it allows a better understanding of the functional topology at scale of slopes to profiles.

Wells Within the catchment several large wells are constructed allowing more detailed examination of the geology at this place. In the study at hand, only the stratification profiles have been recorded without further analysis of the formations

Infiltrability As infiltrability is highly dependent on a set of properties of the location like surface structure, cultivation, soil, vegetation, topography and drainage it is practicable to determine this parameter directly. Admittedly the double ring method is of considerable inaccuracy which could have been omitted with a hood-infiltrometer, still due to very limited transportation capacity and local inaccessibility of such equipment, this standard has been chosen. Beside the relatively high uncertainty of the method the very smectitic soils with very high shrinking and swelling potential need to be considered. Preferential flow might dominate the initial infiltration and altered infiltrability under moist conditions is highly variable in time and space and might not be implemented in the model.

3.3.3 Landscape Analysis

As introduced, there is uncertainty regarding the processes and its parameterization. Section 1.1.2 already motivated this aspect. It was decided that not the few percent less uncertainty in some assorted parameters of very few sampling locations might be key to comprehend the system but a broad approach, allowing an appraisal of as many compartments as possible. Hence leaving the level of singular data and processes towards an understanding of the system itself might be the outstanding argument for the approach to document the landscape's properties. At first it was planned to start a mapping of land cover and surface dynamics, which soon became unachievable due to the variability and the size of the catchment. At the same time remote sensing allows several approaches towards the identification of structural and functional entities.

A combination of soft data from interviews with farmers and concerned NGOs, scientific knowledge, ground "truth" data and remote sensing is hence proposed as mean of landscape assessment. A large part of the field work has been assigned to rather general landscape approach. Several panorama pictures from local elevations, about 85 detailed surface descriptions, some records of landscape sequences and an understanding of the landscape were derived from this.

4 Laboratory Analysis

4.1 Mechanical and Chemical Soil Analysis

As a great courtesy of the College of Agriculture, Indore, it was possible to analyze the samples for Munsell color, pH value, grain size distribution, organic carbon content and cation exchange capacity at the Dryland Agriculture Project laboratory.
This chapter introduces which parameters have been addressed by what method. The results are collectively given in appendix 12.4. Even though the respected properties which have been analyzed need to be considered as uncertain in terms of representativeness of the samples, applicability of the analytic method and the accuracy of the utilized equipment, as explained in chapter 1 this data is somehow substantial for the employment of a mechanistic hydrological model like WASA. It will also be used for the cropping agent, as the routine will decide about the locations suitability for the one or the other crop upon physical and chemical properties beside other factors. (See also the introduction about needed parameters in section 3.1.1 ff.)

pH value was assessed with a standard glass-electrode pH-meter. In spite of the fact that the apparatus was protected against fluctuations of the power supply, it was recognized that still rather high influence of the electric current on the measurement persisted. Hence the confidence interval for this data is assumed to be about 0.4 pH, as measurements of distilled water varied between 7.2 and 7.6 pH. Moreover there will be a small bias of the data tending to higher pH, as the distilled water might not be neutral.
The same inaccuracy was found with all electronic balances, which needed to be tared frequently.

Grain Size Distribution was analyzed using the hydrometer method after Bouyoucos (1927) under consideration of (Bohn and Gebhardt 1989). Although the hydrometer method is not internationally accepted as standard it was decided to be applicable in the face of rather siltic and clayic soils with long settling times and in the absence of a highly precise balance. The samples have been prepared in a 1000 ml dispersion of 50g soil, 20ml H_2O_2, 100ml $(NaPO_3)_6$ and distilled water. Hydrogen Peroxide was used to oxidize organic material and Sodium Hexametaphosphate as deflocculant. The dispersion was stirred for 10 minutes.
The method relies on the settlement of dissolved solids after the Stroke's law from the dispersion and thus lowering the dispersion's density which is measured by the buoyancy of a glass buoy. Hence, like the pipette method, it is assumed that after a certain time, the particle class of sand respectively silt settled and do not contribute

to the dispersion's density. E.g. (Bohn and Gebhardt 1989) and many more question the original timings after Bouyoucos (1927) that the content of clay might be faulty estimated when after two hours all silt is assumed as settled. Most papers argue for 6 to 12 hours settling time. At the same time the content of sand, which is assumed to have fallen out after 30 to 60 seconds, is not critic. Still the readings were taken after the original method after 40 seconds and two hours. The results are documented in appendix 12.4.

Organic Carbon was assessed with titration of a dispersion of 3g soil, 10ml 1 N Sodium Dichromat, 20ml H_2SO_4, Diphenylamin-Indicator and 250ml H_2O with 0.5 N Ferrous Ammonium Sulfate.

Cation Exchange Capacity [CEC] was analyzed utilizing the Sodium acetate method. 4g soil and 33ml 1 N $NaOAc$ are shaken 5 min and centrifuged 5 min at 16000 rpm. The liquid solution is transfered into 100ml flutes and filled with $NaOAc$. This is repeated two more times. The samples are washed once more with $NaOAc$. The same procedure is repeated with 3x33ml ethanol. All repetitions are collected in one 100ml flute. Na^+ is then detected in a flame photometer to represent the total CEC of the soil.

4.2 Hydrologic Soil Properties

For the modeling of unsaturated hydraulic conductivity an representation of the water-retention curves of the given soils is essential[1]. Several parameterizations exist for the soil water retention and hydraulic conductivity relationship. Most popular are Brooks and Corey (1964), Campbell (1974) and van Genuchten (1980) (e.g. in Maidment 1993). In order to derive the parameters for the given function the *ku-pf-apparatus* of the UGT GmbH Müncheberg and the *pressure membrane apparatus* have been used.
The analysis has been conducted for five representative soils, sampled with soil sampling rings as undisturbed samples.

Ku-Pf-Apparatus employs the flow process through the ring sample due to soil water evaporation on a free surface of initially saturated samples. Periodically the total weight and the gradient of water movement with two horizontal tensiometers is determined.
The advantage of this method is an analysis of almost undisturbed samples. Yet the presupposition of a steady flux at the upper boundary, inner homogeneity, complete and undisturbed connection of soil and tensiometers and the absence of cracks is not easily given. Certainly for clayic soils the measuring interval is rather short, as the shrinking soil will crack most likely at the tensiomers what ends the measurement.

[1] Of cause one might think of more integrated approaches on catchment scale, which might overcome the limitations of the Richards equation and Van Genuchten/Mualem parameterization. Still the study at hand cannot overcome these restrictions and will follow these standard concepts.

Generally at free evaporation only a matric potential of pF 1.8 can be reached, what clearly is representative for the soil water retention dynamics of sandy soils but not matching the dynamics of silty or clayic soils.

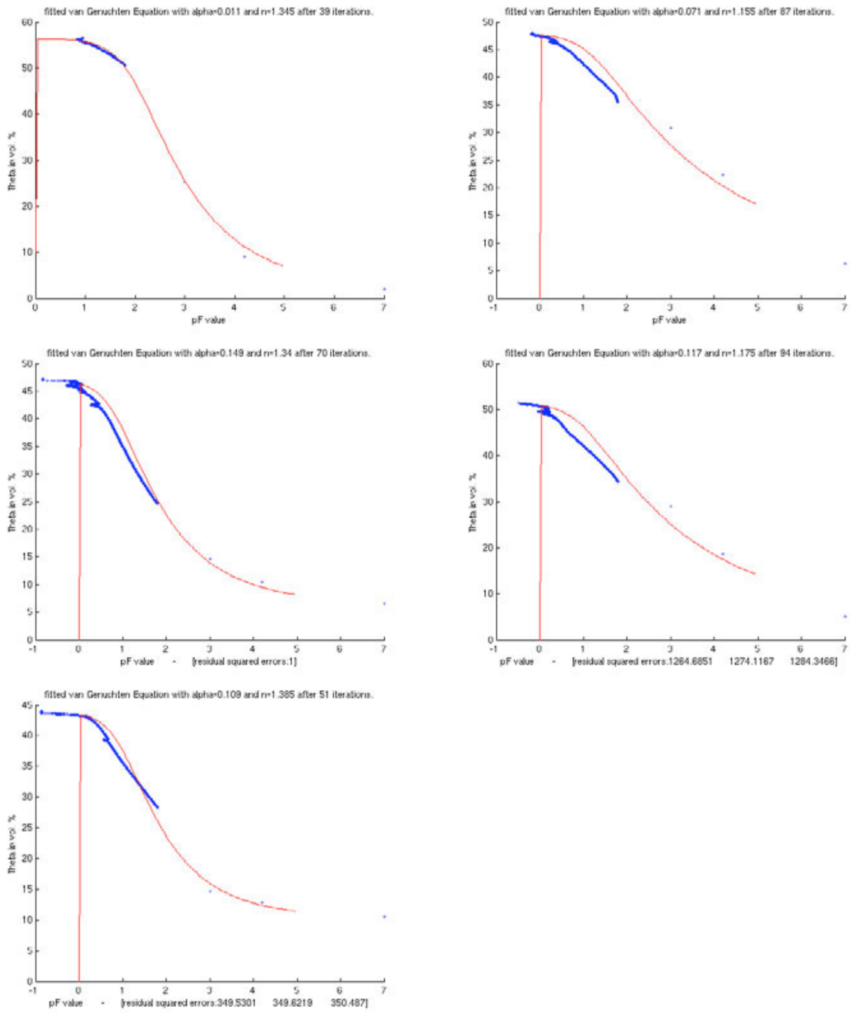


Figure 4.1: Soil Moisture Retention Curves from Ku-Pf-Apparatus and Pressure Membrane Apparatus analysis, fitted Van Genuchten/Mualem Equation Parameters; (a)..(e) for Samples at Position 9, 16, 220, 221 and 23.

Pressure Membrane Apparatus utilizes an excess pressure method to simulate the conditions of higher matric pressure heads. In difference to the original apparatus, a ceramic plate is used as regulating membrane allowing water reduction from the sample as under normal atmospheric conditions. After the pressure application the residual water content is gravimetrically determined (comp. (Brady and Weil 2002)). The apparatus was used at 5 bar with 100ml ring soil samples, taken from the actual 250 ml rings and at 15 bar with disturbed samples.

The recorded data series is then processed for van Genuchten (van Genuchten 1980) parameter estimation in Matlab. The developed script in appendix 12.5 is a least square error curve fitting approach emancipating the single measurements of the pressure membrane apparatus against the vast number of records from the ku-pf-apparatus. As the result is not completely independent from the initial starting parameters of the iteration, it is proposed to use Rosetta (Schaap et al. 2001) as initial estimator. The results are given in figure 4.1.

5 Remote Sensing

In order to gain a broad understanding of the landscape's properties and processes remote sensing based on landsat images is chosen to amend information from maps and field survey. The main focus will lie on a transfer of singular data to continuous catchment scale as needed for the model (see section 3.1). It is aimed to present a pragmatic approach of delineating a human-eco-system with data of different type and quality (see introduction to part II).

The following analysis is based on Landsat 5 TM and Landsat 7 ETM+ images which have been acquired through the Earth Science Data Interface (ESDI), University of Maryland, (; *http://glcfapp.umiacs.umd.edu:8080/esdi/index.jsp*) and the USGS Global Visualization Viewer (GLOVIS) / Earth Explorer, US Geological Survey, (; *http://glovis.usgs.gov*) as publicly available data.

Table 5.1: Landsat ETM+ Band Wavelength

Landsat ETM+ Band Wavelength				
Band	Wavelength	Interval	Spectral Response	span μm
1	0.48 μm	0.45-0.52 μm	Blue-Green	(0.17)
2	0.56 μm	0.52-0.60 μm	Green	(0.08)
3	0.66 μm	0.63-0.69 μm	Red	(0.06)
4	0.83 μm	0.76-0.90 μm	Near IR	(0.14)
5	1.65 μm	1.55-1.75 μm	Mid-IR	(0.20)
6	11.45 μm	10.40-12.50 μm	Thermal IR	(2.10)
7	2.21μm	2.08-2.35 μm	Mid-IR	(0.27)

5.1 Soil Properties

Due to almost absence of permanent vegetation in the catchment and even more due to almost absence of any kind of living vegetation after dry season, the analysis of soils based on its spectral reflectance is of great potential in the study area. E.g. Baumgardner et al. introduces a comprehensive approach to identify soil types and properties from its spectral characteristics. E.g. (Huete 2004) stresses the high potential of remote sensing in arid regions due to very few overlaps of mixed properties.

5.1.1 Reflectance Properties of Soils

As stated earlier the broad classification following the USGA taxonomy (USDA Soil Survey Staff 1999) in Vertisols and Laterites does not apply to the extreme heterogeneity in the Mod catchement. Analysis of (Singh 2004) and (H.K. Jain et al. 1993) base on soil classes which could not be reproduced during the field work. The classification did also not match the purpose of hydrological landscape modeling, as important properties like soil depth where not reflected. Moreover provided soil maps of district authorities and the Geological Survey of India lack necessary updates and detailedness, facing the fact of entire deforestation during the last decades and heavy erosion following this. Thus the current condition of soils as result of a vast number of recent and former soil forming processes needed to be comprehended.

Identification of surface soils from spectral properties have successfully been applied in semi-arid and arid areas (e.g. Goldshleger et al. 2004). During dry season after about seven to nine months without any precipitation and high evapo-transpiration almost no vivid vegetation remains in Mod catchement. Thus soils are virtually uncovered in March to May. The following classification is performed based on a landsat ETM+ scene of April 1, 2000 having a resolution of 30 meters.

The spectral composition of reflected energy from soils mainly depends on its clayic and organic components, surface structure and moisture condition (Baumgardner et al. 1985) (in Huete 2004). As analysis of taken samples states, most soils have relatively high content of clay and loam (see chapter 4.1). Yet there is considerable difference in the mineral composition of this grain fraction. Montmorillonitc clay as 3-layer mineral is highly swelling while binding and releasing water. Kaolinitic clay is a 2-layer clay mineral and thus not swelling. As this has eminent impact on moisture dynamics and land use practice, these classes need to be distiguished. Baumgardner et al. proposes different absorption in near infrared bands between 1.4 and 1.9 respectively 2.2 μm. While montmorillonite is very absorptive due to bound water, kaolinit has a major spectral reflectance there. The landsat ETM+ scene Band 5 ranging between 1.55-1.75 μm is chosen as representative for that. The same band is used for water mapping in surface soils.

Organic matter content has on the one hand strong influence on soil reflectance, on the other hand is organic matter considered as regulator for nutrient condition and biological activity in the soil (H.P. Blume et al. 2002). Additionally a broad number of physical and physiological processes are closely connected to the content of organic matter. Organic matter content above 2% also plays a dominant role in assigning spectral properties, as it masks several reflectance effects (Baumgardner et al. 1985). Mathews et al. (1973) (in Baumgardner et al. 1985) found organic matter to be most highly correlated between 0.5 and 1.2 μm. Stoner (1979) (also in Baumgardner et al. 1985) explains that organic matter is the single most important variable to explain reflectance differences in the spectral range 0.52 to 1.75 μm while the strongest correlation occurred in the visible wavelengths.

Montgomery (1976) and (Baumgardner et al. 1985) found silt content to be the single most significant parameter in explaining spectral variations in soils. Reflectance bands between 0.52 and 0.62 μm are stressed to rule over any other visible or near infrared band for fine silt. This shall be represented through band 2.

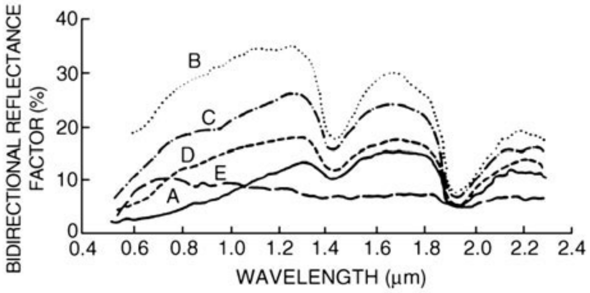


Figure 5.1: In (Huete 2004): Five unique soil spectral signature types; after (Stoner and Baumgardner 1981). The curve forms represent (A) organic-dominated soils with high organic matter contents and low iron contents; (B) minimally altered soils with both low organic matter and low iron contents; (C) iron-affected soils with low organic matter contents and medium iron contents; (D) organic-affected soils with high organic matter contents, not fully decomposed, and low iron contents; and (E) iron-dominated soils with high iron contents and lower organic matter amounts.

5.1.2 Supervised Classification Approach

Considering the given spectral properties a supervised classification based on a false color composite of band 2, 3 and 5 of the landsat ETM+ scene acquired in April, 2000 shall serve to map the soil distribution in Mod catchment.

A supervised classification is on the one hand much more reliable but on the other hand also much more dependent on the training regions of interest (ROIs). Hence the classes which are going to be identified need to be sensibly chosen, to be distinguishable under the concepts presented above and to have an impact on the water-household and land use which can also be represented in data from analysis and literature in the upcoming steps. They also need to be distinguishable entities, so the classifier does not result in rather random results.

Here a maximum likelihood classification (e.g. Richards 1995) was chosen, calculating the probability of each pixel to belong to a class defined by the training ROIs. The algorithm has been applied without threshold definition, hence all pixels have been classified according to the maximum likelihood to belong to a certain class.

Class Identification based on statistical methods from field information significantly lacks samples for a due classification algorithm. Hence the classes needed to be derived from more than laboratory analysis. Basically three different sets of soil classes have been used in a supervised classification. The training ROIs were chosen from the field survey, where the class' properties could be most significantly be found. The results have than be cross-validated using other sampling positions with detailed observations and through checking the overall plausibility of the classified entities in the catchment. This enables a testing of both, the identified classes and the representation of the ROIs through these classes. The finally identified classes are given in table 5.2.

ROI Identification also is not matter of subjectivity even if (geo)statistical identification algorithms fail due to a lack of observations and high variability. The following figure 5.2 is showing false color composites of band 2,3 and 5 of the ETM+ image acquired in april 2000 of the central part of the catchment. The sampling sites are marked in respective classes according to the found situation concerning the USDA soil class, color, depth and crack occurrence.

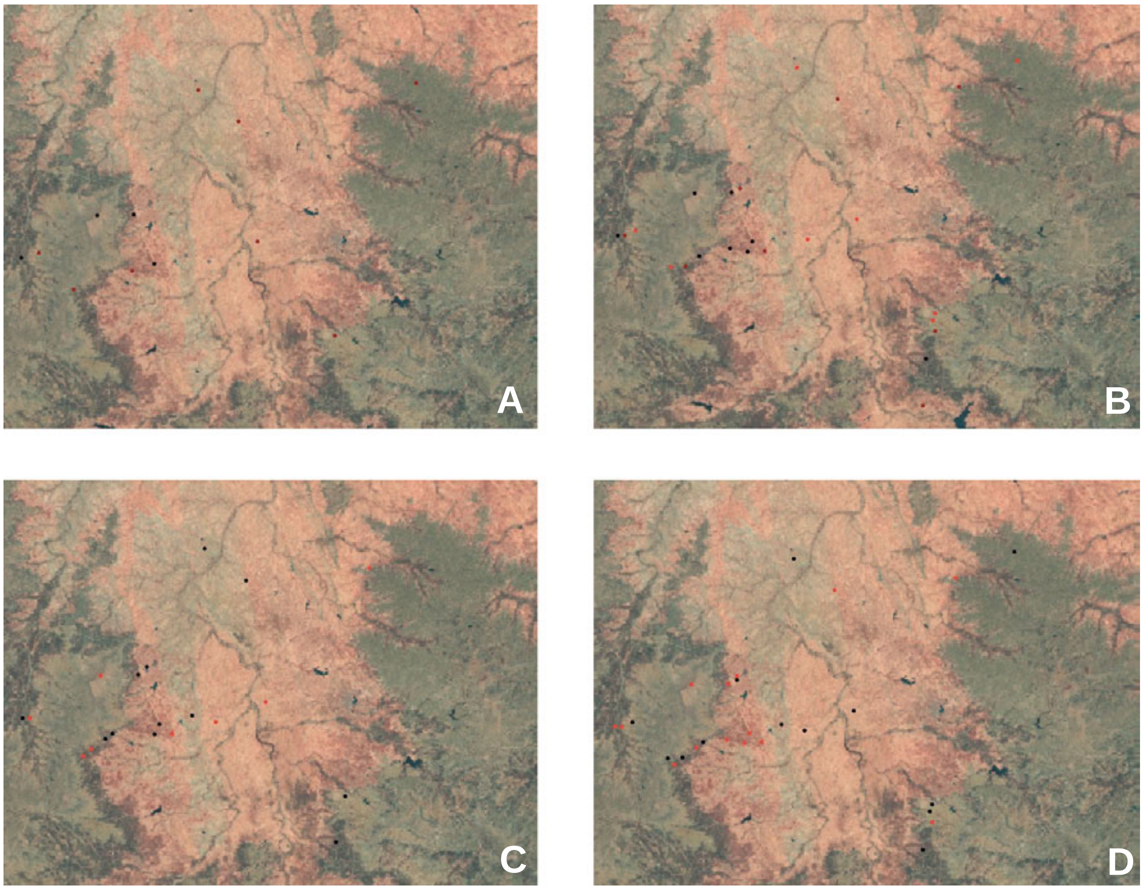


Figure 5.2: Landsat ETM+ Band 2, 3, 5 composite; April 2000; Central Mod Catchment, Jhabua District, Madhya Pradesh, India; (A) USDA classes black: clay, red: clay loam, brown: loam, grey: sandy clay loam; (B) Soil Color black: black, red: red, brown: brown, grey: darkbrown; (C) Soil Depth black: >80 cm, red: <80 cm; (D) Cracks black: no cracks, red: cracks >5 cm

The ROIs for the supervised classification are given in map 5.4 of the false color composite of band 2,3 and 5 of the ETM+ image taken in April 2000.

5.1.3 Cross-validation of Classified Entities

As mentioned above, the taken samples in the field are too few to allow any sound (spatial) statistics. Additionally the high variability of soil classes in this region on a very small scale results in mixed pixels. Thus there are two problems: a) the taken

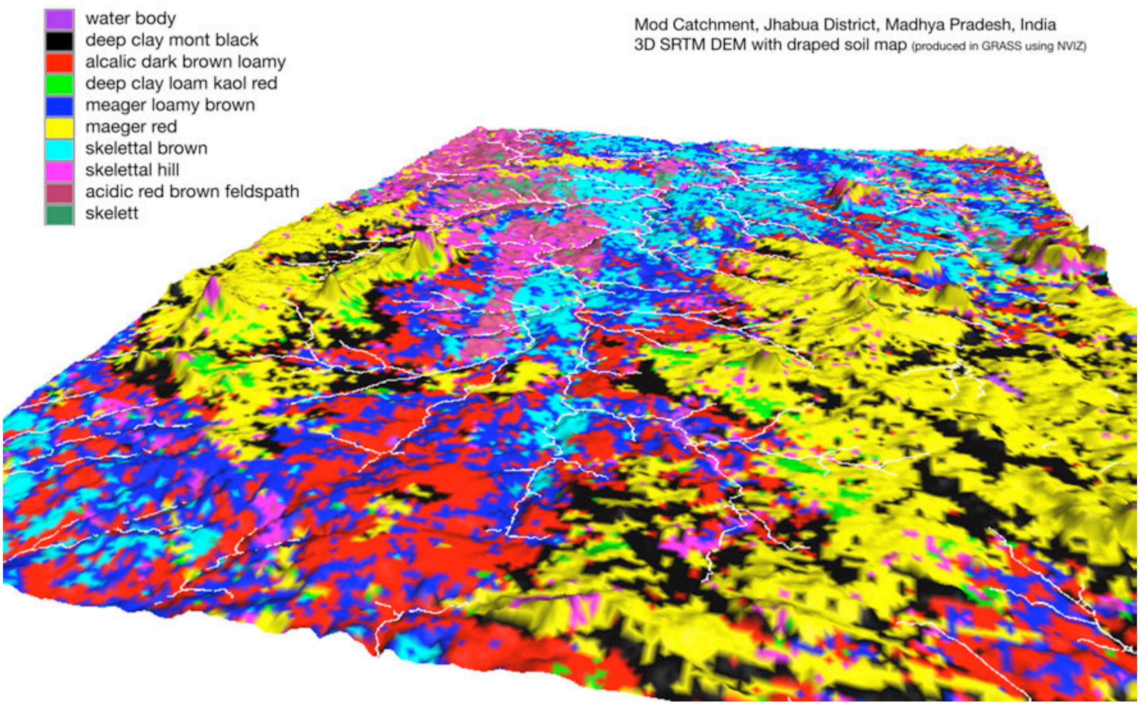


Figure 5.3: 3D SRTM DEM with draped soil classes after supervised classification, Mod Catchment, Jhabua District, Madhya Pradesh, India; produced in GRASS using NVIZ; view from south, relief exaggerated 8.46 times

soil samples might not be representative for a lager area at this place and b) a rather high noise in the classification result indicates, that the classes represented by the ROIs are not distinguishable from the spectral properties of the used bands.

Table 5.2: Identified Soil Classes in Supervised Maximum Likelihood Classification, samples in brackets have been used as training ROIs

No.	class name	mapcolor	share	samples
1	water body	purple	0.25%	xx
2	deep clay mont black	white	8.74%	(4), 12, (13), 14, 16, 22
3	alkalic dark brown loamy	red	11.83%	4, (7), (8), 9, 10, 220, 223
4	clay loam kaol red	green	1.57%	18, 19, (23), (A16)
5	meager loamy brown	blue	18.18%	(1), 3, 5, 20, (213), A18
6	maeger red	yellow	24.53%	(11), 15, (17), 21, A8, A10, A17, A20
7	skeletal brown	cyan	18.88%	(2), (X2)
8	skeletal hill	magenta	6.10%	(X1)
9	acidic red brown feldspath	maroon	8.15%	24, (25), 221
10	skelet	sea green	1.77%	26

The best result is presented in fig. 5.3 and 5.6. To remove the remaining noise in the classification result a five pixel moving window calculating the median was applied using r.neighbor in GRASS. The 30 meter grid is thus smoothed to a 150

Figure 5.4: Landsat ETM+ Band 2, 3, 5 composite; April 2000; Mod Catchment, Jhabua District, Madhya Pradesh, India; boundary of catchment purple line

meter median, which is proposed as reasonable scale to decrease overfits due to local variance.

Figure 5.5: Panorama over Samoi; from western hill towards Mod river bed and Ranapur

Table 5.2 presents the identified soil classes and assigned samples. Those having been used to train the classification are in brackets. The other shall now serve to cross-validate the classification. It will be recognized, that e.g. sample 4 appears twice which is due to inaccuracies in the ROI-identification and a newly assigned class after the smoothing process.

The cross-validation has to check the consistency of the classification with the found situation at all other ground "truth" locations. For a better comprehension it is referred to chapter 5.1.4, to figure 5.6 and to table 12.4 (in appendix), because even in several occasions the classification does not fully comply with the sample's properties, it generally does in a broader context of the location with only low divergence. Additionally to the here presented examples further, more descriptive data from the field work was used for randomly checking the plausibility of the classification.

Deep Clay Montmorillonitic Black Soils are identified for samples 12, 14, 16 and 22 by 4 and 13. All belong to clay soils after the USDA classification and showed to be rather deep during the field work. This class does match very well with the exception of sample 12, which was taken on a slight slope very close to a rather flat black soil field. The color of these soils is black and dark brown. All are very homogenous with generally no skeletal gravels. Hence it is concluded, that the classification of this class is justified and valid throughout the catchment.

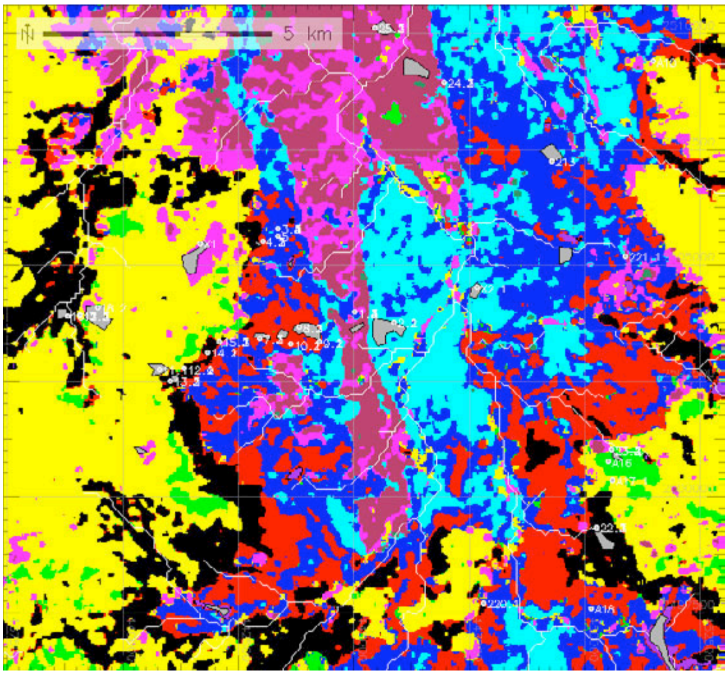


Figure 5.6: soil classes in central catchment of mod river, result from maxlik classification smoothed using 5 pixel median in GRASS, training ROIs for classification are marked in grey, soil samples are marked

Alkalic Dark Brown Loam Soils are identified for samples 4, 9, 10, 220 and 223 by 7 and 8. Most of the samples (excluded are 4 and deep layers of 7 and 8) are classified as loam. The color is identified as black to brown. The average pH value of these samples is almost 9 pH. Although it competes with the class of the Meager Brown Loams figure 5.3 shows, that the Alkalic Dark Brown Loams manly are to be found on gentle slopes or eroded plateaus, hence having finer texture, while Meager Brown Loams are more prominent in areas of higher erosion and are more degraded.

Clay Loam Red Kaolinitic Soils are classified for samples 18 and 19 by 23 and A16. All samples are explicitly very red soils with relatively neutral pH. They are classified as clay loam. This class is connected to the Meager Red Soils which have generally similar properties but are more shallow. So even at site 18 and 19 the soil was not very deep, yet it was used for kharif agriculture, while the Meager Red Soils are highly weathered slopes of the local hills and mostly used as grasslands. Thus one might argue to combine both classes, but as land use is also connected to soils it remains separated here.

Meager Brown Loam Soils are identified for samples 3, 5, 20 and A18 by 1 and 213. As stated earlier this class is connected to the Alkalic Dark Brown Loam Soils. In comparison the CEC is almost half here. All sites are used for kharif agriculture. Only in local depressions also one rabi crop might be possible with rather high fertilization.

Meager Red Soils cover one fourth of the catchment. Through samples 11 and 17 sites 15, 21, A8, A10, A17 and A20 have been identified to belong to this class. Despite the fact that sample 15 is an exception here, the soils are red with relatively low ph beyond neutral. For sample A8 also CEC was determined with a very low value. In the field these areas appear as hilly deserted shallow soils, which are generally not cropped in rabi and mostly are left as grasslands. With exception of sample 11, infiltration was rather moderate with 150 mm/h.

Acidic Red Brown Feldspathic Soils are a separate class found at sample 24 and 221 and defined by sample 25. The presence of feldspar is rather random and many soils in the catchment are connected to this mineral. The peculiarity here is the very young formation of highly weathered bedrock to initial soils. This also results in relatively vaguely known properties.

Skeletal Soils are very prominent in the northern part of the catchment and at the undulating river banks. The given classification subdivides three classes which is meant to distinguish areas capable for low production agriculture. grasslands and highly eroded areas, which are major areas for surface runoff generation. Here cross validation can only be drawn to observations in the field, as samples are lacking. Figure 5.7 presents examples of all distinguished classes at the respective position from the classification.

Figure 5.7: Different Skeletal Soils in Mod Catchment (a) Skeletal Brown Soil near Malwan, (b) Skeletal Hill Soil between Samoi and Tandi, (c) Skeletal Surface near Surdiya, Feb. 2006

Moreover the panorama pictures taken in the field can serve as intermediate step between satellite image and ground "truth" data. The images in figure 5.8 are taken from the positions marked in map 3.1. Comparing the general soil sequences, this too is an argument for the plausibility of the classification at hand and to neglect the given soil map.

5.1.4 Description of the Soil Classes

Each identified soil class will be described in this section as it will be used with the given parameterization in WASA. Each class is summarized in a short table, where *skelet* describes the mass-percentage of stones [%], *sand, silt & clay* are given as mass-percent of the sieved sample hence without the skeletal fraction [%], *cation exchange*

Figure 5.8: Panorama Pictures, Mod Catchment, Jhabua District, Madhya Pradesh, India
all taken by Conrad Jackisch during field survey Jan-Mar 2006

Panorama 1: Jhabua Hill near Kalapipal (228)

Panorama 2: Hilltop Dhamini/Puwala (D1)

Panorama 3: Budhashala (C5)

Panorama 4: Sardapura (D6)

Panorama 5: in Mod Junction near Ranapur (43)

Panorama 6: near Chagola (near 50)

capacity (CEC) is given in mol(+) per gram of soil [$\frac{mol^+}{g}$], *organic carbon* content in per cent of mass [%], *depth* in meter [m], *bulk density* (BD) in [$\frac{g}{cm^3}$] and infiltration rate as *saturated conductivity* in [$\frac{mm}{h}$].

Deep Clay Montmorillonitic Black

This fine-grained clayic black soil occurs in local depressions and alluvial depositions close to the stream network. This class is represented by the sample-sites 28, 55, 105, 106 and 146. According to the final supervised classification based on landsat images of the region of april 2000 this class covers 8.74 % of the catchment. It corresponds very well with the characterization of Black Soil in (Tomar et al. 1995) and (H.K. Jain et al. 1993).

For parametrisation of WASA, the mean of all analyzed samples of this class not deeper than 0.6 meters is extracted to the following parameter set:

skelett	sand	silt	clay	USDA	CEC	Corg	horizons	depth
0	20.1	23.9	56.0	clay	750.1	0.6	1	2.5

ph	BD	Θ_s	Θ_r	α	n	k_s	suction	shrinking
8.34	1.7	0.383	0.073	0.944	1.21	60	48.8	27%

Additionally it has to be stressed that the high content of 2:1 clay minerals causes this soil class to be of most volumetric variability. During the field survey deep cracks of more than 2 cm width reaching deeper than 0.7 meters have been no exception for this soil. The laboratory analysis could identify a shrinking of 27% comparing saturated and oven-dry condition of this soil. (see fig. 5.9)

Figure 5.9: Deep Clay Montmorillonitic Black Soil, Samoi upper plateau, Ranapur Block, Jhabua, India, 29-Jan-06

Alkalic Dark Brown Loam

Although this loamy soil covers about 11.83% and has been recorded several times during the field survey, only the sample 223 and 220 have been analyzed entirely. This soil can be regarded as certainly common for the south-western plateaus of the catchment, where the soils are weathered and intensively used. Refering to Tomar et al. (1995) this soil could be classified as Mixed Red and Black Soil.

For parametrisation of WASA, the mean of all analyzed samples of this class not deeper than 0.6 meters is extracted to the following parameter set:

skelet	sand	silt	clay	USDA	CEC	Corg	horizons	depth
16.5	39.77	30.99	29.24	loam	475.7	0.49	2	1.2

ph	BD	Θ_s	Θ_r	α	n	k_s	suction	shrinking
8.05	1.8	0.305	0.0662	0.21	1.4	90	50.1	-

The Dark Brown Loam is a rather silty soil. The clay minerals appear to be both, kaolinitic and smectitic origin. The effects of swelling and shrinking are very limited. Due to its position on uplands and slight slopes, and due to the own water retention capacity these sights are rather dry lands with medium fertility during sufficient water availability. The upper horizon of about 0.2 meters shows a share of skelettal gravels of about 16.5 per cent, while the lower body is rather homogenous and slightly more clayic. (see fig. 5.10)

Figure 5.10: Alkalic Dark Brown Loam, Bhandakhapar, Udaigarh Block, Jhabua, India, 6-Feb-06

Clay Loam Red Kaolinit

This explicitly red loam covers only 1.57% of the catchment. As strongly weathered soil its clay minerals are of 1:1 structure and kaolinitic origin. In opposition to its genesis, this soil class yet is generally about 1 meter deep and very homogeneous in its composition without any stratification. Samples no. 147, 107, 116, 151, 144, 145, 52, 143, 124, 125, 126 and 129 represent this class. (see fig 5.11)

skelet	sand	silt	clay	USDA	CEC	Corg	horizons	depth
14	45.47	27.85	26.68	loam	342	0.51	1	1.0

ph	BD	Θ_s	Θ_r	α	n	k_s	suction	shrinking
7.43	1.8	0.45	0.105	0.205	1.37	80	56.7	-

Meager Brown Loam

This class covers 18.18% of the catchment. This prominent soil class can be found on gentle slopes all across the catchment. It is referred to as “normal” soil by the local

Figure 5.11: Clay Loam Red Kaolinit, Ban, Ranapur Block, Jhabua, India, 6-Feb-06

farmers. (see fig. 5.12)

skelet	sand	silt	clay	USDA	CEC	Corg	horizons	depth
29.7	36.69	33.18	30.13	clay loam	-	-	2	1.2

ph	BD	Θ_s	Θ_r	α	n	k_s	suction	shrinking
8.5	1.8	0.48	0.050	0.18	1.32	50	43.0	-

Figure 5.12: Meager Brown Loam, Samoi, Ranapur Block, Jhabua, India, 29-Jan-06

Meager Red

24.53% of the catchment are such heavily eroded meager and very shallow soils. It can only be used as grassland. (see fig. 5.13

skelet	sand	silt	clay	USDA	CEC	Corg	horizons	depth
35.1	39.28	38.17	22.58	loam	330	0.37	1	0.2

ph	BD	Θ_s	Θ_r	α	n	k_s	suction	shrinking
7.69	1.9	0.49	0.043	0.205	1.37	115	56.8	-

Skeletal Brown

This class is similar to the meager brown loam with high content of rocks and covers 18.88%. Fig. 5.14 gives an impression. The physical and chemical properties are

Figure 5.13: Meager Red, Dokhal Ban, Ranapur Block, Jhabua, India, 6-Feb-06

assumed to be the same like meager brown loam.

Figure 5.14: Skeletal Brown, Sagola, Ranapur Block, Jhabua, India, 31-Jan-06

Skeletal Hill

This class covers 6.1% of the catchment area and shall only be named here.

skelet	sand	silt	clay	USDA	CEC	Corg	horizons	depth
77.8	48.24	26.6	25.2	sandy clay loam	-	-	1	0.2

ph	BD	Θ_s	Θ_r	α	n	k_s	suction	shrinking
6.69	1.8	0.49	0.043	0.205	1.37	85	58.8	-

Acidic Red Brown Feldspathic

Above feldspathic bedrock these loamy soils develop. This class covers 8.15% of the catchment. (see fig. 5.15)

skelet	sand	silt	clay	USDA	CEC	Corg	horizons	depth
23.2	39.24	36.6	24.2	loam	215.8	0.48	2	1.0
-	27.44	33.96	38.6	clay loam	-	-		

ph	BD	Θ_s	Θ_r	α	n	k_s	suction	shrinking
6.8	1.7	0.48	0.050	nan	-	156	45.1	-

Figure 5.15: Acidic Red Brown Feldspathic, Uberao, Ranapur Block, Jhabua, India, 14-Feb-06

Skelet

This class is very similar to meager red soils but containing far less rocks. It can be regarded as wasteland where even the grass production is very low due to meager and dry conditions as to be seen in fig. 5.16. The general properties are assumed to be like meager red soil.

Figure 5.16: Skeletal Brown, Baldimol, Ranapur Block, Jhabua, India, 28-Jan-06

Water Body

This class refers to the lakes in the catchment. As they are no explicit reservoirs and of minor importance it is regarded as separate “soil”-class to be included in the model.

5.2 Land Cover Analysis

An analysis of the land cover was conducted in analogy to the soil analysis. In october directly after the monsoon spell, all vegetation did emerge and develop, provided that at least average precipitation had taken place. Hence images of this period shall serve as basis for land cover identification.

5.2.1 Spectral Properties and Band Selection

A vast number of studies deal with land cover analysis based on remote sensing. For Landsat ETM+ imagery basically composites of bands 2, 3 and 4 are used for this purpose. As this includes near infrared it is rather sensitive to moisture and open water surfaces. Several studies also propose the band combination 4, 5 and 3 which does emphasize the moisture regime for vegetation analysis even more. In order to identify vivid vegetation also several indices have been developed and applied like the Normalized Difference Vegetation Index (NDVI) (e.g. Tucker 1979) and its numerous modifications reaching out for LAI and moisture stress determination.

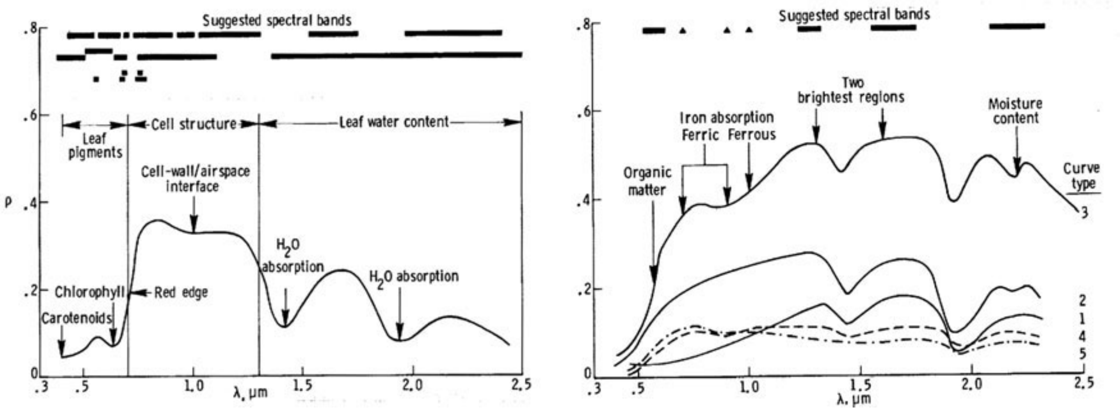


Figure 5.17: In (Bowker et al. 1985): (A) Typical vegetation reflectance curve showing dominant factors controlling leaf reflectance. Vane et al. 1982; (B) Typical soil reflectance curves for the five major types of curves. Types 1-3 proposed by Condit (1970) and types 4 and 5 by Stoner and Baumgardner (1980).

At the same time as (e.g. Asner and Lobell 2000) point out, high variation of vegetation and bare soil on small scale of few meters makes it especially in semi-arid regions difficult to determine its spatial extent from satellite images. They argue to make use of very consistent properties of minerals in comparison to variable spectral properties of plants. For the study at hand band combination 4, 5, 3 was rejected, as this had been used of soil class identification already and because greenery over moisture as predictor for vegetation shall be stressed in this semi-arid catchment. So the classical 2, 3, 4 band combination is proposed for a maximum likelihood supervised classification. At the same time a simple subtraction approach using the spectral properties of bare soil after dry season (see chapter 5.1.1) and vivid vegetation after the monsoon shall serve as estimator for vegetation and land use.

5.2.2 Monsoon Rains and Potential Vegetation

Figure 5.18 illustrates quite impressively post-monsoon vegetation depending on a minimum of precipitation during the monsoon season. While in 2000 only about 400 mm were received and vegetation is very low, in 2001 after a monsoon with 700 mm we find a vivid vegetation cover in most parts of the catchment.

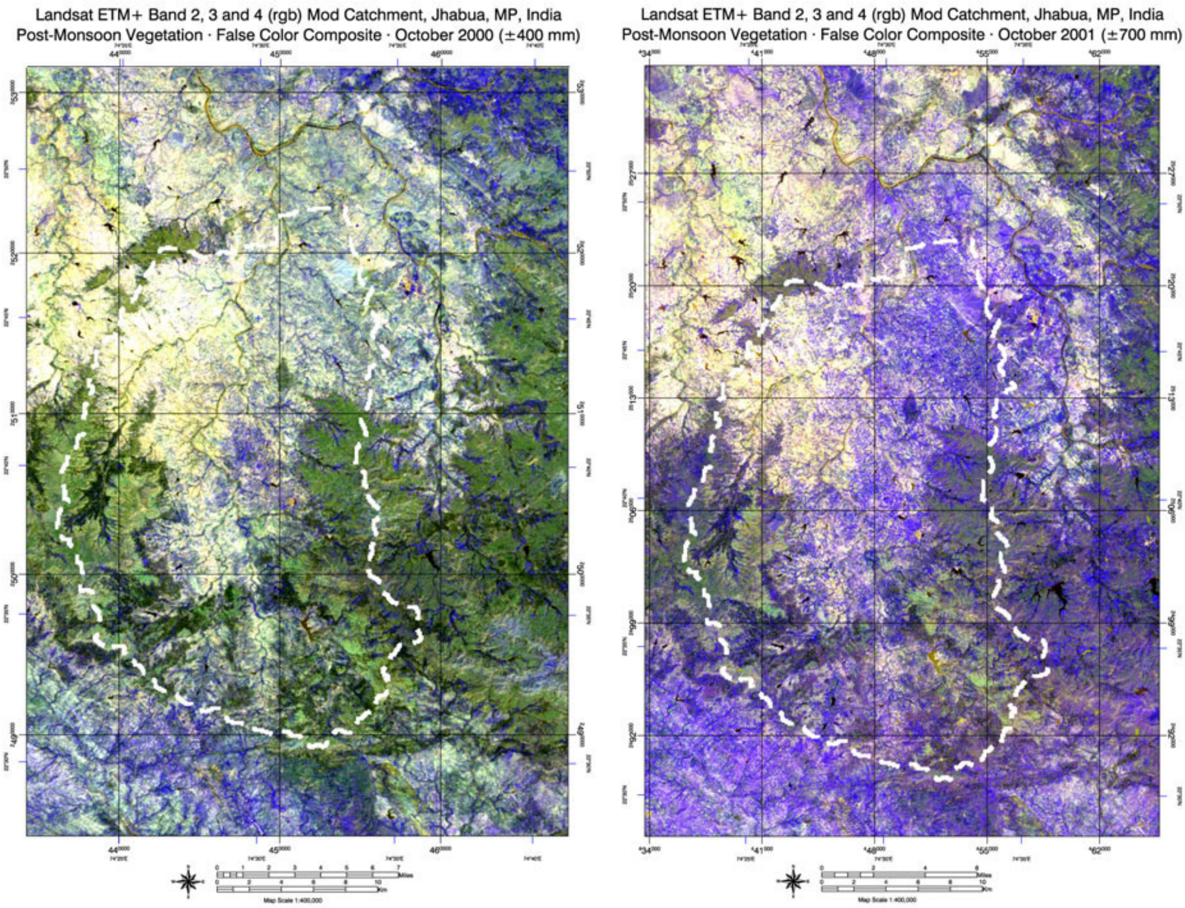


Figure 5.18: Landsat ETM+ Band 2, 3 and 4 (rgb) Composite after Monsoon Spell (A) 2000 and (B) 2001, Mod Catchment, Jhabua, Madhya Pradesh, India

A calculation of Normalized Difference Vegetation Indices (NDVI) (e.g. Tucker 1979) resulted in a similar picture. Inside the catchment in 2000 only 1.89% of the area where covered with an NDVI greater zero. In 2001 it where 22.8% with a maximum at 0.48 and a mean of these nonzero NDVIs of 0.07. The records of kharif and rabi agriculture prove this estimation. While 2001 can be seen as average, in 2000 only half the kharif productivity (averaged over all crops) was reached. For rabi the impact is even more striking as in 2000/01 almost no agriculture took place.

Hence the landsat ETM+ image of 18-oct-2001 was used for land cover analysis to derive a realistic approximation of the situation in the basin. Moreover a landsat TM image of 09-oct-1989 (after a monsoon spell of about 800 mm) is used for the same supervised maximum likelihood classification to compare the results.

5.2.3 Land Cover Classification Result

In figure 5.19 the results are presented. Both resulting maps from the classification have been smoothed as median of a 5 pixel moving window to erase noise and overfits. It has to be mentioned, that these results are based on the same ground data but have not been trained with identical ROIs. Hence a certain bias exists. Furthermore the images where derived from different satellites after different monsoons and with a temporal difference of more than a decade. As introduced earlier (see chapter 2.2) there still is a high dynamic in land use because of deforestation, erosion and infrastructural development.

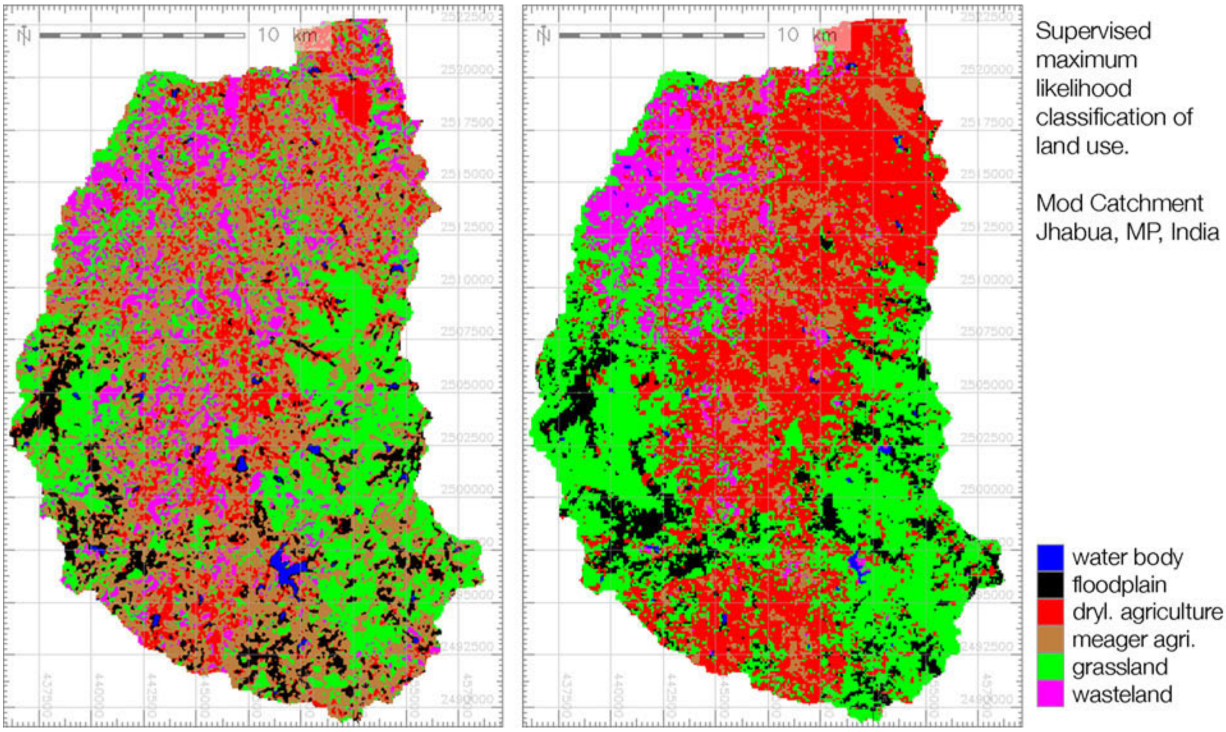


Figure 5.19: Land Cover Classification of Mod Catchment, Jhabua, Madhya Pradesh, India. Result generated using supervised maximum likelihood classification based on ground data. (A) Basis is Landsat TM of 09-Oct-89 (B) Basis is Landsat ETM+ 18-Oct-01.

It is obvious, that both results in figure 5.19 differ considerably. Especially the differentiation of the last four classes is very difficult, as due to very small spatial entities these classes occur in mixed pixels and gradually merge in the field. At the same time prominent structures like classified floodplains and grasslands are very much alike in both results. The dominating wasteland in the north-western parts of the basin and the very undulating characteristic of the northern agricultural lands can be identified, too.

The proposed simple subtraction and further classification did not prove as applicable. Even though it was possible to identify the broader landscape classes the noise is very high and the classes are not properly distinguishable. Neither a supervised clas-

Table 5.3: Land Cover Classification Area Shares. (A) Oct. 1989, (B) Oct. 2001

No.	Class	share 89	share 01
1	water bodies	0.72%	0.36%
2	floodplains	7.48%	8.44%
3	dryland agriculture	13.08%	36.11%
4	dryland meager agri.	39.57%	9.93%
5	meager grassland	27.59%	9.23%
6	wasteland	11.56%	35.94%

sification nor a manual quantitative classification returned a convincing result here.

Generally the results are plausible compared to the observations during the field work. Although this study cannot go into further detail here, it is pointed out that again a high uncertainty about the identified classes remains. The alternative would have been an extensive land use mapping campaign or the use of statistical data (see chapter 6.1). As statistical records are not spatially explicit (see chapter 3.2) and of high uncertainty too, this has not been applicable for the study at hand. At the same time during the field work only dry-season conditions could be recorded, hence a comprehensive land use mapping was not really possible. Thus the land cover map resulting from the supervised classification of the ETM+ image of 18-oct-01 is accepted as best guess for the further analysis.

5.2.4 Cross Validation of Land Cover Analysis

The result of the cross validation of the land use classification is presented in table 5.4 and figure 5.19. While the method delivers quite well identification of flood plains and local depressions other classes bear considerable erroneous determination. A certain bias can be found that meager grassland is most often erroneously classified. Hence unmixing different kinds of vegetation and especially differentiate between different kind of dryland agriculture is only roughly possible using this method.

5.2.5 Description of Land Cover Classes

Floodplains

Mainly in local depressions and at shallow river banks sufficient water is received and more importantly not quickly transfered from to enable agriculture of crops with greater water demand. Despite the probability that there might be a bias due to likely accumulation of deep black soils at this position, it still needs to be separated from dryland agriculture, as subsurface flow and local water availability differ. In most years there are no limitations for rabi crops and in some cases a third cropping can be possible.

Table 5.4: Land Cover Classification Cross Validation Result. Comparison of Supervised Maximum Likelihood Classification of Landsat ETM+ Image 18-Oct-2001, Band 2, 3 and 4 with Ground Data.

No.	Class	area	correct	wrong	certainty	what wrong
1	water bodies	0.36%	3	0	1.00	
2	floodplains	8.44%	6	1	0.86	5@22
3	dryland agriculture	36.11%	7	7	0.50	2@55,105; 5@119,134,141; 4@46-47
4	dryland meager agriculture	9.93%	8	13	0.38	3@3; 5@53,60,106,124,125,129,131, 144,145; 3@118,128,135
5	meager grassland	9.23%	12	7	0.63	3@23-26,115; 4@35,204
6	wasteland	35.94%	4	5	0.44	2@27,28; 5@117,214,29

total samples respected: 73; total correct: 40; total wrong: 33; total heavy divergence*: 4
*(faulty categorization of completely different land use mode; Δ(classno.)>2)

Dryland Agriculture

This can be regarded as most common type of agriculture in the region. Generally kharif and rabi cropping is possible, while the latter is depending on some initial irrigation. In dry season these fields most likely will remain prepared for the onset of the monsoon without a third crop. This class is subdivided into meager agriculture, as in case of more shallow soils, absence of water harvesting structures in relative proximity or a lack of irrigation facilities kharif productivity might be much lower then at the other patches. As the model does not have an (explicit) implementation of irrigation structures, this shall be represented by the classification.

Meager Grassland

Large plains were found to turn the landscape into greenery during monsoon. Yet the soils are very shallow and gravelly that agriculture is impossible. These areas dry up quickly after monsoon spell and are prone to further wind and water erosion.

Wasteland

Extensive fields of gravels, bedrock and sparse vegetation are too no uncommon picture in the catchment. Often without any vegetation this class might be source of surface runoff and does not retain much water during monsoon season.

6 Additional Data

6.1 Statistical Data

Statistical Year Books

The district administration publishes every year a statistical year book about common figures of the district and tahsils like employment, productivity and agriculture. Every ten years there is a census for the district which is also published there. For this study some land use related data was intended to be used, as it was assumed to be suitable for an integrated approach to contribute to the findings from field work and remote sensing. It was also aimed to address development and verification of crop production and land use modeling and the general behavior of the agent with statistical data from the regional administration.
Major obstacle to a due integration of this information is the almost undeterminable geographic reference units. It is possible to aspire somehow vague boundaries of villages, blocks and tahsils. Because of inconsistency of such entities with natural structures (e.g. like watershed) and unreferenced source of data in these compendia could not be used in the study at hand.

Further Administrative Statistics

Much more fruitful proved to be data from specific offices. Although all administrative units face the same problem of weak geographic reference, the more specific information of cropping in the respecting seasons for each block or tahsil was found representative for the overall behavior of the human-eco-system. Especially the district offices of the Department of Agriculture and the MANDI (Agricultural Marketing Board) proved to be of source of detailed information about cropping specific information bridging the farmers' descriptions and general information about cropping practices. Statistics about cropped area, harvest amounts, market prices (each month) and irrigation sources and area were of great support and reasonable quality. Other departments are also source of information about the state and the development of the region. Research here turned out to be a perfect source for shared experiences from the local officers and hence soft data, while figures and reliable hard data could not be gathered often.

6.2 GO and NGO reports

Many governmental and non-governmental organizations (GOs and NGOs) work since long time in the region. They certainly have lots of data about the state of society and

agriculture, which is based on observations during their projects. Again this cannot serve as source of precise figures with due geographic reference and holistic process representation. But as these organizations clearly focus the driving factors and the most urgent needs of the communities. Hence their information is a rich collection of available data from previous studies and local experiences. Certainly when it comes to emphasizing plausibility over figure accuracy such information is crucial. Broadening the view towards a more holistic system understanding on catchment scale such data might be of even better integration in the development of algorithms focusing major drivers.
The study at hand mainly employed (H.K. Jain et al. 1993) (NCHSE - National Centre for Human Settlements & Environment, Jhabua) and (Agrawal 2006) (GVT - Gramine Vikas Trust, Jhabua).

6.3 Interviews

Field work in environmental science often does mean a more or less extensive measuring campaign trying to comprehend the current state from quantifiable properties. Using interviews as source for system understanding is rather uncommon in environmental science, while social science developed a considerable methodology for that. So even people will not present the van Genuchten parameters of their fields' soils or a detailed sketch of subsurface heterogeneity, still they are source of vast information about landscape development, preferential processes and process paths or decision patterns.
Again referring to section 1.1.2 it shall be pointed out, that system understanding has much to do with plausibility. In order to estimate reasonable parameters and process descriptions such information is crucial.
It can be referred to *Qualitative (Social) Research* e.g. *http://gsociology.icaap.org/* or (Lamnek 1993) and a whole disciplinary branch connecting qualitative information with artificial intelligence, statistics and modeling. Without going into detail here it shall be acknowledged that the study at hand at this time could not exhaustively make use of such methods, nor could qualitative data really be transformed into more than plausibility checks and estimation improvements. Aiming towards an integrated representation of more or less *ungauged* human-eco-systems in hydrological and environmental modeling there is still an open field of research on applicable methods and technical feasibility of such integration.

Part III

Hydrologic Modeling in WASA

7 Application of WASA as semi-distributed model for semi-arid tropics

WASA, which stands for "Model of Water Availability in Semi-Arid Environments", was developed by (Güntner 2002) and (Guentner and Bronstert 2004) to enable the quantification of water availability in semi-arid regions. It is employed in the Spanish-Brazilian-German research project SESAM (Sediment Export from Semi-Arid Catchments: Measurement and Modelling) (see also *http://brandenburg.geoecology.uni-potsdam.de/ projekte/sesam/*) as deterministic rainfall-runoff model for continuous simulation of water-transport processes.
The temporal resolution is usually one day, while an hourly simulation is implemented. Refering to spatial resolution WASA is a semi-distributed model, but can gain the aspect of a distributed model in the sense, that the study area is sub-divided into smaller hydrologic units or catenas with reference to its topology in a hierarchical top-down disaggregation scheme.
One central intention of WASA is to overcome calibration of conceptual parameters to fit the model to match a measured reality. Although a large number of input parameters needs to be provided impling uncertainties and adjust-abilities too, the model is applicable in regard to ungauged catchments. It is regarded to be suitable to represent the driving processes and providing an open structure for further adaptation of routines at the applicable scale.
This chapter will introduce briefly the model's concept and new approaches to extent its functionality. For a more detailed description see (Güntner 2002), (Guentner and Bronstert 2004) and (Müller et al. 2005).

7.1 WASA in a Nutshell

Structure of spatial modeling units

In order to capture the influence of land-surface properties, soil moisture patterns and runoff generation on a process adequate scale, WASA hierarchically disaggregates five spatial scale levels. Figure 7.1 (Güntner 2002) gives an overview about these entities.

The first two levels disaggregate the whole catchment into sub-basins which form the most general and largest unit inside the model. In the study at hand the algorithm r.watershed (Ehlschlaeger 1989) in GRASS GIS (GRASS Development Team 2006) was used to identify 64 sub-basins within the Mod catchment. Each is further

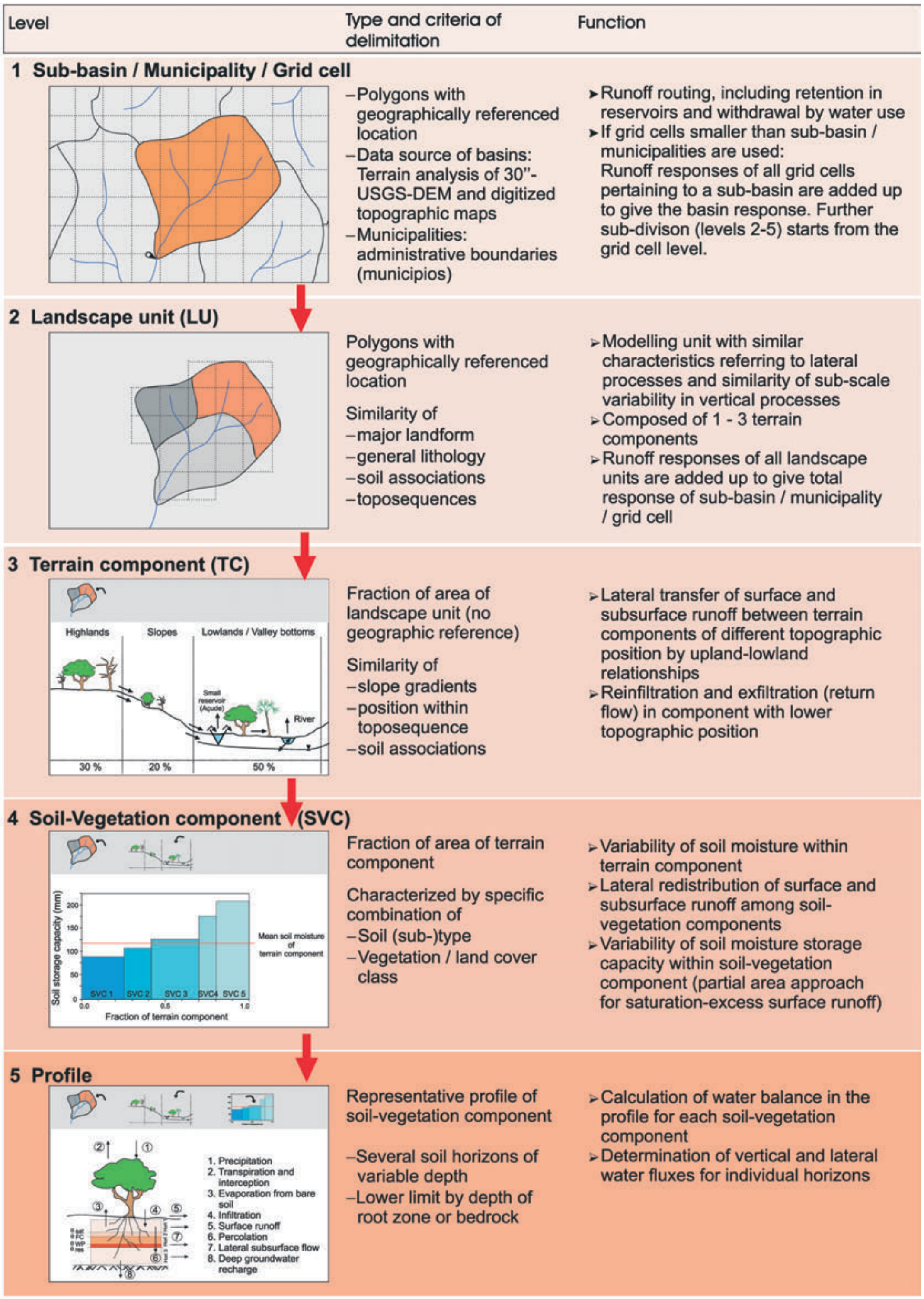


Figure 7.1: Spatial Entities in WASA in (Güntner 2002)

subdivided into landscape units (LUs), witch can be regarded as catenas or major functional entities of the model and still are to a certain degree geographically explicit. While run-off routing as river flow is calculated on sub-basin scale, the LUs comprise all water movement of the subordinate units.
The next devision is called terrain components (TCs). These are fractions of a LU identified to be as homogenous as possible in regard to slope, length and qualitative and quantitative properties. The LUMP-algorithm (Landscape Unit Mapping Program) (Francke et al. 2007) uses a semi-automated approach to classify catenas and identify TCs using a cluster analysis of the given input aspects (see section 7.1.3). TCs are the units where lateral run-off and re/exinfiltration take place and the soil-vegetation-components (SVCs) are governed.
These are the smallest entities inside WASA which comprise all local processes of infiltration, soil moisture control, evapotranspiration, percolation etc. Each SVC itself is defined by a vegetation and soil class, which bear information of soil horizons and its physical properties, rooting zones and leaf area index.

7.1.1 Temporal Sequence of Process Modeling

The temporal sequence of process modeling related to soil moisture dynamics and runoff generation within each timestep is described by the following outline (Güntner 2002) and is calculated for all SVCs and every TC starting with the TC of highest topographic position:

Update of soil moisture of all horizons due to lateral subsurface flow from previous timestep. If the soil water content of a profile exceeds saturation, the surplus lateral inflow becomes surface runoff.

Determine retention of precipitation in interception storage and calculate interception evaporation.

Determine saturation excess surface runoff by precipitation or lateral surface inflow in same timestep from upslope TCs.

Calculate infiltration from rainfall and lateral surface flow.

Update soil moisture of all horizons by the infiltrated amount of water.

Calculate evapotranspiration (soil surface and plants as f(soil moisture)) and update soil moisture.

Calculate vertical water flux to next deeper horizon and determine lateral subsurface flow volumes to adjacent SVCs and downslope TC or river and update soil moisture.

Determine saturated fraction of SVC as f(soil moisture) of the profile.

Add up lateral outflow of all SVCs of the current TC and distribute among river runoff and inflow to downslope TC.

7.1.2 Process Representation

Although extensive process description and presentation cannot be accomplished here, the major modules and concepts of WASA will be pointed out with special attention on critical and altered routines.

WASA Modules

The *Hillslope Module* comprises the modeling of the hydrological and sediment-transport processes taking place on the hillslopes. Its output, consisting of water and sediment fluxes, is passed to the river module for further processing. The hydrological modeling accounts for interception, evaporation, infiltration, surface and subsurface runoff, transpiration and ground water recharge over the described spatial constituents.
The *River Module* is a spatially distributed, semi-process-based approach to calculate water and sediment transport through the river network similar to routing routines in the eco-hydrological models SWAT (Arnold and Allen 1996) or SWIM (Gaze et al. 1997). The routing provides two options based on the kinematic wave approximation: the Muskingum river routing method and the variable storage method. Flow rate, velocity and flow depth are calculated for each river stretch and each time step using the Manning's equation. A trapezoidal channel dimension is used to approximate the river cross-sections. If water level exceeds bankfull depth, the flow is simulated across a pre-defined floodplain. Sediment transport can be modeled using the transport capacity concept.
The *Reservoir Module* is included to enable the calculation of non-uniform sediment transport along the longitudinal profile of a reservoir and of the reservoir bed changes caused by deposition/erosion processes. It is based on a deterministic, process-based one dimensional modeling approach, named SEMRES Model. This module has not been used in this study.

Process Concepts

Interception is originally represented in a simple bucket approach employing an interception coefficient after Dickinson 1984, Menzel 1997 and Zhu et al. 1999 (all in Güntner 2002). Thus a film of 0.25 mm of water is assumed to be captured by the plant's canopy, which is represented by the actual LAI of a certain SVC. After Dickinson 1984 (in Güntner 2002):

$$I_c = h_I \cdot LAI \tag{7.1}$$

According to (Menzel 1997) (in Güntner 2002):

$$P_I = min(I_c \cdot [1 - exp(-0.75 \cdot P)], I_c - I_{t-1}) \tag{7.2}$$

where I_c is the capacity of the canopy's interception storage $[mm]$, h_I stands for the interception coefficient which is assumed for 0.25 mm (Menzel 1997), LAI is the leaf area index, P_I is the intercepted precipitation $[mm]$, P stands for the actual

precipitation $[mm]$, and I_{t-1} represents the water inside the interception storage at the previous time step.
The approach of Von Hoyningen-Hüne (Hoyningen-Huene 1983) gives a slightly more LAI-sensitive calculation of the intercepted precipitation and is used in SWAP (Kroes and van Dam 2003):

$$P_I = h_I \cdot LAI \cdot \left(1 - \frac{1}{1 + \frac{(LAI/3) \cdot P}{h_I \cdot LAI}}\right) \tag{7.3}$$

This equation was used to modify the original WASA approach, because of the more plant-development-sensitive character which should come up with the coupling with the de Wit's algorythm (see 7.2.1). Although Menzel provides more detailed possibilities to estimate interception and its evaporation, the given simple bucket approach has not been altered.

Evapotranspiration is calculated in a two-layer approach after Shuttleworth & Wallace (in Güntner 2002) which itself is based on Penman-Monteith. As this employs a system of surface and aerodynamic resistances for a vapor pressure gradient, it aims to represent the whole soil-plant-atmosphere-system. For the calculation of potential evapotranspiration (ETP_{pot}) these resistances are neglected. Compared to data from the evaporation pans, the model gravely underestimated ETP_{pot} at only about 30%. Especially during dry season the approach failed. E.g. (Kovoor 2006), (Droogers and Allen 2002) and (Allen et al. 1998) argue, that Penman-Monteith (PM) is not applicable in arid or semi-arid conditions. Here Hargeaves (Droogers and Allen 2002) delivers much better performance. (see 7.2.4) Concerning actual evapotranspiration (ETP_{act}) Shuttleworth & Wallace might still be the best estimator - even the structural underestimation should persist - as it considers properties of the standing vegetation like height, stomatal resistance and heat flows through the canopy and thus allows an implementation of a more realistic vegetation interaction with the hydrologic processes.

Infiltration is modeled in WASA based on Green-Ampt in adaption of Peschke 1977/1987 and Schulla 1997 (in Güntner 2002) for layered soils. The modifications allow lateral surface inflow. Additionally effects of rainfall intensities below time step scale, macropores and small-scale variability shall be compensated with a scaling factor for the wetting front movement.

The *Soil Water Module* is balancing incoming fluxes and outgoing fluxes at the scale of a soil profile of a SVC. The algorithm does not allow reverse fluxes like capillary rise. Yet the determination of a current rooting zone allows the plant to interact with all horizons within its reach for transpiration. According to each layer the actual water content is averaged, thus the model is sensitive to the degree of detailedness of the input parameters. In (Güntner 2002) it is summarized as incoming fluxes:

- Infiltration, being added to soil moisture in the uppermost horizon,
- Lateral subsurface flow (from terrain components of upslope position and from adjacent soil-vegetation components of the same terrain component,

- Percolation from above horizon.

and outgoing fluxes:

- Evaporation at the soil surface being substracted from soil moisture in the uppermost horizon,
- Transpiration by vegetation where the total transpiration of the canopy determined in the ETP_{act} calculation is distributed among all horizons in the root zone to be substracted from soil moisture by using a weighting factor for each horizon. The weighting factor is determined as the fraction of available field capacity in the horizon relative to total available field capacity in the root zone. The sum of weighting factors for all horizons equals one,
- Percolation to the next horizon below, or to deep groundwater for the lowest horizon,
- Lateral subsurface flow (to terrain components of downslope position or to the river and to adjacent soil-vegetation components of the same terrain component.

For each SVC within a TC the generated runoff is separated into runoff into a lower TC and into runoff into SVCs of the same TC, as SVCs are assumed to be rather distributed patches than defined blocks inside a TC and lateral redistribution occurs among them. Additionally among TCs along a catena redistribution is assumed into downslope TCs according to its fraction of the LU.

Deep groundwater is only represented in a bucket approach, because in semi-arid areas, surface and near-surface hydrology is hardly influenced by groundwater. In case of saturated soil zones above the bedrock these flows are handled in the soil water module. Where groundwater does not affect surface hydrologic conditions, percolated water is assumed to be lost and does not contribute to the hydrologic cycle anymore. If the groundwater body has significant influence on streamflow, a conceptual approach can be utilized to redistribute percolated water which left the soil zone to either contribute to the river network or to be further lost to deep groundwater.

Reservoirs have been central concern for the representation of the hydrology in Ceará, Brazil. WASA offers an approach to distinguish between small or medium size reservoirs, which are connected through a cascade routing scheme and large reservoirs with an explicit calculation of the water balance. As reservoirs are of minor importance at present in the Mod river catchment this routine has not been employed.

7.1.3 Landscape Unit Mapping Program (LUMP)

WASA offers a broad method to describe and analyze the water household of a catchment. Its physical description with almost no calibration options yet depends highly on the identification of the spatial and qualitative entities. In order to decrease subjectivity and considerable effort in delineating such landscape units (Francke et al. 2007) developed LUMP as semi-automated algorithm, which was enhanced during data preparation for the study at hand. Its functionality is detailedly documented in (Francke et al. 2007) and following technical papers.

The routine is able to delineate elementary hillslope areas, which mainly uses DEM operations in GRASS (GRASS Development Team 2006) like r.watershed and r.mapcalc. In order to find representative catenas in terms of LUs in WASA a statistical method after Cochrane & Flanagan (2003) (in Francke et al. 2007) is used to consider topological and qualitative attributes rather then randomly chosen hillslopes. LUMP then classifies all catenas into a given number of classes according to specified objectives like horizontal and vertical length, shape and supplemental properties in a cluster analysis. The LUs are further subdivided into series of TCs with most possible inner homogeneity, especially in regard to topology. For these calculations MATLAB is used. Finally gained classes are united into a database suitable for WASA, where further specifications of all classes at each scale are added.

7.2 Coupling WASA with the WOFOST approach of dynamic crop modeling

WASA was developed based on data from the joint Brazilian-German research project WAVES (Water Availability and Vulnerability of Ecosystems and Society in the North-East of Brazil) (Gaiser, 2002 in Güntner 2002) for the bush-land dominated Federal State of Ceará. Thus vegetation dynamics are implemented through determination of common phenotypical cycles defined by the onset of the rainy season and other stage-breakpoints like leaf and root development. Since in a monsoon driven semi-arid environment water limited growth of crops and natural vegetation cannot be considered as equal in every year (see chapter 2.2 and 5), a dynamic soil-water-atmosphere-plant-system needs to be described by its interactions instead of anticipated growth-patterns.

7.2.1 The 'School of de Wit' for Plant Modeling

The 'School of de Wit' (Bouman et al. 1996) has given a large number of approaches to explain the functioning of crops as a whole. Models like SUCROS (e.g. van Laar et al. 1997), WOFOST (e.g. Boogaard et al. 1998) and SWAP (e.g. Eitzinger et al. 2004) and (Kroes and van Dam 2003) have been successfully applied under various conditions for crop and plant development simulation under different climatic conditions. In spite of the fact that SWAP also realizes a simulation of hydrologic conditions through a multi-1D coupling of entities, it cannot be considered as process oriented hydrologic model. Its limitations clearly start outside well defined lowland conditions.

Basis of the de Wit approach is the assumption, that plant development can be represented by temperature quanta and CO_2 assimilation through photosynthesis and is determined by temperature, moisture stress, radiation and development stage. All models above exploit more or less the same routine to couple plant-specific factors with rather conceptual and partly physical concepts for plant physiology.

7.2.2 WOFOST crop module

As introduced and detailedly explained in (Kroes and van Dam 2003) the following framework has been applied, which refers to a crop specific look-up table:

Phenological development stage $[D_S]$ is divided into emergence, which date is specified by the user, vegetative stage, $(0 < D_S < 1)$ when most assimilates are driving crop growth, and reproductive stage, $(1 < D_S < 2)$ when dry matter is mostly allocated to organs. It can be described as

$$D_S^{j+1} = D_S^j + \frac{T_{eff}}{T_{sum,i}} \tag{7.4}$$

where j is the day number and $T_{sum,i}$ represents the temperature sum required to complete a development stage. This is modified with a day length factor normalized to comply with the provided look-up table data.

Radiation fluxes above and inside the canopy are the major drivers of assimilation. Direct and diffuse radiation is calculated using incoming radiation, its transmission through the atmosphere and the sine of solar elevation as

$$PAR = 0.5 \cdot S_0^j \cdot \sin\beta_{sun} \cdot \frac{1 + 0.4 \cdot \sin\beta_{sun}}{\sin\beta_{cor}} \tag{7.5}$$

where PAR is photosynthetically active radiation, S_0^j is global solar radiation at this day, β_{sun} is the effective solar elevation and β_{cor} the integral of the solar elevation accounting for transmission losses. Using an empirical estimator for atmospheric transmissivity after Spitter et al. (1986) the diffuse and direct radiation fractions are distinguished and used for

Instantaneous assimilation rates per leaf layer calculation. After Peat (1970) is

$$A_L = A_{max}\left(1 - e^{\frac{PAR_{trans}}{A_{max}}}\right) \tag{7.6}$$

where A_L is gross assimilation rate $[kgCO_2m^{-2}leafd^{-1}]$, A_{max} is the maximum assimilation rate of a plant and PAR_{trans} is the transmitted light through the canopy.

Daily total gross assimilation rate of the canopy ($DTGA$) is derived through a gaussian integration after Press et al. (1989) over the canopy and the day. This is further modified with a water stress reduction factor estimated as $\frac{TR_{act}}{TR_{pot}}$, where

TR is transpiration. It is further converted into biomass as relationship $1kgCO_2 = \frac{30}{44}kgCH_2O$.

Maintenance respiration takes up an important share in biomass assimilation estimation, as this consumes 15 - 30 % of the produced carbohydrates in a growing season (Vries et al. 1979). Weighed with an organ maintenance coefficient $c_{m,i}$ $[kgkg^{-1}d^{-1}]$ it can be calculated after De Wit et al. (1978) as

$$R_{mref} = c_{m,leaf}W_{leaf} + c_{m,stem}W_{stem} + c_{m,org}W_{org} + c_{m,root}W_{root} \tag{7.7}$$

and

$$R_m = R_{mref} \cdot Q_{10}^{\frac{T_{avg}-25}{10}} \tag{7.8}$$

where R_{mref} are the reference requirements which are modified with a factor for respiration rate per 10 °C temperature increase Q_{10}.

Dry matter partitioning and growth respiration follows crop specific patterns of organ prioritization for distribution of the assimilatae.

Senescence especially of leafs are controlled though a maximum age of a leaf class which is formed in every time step, water stress and shade within the canopy. Newly grown leafs thus contribute to the domain of all leaf classes, while too old, dried or too shaded classes are removed as litter.

7.2.3 Coupling Options and Realization

In WASA a mere external coupling of hydrology and plant development through any kind of look-up table could not account for the deep interactions within the soil-water-atmosphere-plant-system. As WASA enables the simulation of small-scale processes like evapotranspiration, interception and infiltration on SVC-scale and since water stress is common in semi-arid human-eco-systems, the difference of bare soil and standing crop is obvious. As monsoon rainfalls are inter-annually highly variable ranging between 400 and 1600 mm/a which again intra-annualy have very low auto-correlation (see section 2.2.2), an anticipation of certain development traits for major crops would result in a kind of fake reality. As well the highly diverse landscape cannot be predicted without regarding hydrological and meteorological processes.

Hence, plants' physiological development - and moreover harvest estimation - shall be set in place of the standardized annual course of LAI, rooting and stomatal resistance. Relating to enable a progressive decision-support-modeling of a human-eco-system which highly depends on agricultural land use, the decisions taken for cropping and water harvesting, water availability and many more interactions, this step might enhance the models capability towards an exploratory modeling approach. It also shall serve as integral link between the physical and social aspects in the catchment.

Unique SVCs in a Lumped Approach

WASA as semi-distributed model internally does not allow each SVC inside the basin to be described as unique hydrologic unit in its original version. As mentioned earlier, the downscaling of WASA in space and land use interaction also requires an altered handling of the SVC data look-up tables. Before all SVCs of the same class in a a certain TC of a LU are lumped and assumed to behave identically.
In order to account for diverse cropping patterns allowing different crops on identical SVC-classes which are defined by soil and vegetation, to represent each SVC's status of the previous time step and to reckon precipitation heterogeneity, a controller-matrix is implemented to hold the following information for each SVC:

SVC key	area $[m^2]$
vegetation id	soil id
current crop id	irrigation switch
development stage D_S	height $[m]$
leaf area index (LAI)	root depth $[m]$
albedo	cropping cycle
harvest switch	stage of development multi-switch
storage of accumulated temperature quanta	weight of roots
weight of stem	weight of leafs
weight of storage organs $[kg \cdot ha^{-1}]$	stomatal resistance
stored harvests $[kg \cdot ha^{-1}]$	

Additionally the cropping agent (see section 8.1) stores its decision about kharif and rabi crop and date of seeding in this array.
To comply with the given calculation routine in WASA the subroutine CROPSTATUS translates the unique SVC properties in every time step to the needed arrays for the process calculation. For more insights it is referred to textithymo_all.f90, textitcrop_status.f90 and linked subroutines in the WASA source code.

Solar Radiation and Day Length

Originally WASA derives solar radiation as monthly means from a user defined input file. In order to reduce erroneous assumptions and to elevate the model's practicability an algorithm after (Stull 2001) is implemented to calculate extraterrestrial radiation from specified geographic position. Solar irradiance $S = 1370 W \cdot m^{-2}$ after Kyle et al. (1985) (in Stull 2001) is corrected accounting for inconstant earth-sun distance with

$$S_{cor}^{j} = S \cdot (1 + 0.033 \cdot \cos(2 \cdot \pi \cdot j \cdot 365) \quad (7.9)$$

where j represents the julian day number. The solar declination angle is also determined by the julian day number in

$$\delta_S = \phi_r \cdot \cos\left(\frac{2\pi(j - j_r)}{j_y}\right) \quad (7.10)$$

where ϕ_r marks the latitude of the Tropic of Cancer at $23.45° = 0.4093 rad$, j_r is the day of summer solstice (173) and j_y is the number of days per year (365.25).

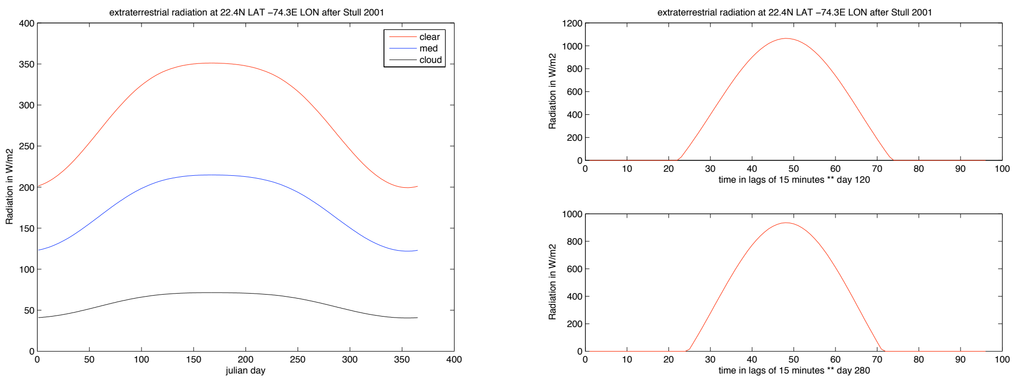


Figure 7.2: Extraterrestrial Radiation calculated after (Stull 2001)

Additionally one sky transmissivity T_K under different sky conditions is taken into account with

$$T_K = (0.6 + 0.2 \cdot \sin \Psi) \cdot (1 - 0.4 \cdot \sigma_{C_H}) \cdot (1 - 0.7 \cdot \sigma_{C_M}) \cdot (1 - 0.4 \cdot \sigma_{C_L}) \tag{7.11}$$

where σ_{C_x} represents cloud coverage at layer x (high, middle, low) and after Zhang and Anthes (1982) (in Stull 2001)

$$\sin \Psi = \sin \phi \cdot \sin \sigma_S - \cos \phi \cdot \cos \sigma_S \cdot \cos \left(\frac{\pi t_{UTC}}{12} - \lambda \right) \tag{7.12}$$

where ψ and λ are latitude in positive north and longitude in positive west $[rad]$ and t_{UTC} is the time in UTC, which is integrated over a day with 15 minute time step. (see Fig.7.2)

Day length is calculated after Kraalingen (1986) in SWAP source code ver. 1.16 (Kroes and van Dam 2003) from julian day number and latitude as

$$DL = 12 \cdot (1 + 2 \cdot \frac{\arcsin \Delta_S}{\pi}) \tag{7.13}$$

where

$$\Delta_S = \frac{\sin \phi \cdot \sin decl_j}{\cos \phi \cdot \cos decl_j} \tag{7.14}$$

with ϕ as latitude $[rad]$ and $decl$ as normalized declination of the sun. DL is further utilized for crop development estimation.

The Plant Development Routine

Based on the 'de Wit' approach and the mentioned examples (see 7.2.1) the routine CROPDEVELOP has been introduced into WASA (for a commented fortran source code see appendix 12.10). The plant specific parameters have been taken from WOFOST and SWAP with references in each headers and are stored in distinct subroutines which are referenced by the subroutine CROPFILE.

Cropping Management A special routine (see appendix 12.9) checks for monsoon onset as initial cropping time for all cropped SVCs and manages harvests after maturity at $D_S \geq 2$ and following cultivations. At this stage cropping patterns are defined by a combination of vegetation and soil class after a simple deterministic look-up table with potential crops for each vegetation class, which is modified whether the soil class realistically allows this cultivation (see appendix 12.9).
In future two possibilities are imagined: A user might specify a list of crops for each vegetation class, holding information about shares of each in the area and cropping patterns. Or cropping patterns are defined for each unique SVC during the LUMP (see 7.1.3) processing.

Modifications to the WOFOST Approach Although the 'de Wit' approach in WOFOST (or SWAP) is relatively open to be coupled in WASA, which can provide most of the needed information at each time step, there have been major difficulties in some details. First of all the crop specific parameters had to be transfered into an fuse-able format. Thus all necessary definition files have been altered into subroutines to cope with various vectors and matrices and to avoid huge empty arrays.
As nutrient transfers are not regarded in WASA and also no information about insufficient fertilizer application[1] of the farmers exists, nutrient-limited growth of the crops is not considered. In contrast water-limited growth is rather common, thus the reduction coefficient $\frac{TR_{act}}{TR_{pot}}$ (see 7.2.2) as the quotient of actual and potential transpiration was estimated to equal $\frac{ETP_{act_{soil,veg}}}{ETP_{pot}}$. This neglects water acquisition by the plant from greater depth without connection to the top soil layer and cannot represent the true water stress of the plant. Yet it is an applicable estimator for the moisture conditions at the site and might be subject to further improvement. To reduce the influence of extreme moisture stress and to consider the fact that in dry season deeper soil layers still contain considerable wetness or are manually irrigated, a bound $1 \geq \frac{ETP_{act_{soil,veg}}}{ETP_{pot}} \geq 0.3$ is set.
Following the argumentation of (van Laar et al. 1997) in SUCROS97 (*"Simple and Universal Crop growth Simulator"*) in order to avoid respiration stress net assimilation rate will only consider respiration after the development stage $D_S > 0.3$. This also applies for leaf death. Here additionally the WOFOST algorithm had to be changed not to consider a new cohort of leafs for every time step and thus detailed leaf age assumptions. An array holding this information for every unique SVC did not appear to be practical. Hence leaf development is summed over all cohorts.
Generally, the theoretical core of the WOFOST subroutine (see 12.10 & 7.2.2) is preserved but had to be re-assembled and re-structured for its implementation.

[1] Jhabua was not found to make any exception in the high amount of fertilizer application which was introduced to all India with the *Green Revolution*. Mainly Superphosphate (SSP) and Nitrate (UREA) are applied in relatively high quantities. Organic farming alternatives are absolute exceptions at this time.

Feeding-back Crop Specific Properties As LAI, stand height, root depth, albedo and stomatal resistance are used in WASA, these parameters are transfered from the crop-status-matrix (see: 7.2.3). In the current version albedo and stomatal resistance are constant and defined according to the original WASA input. For albedo an approach after (Post et al. 2000) is proposed. It was found that soil albedo can be determined by its color value in Munsell notation. Availing the fact that albedo is reduced under wet conditions by 27-45% also the color value is altered. Thus employing the input of wet and dry albedo an estimation of a current value depending on moisture is imagined based on:

$$\alpha_{0.3-2.8\mu m} = 0.069 \cdot C - 0.114 \tag{7.15}$$

with $\alpha_{0.3-2.8\mu m}$ as albedo for a 0.3-2.8μm band as function of C the color value in the Munsell color notation.
Moreover stomatal resistance is not adapted to a current plant stage or conditions. The profound plant specific leaf conductance - water vapor pressure - soil moisture - relationship could be represented in an extension of the crop-specification-files following functions and data according to (Jones 1992). In the study at hand, stomatal resistance is regarded after Hanan & Prince (1997) (in Güntner 2002) as depending on soil water potential and air humidity like in the original WASA.

7.2.4 Further WASA Alterations

Potential Evapotranspiration

WASA calculates evapotranspiration on the scale of soil-vegetation-components (SVCs), the smallest entity in the model employing the Shutleworth-Wallace algorithm (SW), which can be regarded as enhanced Penman-Monteith approach (PM) (see also section 7.1.2). Thus a real-time status of LAI, root depth, plant height and albedo should be known at this point. At the same time, the routine will provide water availability and moisture stress indicators like the relationship of actual and potential (evapo)transpiration (e.g. Kite and Droogers 2000) and (Eitzinger et al. 2004) for the plant development routine. Hence two major modifications of WASA are necessary: a) each SVC needs to be described by unique real-time parameters and b) LAI, root depth, plant height and further albedo need to described as dynamic system. This has been achieved by altering the subroutine hymoall and providing the new subroutine cropstatus (both are to be found as part of the WASA source code in the appendix).

Besides, ETP_{pot} calculation using Penman-Monteith has been found inapplicable in tropical and namely semi-arid conditions (Kovoor 2006) and (Droogers and Allen 2002). In the very dry and hot conditions of Jhabua this algorithm permanently underestimated evapotranspiration gravely. Additionally PM/SW employ a vast number of physical parameters which are not available in a necessary resolution, a necessary certainty and a sensible scale.
Phenomena like weather of convective cells with almost no autocorrelation or even

a simple estimation of air humidity bear a vast number of uncertainties which easily surpass a more physic based and more detailed process description by PM. As certainly for most places of the world precise data of atmospheric conditions and the soil-water-atmosphere-plant-system is rather scarce and if existing of doubtful quality, there is a great need to overcome overparameterized theories in order to find applicable methods with assessable error interactions. Thus for ETP_{pot} a modified Hargreaves approach after Droogers and Allen is employed.

$$ETP_{pot} = 0.0013 \cdot (0.408 S_0) \cdot (T_{avg} + 17.0) \cdot (\Delta T - 0.0123 \cdot P)^{0.76} \tag{7.16}$$

where S_0 is the actual incoming radiation $[\frac{MJ}{m^2 \cdot d}]$, T_{avg} is the mean day temperature $[\,^\circ C]$ and ΔT is the difference of the daily maximum and minimum temperature [K]. Using eq. 7.16 it was possible to simulate ETP_{pot} similar to the measured pan evaporation with data from the weather station Dryland Agriculture Project, Jawaharlal Nehru Krishi Vishwa Vidyalaya, Indore. Yet periods of rather extreme heat have been structurally underestimated. Thus the linear term $(T_{avg} + 17.0)$ has been modified into an exponential form. The modified Hargreaves used is:

$$ETP_{max} = 0.0013 \cdot (0.408 S_0) \cdot \left((T_{avg} + \beta) + exp(\frac{T_{avg}}{\gamma} - \delta) \right) \cdot (\Delta T - 0.0123 \cdot P)^{0.76} \tag{7.17}$$

The parameters β, γ and δ are adjustable to the records from pan evaporation e.g. using the suggested algorithm *ep-hargreaves.m* given in appendix 12.7.

Wind Speed and Stand Height in Evapotranspiration Calculation

The given version of WASA was employing wind speed and stand height data for the calculation of actual evapotranspiration. While stand height was given through the simple growth pattern look-up table (see section 7.1) and somehow varied over the year, wind speed was set to a constant value of $2km/h$.
Without going into detail about the effect of wind on evapotranspiration here, it shall be noted that a file containing the mean daily wind velocity in the catchment has now to be provided by the user and used in the aETP routine. In the study at hand this aspect was additionally introduced in the preprocessing scripts. Here this time series was derived from the daily medians of ten year observations at the meteorologic station at the College of Agriculture, Indore. These medians have been smoothed as means of a five-day moving window (see appendix 12.6 for commented matlab code).

Maximal Thickness of Soil Domain

TCs and SVCs may consist of differently layered soils. Thus water fluxes take place over a defined vector at the boundaries to be compatible, which needs to be consistent with the maximal thickness of the soil domain. Since WASA has been developed for a distinct set of data, the maximal thickness of the soil domain had been derived from the number of layers, which of cause gives considerable inflexibility to its application with various data and locations. It is altered to base on information of the real thickness instead and does allow deep homogeneous and stratified shallow soils to work together, as needed to represent the catchment's characteristics.

Interception

Test-runs showed some difficulty with interception representation. The original algorithm did employ an approach of maximum interception storage capacity (SI_{max}) as in WASIM-ETH (eq. 7.18) (Schulla and Jasper 2000) and is altered to intercepted precipitation (P_i) (eq. 7.19) after Von Hoyningen-Hüne and Braden (1983/1985) (in Dam et al. 1997).

$$SI_{max} = v \cdot LAI \cdot h_{sl} + (1 - v) \cdot h_{sl} \tag{7.18}$$

$$P_i = h_{sl} \cdot LAI \cdot \left(1 - \frac{1}{1 + \frac{v \cdot P_{gross}}{h_{sl} \cdot LAI}}\right) \tag{7.19}$$

with h_{sl} as maximum height of water at a leaf surface which is estimated as $h_{sl} = 0.25mm$ (Menzel 1997), v as crop specific soil coverage by vegetation, which is estimated as $v = \frac{LAI}{3}$ (Dam et al. 1997) in equation 7.19 and P_{gross} as gross precipitation. While the approach after Schulla and Jasper was developed for mountainous catchments and enables a good approach to deal with rock surfaces, it lacks sensitivity in vegetation development interaction. The chosen equation also slightly altered the whole interception algorithm as to be followed-up in *soilwat2.f90*.

7.3 Performance and Results

All modifications have been tested with meteorological data[2] from weather stations within the catchment and in Indore for the years 1992 through 1996. The discharge from the Mod-River-Basin has only been recorded during this period by one gauge in six hours resolution. There is no other gauge to validate the model with. For the overall performance of the model in dynamic representation, also data for pan evaporation and satellite images of soil moisture are employed[3].

For the performance analysis the '*original*' WASA approach including the integrated crop development routine (see section 7.2.3) is compared with the altered WASA model also including modifications to process representation (see section 7.2.4). Both realizations do not employ the decision agent presented in chapter 8.

The '*original*' WASA routines showed a high underestimation of potential evapotranspiration and discharge from the catchment resulting in unrealistic water accumulation within the basin. Yet the general dynamics of dry and wet season and the impacts of a very strong monsoon for the whole dry season were reflected. Especially critical has been the performance during a year of a strong monsoon in 1994, where not even 60% of the water balance could be explained by the model. Figure 7.3 and

[2]The preprocessing of the meteorologic time series had to deal with inconsistent time series and records of different temporal resolution. An algorithm was developed to process all available meteorological data from stations in Jhabua, Ranapur, Megnaghar, Udaigarh and Indore into a consistent and locally adapted data base for the modeling. The commented source code is given in appendix 12.6.

[3]As introduced in chapter 5 there was no satellite image freely available for this period for a due comparison. A visualization tool representing the soil moisture dynamics of each TC on daily time step was developed an is given in appendix 12.11.

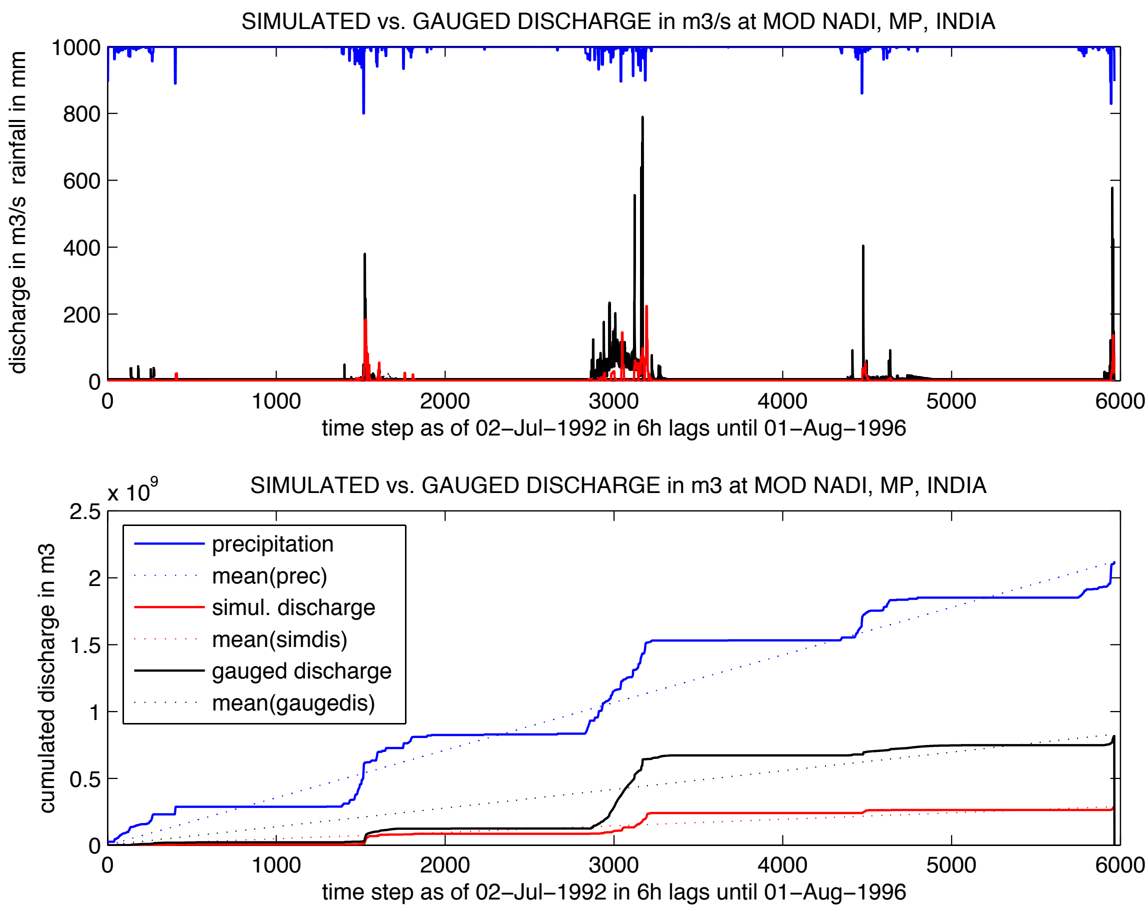


Figure 7.3: Original WASA Performance - Simulated vs. Gauged Discharge - Original WASA version 9/06 Time Series Mod Catchment, Madhya Pradesh, India, 1992-1996

table 7.1 introduce the original model performance.

In comparison figure 7.4 and table 7.2 present the simulation results with the current state of process representation. The graphics already clearly point out, that the altered processes description can improve the model's performance. Although the indicators in table 7.1 and 7.2 do not propose any ultimate improvement, the water balance and hence the overall behavior of the hydrologic system can be explained much better now. For the study at hand the plausibility of the hydrologic behavior and the compliance of the overall water balance[4] is considered as much better measure of the model performance. Additionally figure 12.8 in appendix 12.8 presents the details for each rainy season.

[4] One shall keep in mind, that even highly sophisticated indicators exist as it is pointed out in the following section 7.3.1, the water balance as representation of the continuity equation is the only physical first principle in hydrology.

Table 7.1: Quality Indicators of Simulations. Original WASA version 9/06 Time Series Mod Catchment, Madhya Pradesh, India, 1992-1996

WASA Model Quality Indicators for Discharge from Catchment									
Run	MSE	$\sum \Delta Q$	$\sum$ abs(ΔQ)	R	bias	C2	ISE	RS2	E
WASA all TS	749.54	-24528.3	34971.6	0.48	-4.20	0.00	4.25	0.98	0.21
rain season 1	39.99	-740.2	1091.3	0.48	-1.70	0.00	2.88	0.99	0.96
rain season 2	73.44	-1153.4	3668.6	0.53	-1.73	0.00	1.24	1.00	0.93
rain season 3	1050.18	-18055.5	23858.7	0.43	-25.50	0.00	0.91	1.00	0.34
rain season 4	45.64	-2293.7	3594.3	0.48	-3.59	0.00	1.28	1.00	0.95
8 day means	251.65	-23633.0	28437.4	0.64	-4.03	0.03	NaN	NaN	0.34
See equations 7.24 - 7.29 for indicator description.									

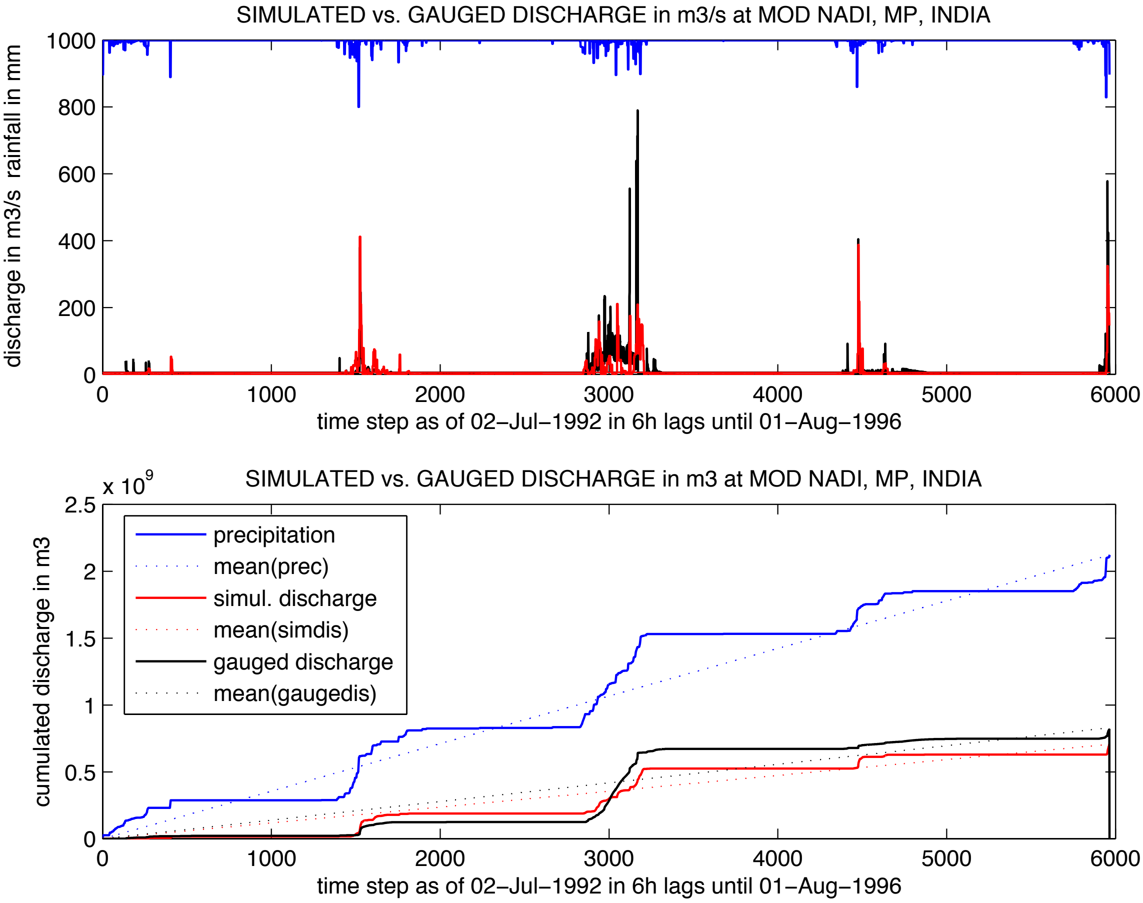


Figure 7.4: Modified WASA Performance - Simulated vs. Gauged Discharge - Modified WASA w/ WOFOST version 10b/06 Time Series Mod Catchment, Madhya Pradesh, India, 1992-1996

7.3.1 Quality Assessment

To address the quality of a hydrologic model several statistic standards exist. E.g. (Weglarczyk 1998) shows how interrelated common algorithms are and how these can be compared for a more general model quality interpretation.

Utilized Algorithms and Assumptions

As first estimators of cause Sum of Errors ($\sum \Delta Q$), Sum of Absolute Errors ($\sum abs(\Delta Q)$), Mean Squared Error (MSE), Bias (B) and Linear Correlation Coefficient (R) are calculated, while the time series of gauged discharge is assumed to represent truth and the calculated discharge from WASA is scaled to meet the same time step resolution (in first case 6h).

$$B = mean(Q_c) - mean(Q_o) \tag{7.20}$$

$$\sum \Delta Q = \sum_{i=1}^{\infty} (Q_c - Q_o)_i \tag{7.21}$$

$$\sum abs(\Delta Q) = \sum_{i=1}^{\infty} abs(Q_c - Q_o)_i \tag{7.22}$$

$$MSE = mean(\Delta Q^2)_{i=1}^{\infty} \tag{7.23}$$

$$B = mean(Q_c) - mean(Q_o) \tag{7.24}$$

$$R = \frac{cov(Q_o, Q_c)}{s_o s_c} \tag{7.25}$$

Additionally Nash-Sutcliffe's Efficiency Coefficient (E), the Integral Square Error (ISE), the Squared Special Correlation Coefficient (R_S^2) and Murphy's Conditional Bias (C^2) are calculated using the following equations:

$$E = 1 - \frac{MSE}{s_o^2} \tag{7.26}$$

$$ISE = \frac{\sqrt{MSE}}{m_o} \tag{7.27}$$

$$R_S^2 = 1 - \frac{MSE}{s_o^2 + m_o^2} \tag{7.28}$$

$$C^2 = \left(\frac{s_c}{s_o} - R\right)^2 \tag{7.29}$$

Even though a wide range of algorithms describe many properties of the fit of a modeled to a measured time series, they are still based on any kind of mean. Thus all standard methods like the given equations 7.24-7.29 (in Weglarczyk 1998), (Nash

and Sutcliffe 1970) and (Aitken 1973) base on the assumption of stationarity as they employ mean or variance. Regarding the monsoon driven discharge dynamics, there is no stationarity - not intra-anually because of dry and wet season and not within a single rainy season, as intensive rainfall is limited to few singular events. One might hence tend to reduce the statistical population to comparable events, which in this case would mean to drop all realizations with no flow, but still the formal criterion of any kind of mean is violated. At the same time the very important fact of the onset of discharge and its dynamics between flash floods and no flow will not be regarded under such perspective.
Figure 7.4a proposes a good fit of modeled discharge to the measured time series. Besides the rainy season of 1994 (around time step 3000) the flash flood at intensive rainfall events and overall discharge dynamics during rainy season appear to be well simulated and to fit in time and mass. But when it comes to higher precipitation amounts like in 1994, almost no fit seems to exist. The model seems not capable to replicate base flow.

7.3.2 Performance of the Cropping Module

In order to analyze the performance of the cropping module the development of crops on exemplary SVCs has been supervised. It was observed how LAI and organs develop, how the assimilates are transfered into biomass and how water stress influences the crop development.

LAI and Organ Development

The development of a plant is represented through a couple of indices as introduced in section 7.2.2. While the overall development stage is determined by accumulated temperature quanta, which is a relatively simple algorithm, the development of the plant's leafs and other organs is a more complex system. Hence it was assumed that the resulting parameters here are representative indicators to judge about the routine's performance.
The realizations have been compared to literature information about typical behavior of each crop (e.g. Franke 1994, Norman et al. 1995). It could be found, that generally the LAI and stem development was calculated within the given "normal". It could also be observed, that crops like sugar cane developed a very high LAI and needed a rather long time until maturity while other crops like pigeonpea reached lower LAI values and developed more quickly. In addition the date of harvest complied with reports from the region.

On the other hand one has to point out the highly idealistic nature of a model not regarding multi- or inter-cropping. Irrigation has not been considered, neither. Soil fertility and fertilization did not influence the crop development in the model. The de Wit approach itself also lacks several important site- and plant specific parameters, which are necessary to represent crop productivity beyond the scale of large scale in-

dustrial agriculture. The whole approach has not been entirely stress tested in every regard. An additional discussion is given in chapter 10.
The organ (e.g. grains) development was compared to crop productivity data provided by the Department of Agriculture, Jhabua, and was found to be generally underestimated at about 70%. At the same time the data calculated by the model and the figures collected by the authorities might not base on the same reference. While WASA/WOFOST is simulating dry mass production, the measured production from field harvests includes some degree of water of the crops. Owing to the fact of this uncertainty, the simulation was assumed to be plausible at this point.

Water Stress Influence

Water-stress might be a prominent condition for crops in the catchment. Disregarding effects below daily time step, the routine should be capable to represent effects of dry conditions on the site in terms of lowered productivity. In the initial testings the effect proved to prevent many crops from emerging at all, as the water-stress assumed as quotient from actual and potential transpiration or here evapotranspiration (see section 7.2.3 for this discussion) resulted in too high respiration rates. To avoid this and to acknowledge germination to be more independent of the actual moisture condition and nursing to be supported by the farmers through irrigation if necessary[5], water stress was only allowed for a development stage above 0.3. After this modification the routine proved to somehow be capable of the representation of different moisture regimes. Simulations prove to comply in elevated or decreased productivity depending on the annual precipitation.

[5]It was explained by many farmers and NGOs that wherever possible especially during the germination irrigation is provided.

Table 7.2: Quality Indicators of Simulations. Modified WASA w/ WOFOST version 10b/06 Time Series Mod Catchment, Madhya Pradesh, India, 1992-1996

WASA Model Quality Indicators for Discharge from Catchment									
Run	MSE	$\sum \Delta Q$	$\sum$ abs(ΔQ)	R	bias	C2	ISE	RS2	E
WASA all TS	741.58	-5597.5	40045.6	0.57	-0.96	0.10	4.23	0.98	0.22
rain season 1	70.20	-281.6	1296.7	0.57	-0.71	0.10	3.81	0.98	0.93
rain season 2	137.82	2824.7	5204.0	0.61	4.33	0.12	1.70	1.00	0.87
rain season 3	923.13	-9717.2	24906.9	0.53	-13.72	0.07	0.85	1.00	0.42
rain season 4	110.92	1424.8	5501.6	0.56	2.23	0.15	1.99	1.00	0.89
8 day means	225.94	-6420.7	28360.4	0.69	-1.10	0.06	NaN	NaN	0.41
See equations 7.24 - 7.29 for indicator description.									

8 Alternations towards a Decision Support System

It was shown, that this modified WASA can be an interesting tool for simulation of hydrologic and land use specific processes in semi-arid regions. Although there remains a relatively high degree of uncertainty as a matter of fact in a more or less ungauged catchment, the synopsis of the process oriented hydrologic model WASA and the relatively universal plant development algorithm of WOFOST shall now be adapted to simulate possible land use strategies and to calculate relevant parameters to deduce beneficial or faulty strategies under economical and ecological perspectives. This section will give an overview about the developed knowledge based agent which decides about cropping after a given strategy and the weather scenario generator which was developed to minimize the influence of any anticipated weather realization over land use specific interactions.

8.1 The Cropping Decision Agent

In order to analyze land use strategies a knowledge based agent (e.g. Russell and Norvig 2003) has been developed. Its main task is to simulate the cropping decision based on knowledge about local properties and based on certain constraints. This shall serve to identify policies for land use optimization.

8.1.1 The Agent's Concern

In every year on every SVC the decision has to be taken what crop to plant for kharif and rabi season. Additionally the decision about the time of seeding has to take place. In the given framework of infrastructure, environment and ecology of cause there is a vast number of impacts which cannot be regarded here or outreach the decision's impact. But if one drops superordinate external drivers like subsidies or oil price the decisions become rather logical consequences of the economical circumstances and the location. Hence an agent could be used to simulate harvest or profit maximization. It could also opt for minimal erosion or best adaptation on the forecasted weather or local conditions.
In this study nine different agent constraints have been employed:

1. best local adaptation, which takes into account soil, potential vegetation, erosivity and fertility

2. maximal profit, comparing only input and market prices

3. local adaptation and weather anticipation, which accounts for suitable soils and potential vegetation plus water consumption of the crop with knowing the weather of the year
4. weather anticipation and minimal erosion
5. weather anticipation and soil fertility
6. minimal inputs for seeds and no labor intensive crops to minimize the risk of losses
7. maximal profit and wrong weather anticipation, which shall maximize the possible profit and opt for water consumptive crops even in dry years and vise versa
8. full consideration of knowledge - all aspects are taken into account
9. weather adaptation only, which disregards all factors and only adjusts crops on the known precipitation of the year.

8.1.2 Technical Realization of the Agent

Technically this agent is programmed as a set of weight assigning arguments. For each concern the local parameters are compared with the agent's knowledge base and result in values between 0 and 1 for less or more liked combinations. According to the agent's concern on each SVC (see Fig.7.1) every potential crop gets a weight as the product of all regarded aspects. The agent will decide for the crop with the highest ranking, which also suits the season. In case of two or more competing high ranked results, there is a random decision among all competitors within 40% below the value of the highest rank.
This algorithm takes place some weeks before the monsoon onset and decides the land use of a SVC for the whole year - like a farmer would buying seeds. It is transferred into the cropcontrol-array (see 7.2.3).
The commented fortran source code of the subroutine is given in the appendix 12.14.

8.1.3 Knowledge Base

Certainly such an agent is highly sensitive to the knowledge base beyond. The applied structure unites two aspects: Modified circumstances can easily be updated for new simulations, hence the decision support model becomes more universal; and the agent's decisions can be reproduced also without altering or fully understanding the whole model.
The knowledge base consists of three files:

Cropping Knowledge Base Based on (Norman et al. 1995), (Franke 1994), (Rehm and Espig 1991) and annual reports of the Indian Commission for Agricultural Costs and Prices (CACP) (*http://dacnet.nic.in/cacp/RPP/pp.html*) the following knowledge base in Table 8.1 has been compiled.

Table 8.1: Knowledge Base of Agent's Decisions - Cropping

no	crop	kharif	rabi	water consump.	water stress resist.	water logg resist.	min. water mm/a	fertilize in rabi	soil fertility
1	pigeonpea	1	2	1	1	0	300	1	1
2	millet	2	1	0	2	0	180	1	0
3	sunflower	0	2	1	1	1	250	1	1
4	sorghum	2	1	1	1	1	500	1	1
5	chickpea	1	2	1	1	1	300	0	1
6	maize	2	1	2	0	0	500	2	2
7	cotton	2	0	2	2	1	600	1	1
8	groundnut	2	1	2	1	1	500	1	1
9	sugarcane	2	0	2	2	1	1200	2	2
10	soybean	2	1	2	0	1	500	2	1
11	casawa	1	1	1	2	2	750	1	0
12	wheat	1	2	1	1	1	250	1	1
13	grass	2	2	0	1	1	100	0	0
0=not possible; 1=possible; 2=preferred						0=low; 1=med; 2=high			

no	pref. soil	alt. soil	alt. soil	labor intensity	prod. costs A2+FL	prod. costs C2	harvest price low	harvest price high	erosivity
1	2	3	1	1	930	1379	1400	1750	1
2	2	1	0	1	485	620	500	659	1
3	2	1	3	1	300	300	300	300	2
4	2	3	1	1	578	745	500	759	1
5	2	3	1	1	727	1188	1300	1500	2
6	2	3	1	1	445	579	510	630	3
7	2	3	0	2	1893	2921	1800	2800	3
8	2	1	3	1	1197	1517	1400	2000	1
9	3	2	1	2	100	100	200	200	3
10	2	1	3	1	678	979	1100	1650	2
11	2	1	0	0	50	50	100	100	1
12	2	3	1	1	424	640	600	900	2
13	2	1	3	0	1	1	100	100	0
1=sand; 2=loam; 3=clay					Prices in Indian Rupees per Quintal				

Soil and Vegetation Knowledge Base In order to meet the information needed to evaluate the adaptation of a crop on the local properties two more knowledge bases were introduced: Tables 8.2 and 8.3 present the texture classes a soil belongs to and the degree of cultivation which is most likely at the position. These files also account for decision restrictions due to general limitations, e.g. that wasteland can not easily be used for intensive agriculture or skelettal soils are unsuitable for crops.

8.2 Weather Generator

A second central concern to develop a sound decision support system is a high number of anticipated futures. This study will not fully surpass the restrictions of scenarios as the aim is to present a possible set of methods. It neither is destined for a Monte-Carlo simulation of millions of possible realizations of weather. In order to represent

Table 8.2: Knowledge Base of Agent's Decisions - Soil

soil id	class 1	class 2	CEC	description
1	0	0	0	water bodies
2	3	0	750	deep clay montmorillonite black
3	2	3	475	alcalic dark brown loamy
4	2	3	342	deep clay loamy kaolinitic red
5	2	3	309	meager loamy brown
6	2	0	330	meager red
7	2	4	209	skelettal brown
8	4	2	109	skelettal hill
9	2	0	215	acidic red brown feldspar
10	4	0	59	skelett
1=sand; 2=loam; 3=clay; 4=skelett; 5=no soil				

Table 8.3: Knowledge Base of Agent's Decisions - Cultivation

veg id	crop class 1	secondary option	description
1	0	0	water bodies
2	1	2	floodplains
3	4	0	wastelands
4	3	4	meager grasslands
5	2	3	dryland agriculture
6	2	3	dryland meager agriculture
0=none; 1=intensive; 2=crops; 3=meager; 4=grass			

the precipitation characteristics of Jhabua a rather simple weather generator was developed to randomly generate time series of precipitation, humidity and temperature which is based on past observations and will calculate plausible data frames. The commented matlab source code is given in annex 12.13.

8.2.1 Technical Description of the Weather Generator

The script reads in existing time series - in this case from the weather station of the College of Agriculture, Indore - and analyses minimal, maximal and mean values for each parameter at each day. This results in a band of most probable realizations which will be further used to weight a random generation.
As both, the weather and the concern of this study mainly depend on rain, precipitation was chosen as driving parameter above all other variables. A random function choses the year to belong to high (850$<$x$<$1400 mm), medium (550$<$x$<$850 mm) or low (350$<$x$<$550 mm) annual precipitation. Then the annual precipitation will be compared to statistics of existing records to define the number of rain events in five intensity ranges and the period of their occurrence. An algorithm balances the realizations to comply with the observed constraints and bounds. This is done in two steps: First, the rain event of a discrete intensity range is assigned and second, the

precipitation of each intensity range is distributed to these events.
After each day has been assigned a precipitation the remaining parameters are adjusted according to maximal likeliness in past observations.

8.2.2 Plausibility of the Generated Time Series

In the script a simple plausibility check is performed to compare the generated time series with the analysis of the observed data. It must be pointed out, that this statistical approach is not based on process understanding like more complex monsoon prediction models (e.g. Zehe et al. 2006) which aim to consider the monsoon propagation onto the sub-continent based on atmospheric conditions, nor is it a statistical linear model which tries to reproduce the parameter interactions based on linear statistics. Hence the results might have still potential to improvement but, looking at the time series and statistics, still have sufficient plausibility for simulations in the study at hand. Figure 8.1 gives an overview about recorded and generated time series.

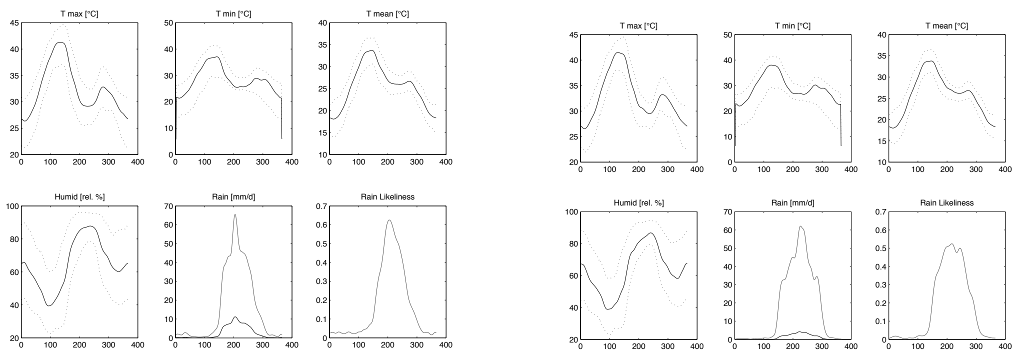


Figure 8.1: Analysis and Overview of (left) Observed and (right) Generated Weather Time Series

9 Scenarios and Application

This chapter will present the results from the application of the developed model and its utilization as decision support tool. It will also point out several limitations of the model and concept requirements for a sound simulation of land use and hydrologic processes, which will be discussed in the next chapter. Uncertainties and certainties of the results from this study shall be tested. It will also conclude the scope of this study to present a possible framework for an integrated decision support model comprising expert knowledge from the field, general process understanding and representation in a model including predictions of most likely realizations based on the identified system constraints.

The developed new version of WASA including the cropping routine based on WOFOST (see section 7.2.3) and an agent (see section 8.1), which is responsible for cropping decisions, has been applied to over twenty different weather sequences of 25 years each for the nine different agent constraints.

9.1 Simulation Result Analysis

9.1.1 Limitations

Running simulations for 21 weather scenarios and nine agents results in a huge amount of data. If only annual means or harvest results were of concern, the analysis was rather simple. Since in semi-arid areas Hortonic discharge is prevalent and the discharge or even the whole hydrologic behavior is dominated by very few extreme events one needs to zoom into the data and analyze variations beyond annual means or sums.
Additionally there is a spatial problem. Cropping patterns are not at all homogeneously distributed across the catchment. Regarding the large spreads of wastelands, eroded hill sides, skeletal drylands etc. possibly only one third of the catchment is involved in the land use-hydrology-interactions. Hence an average of all LUs or subbasins might also not be capable to represent the model's performance.
As a third obstacle it has to be pointed out that there is hardly any direct link between all predictors and realizations. Complexity in possible interactions of several drivers and processes might be a strength of the proposed model here, but is also hindering its utilization.

9.1.2 Analyzing Land Use Impact on Intra-annual Hydology

In appendix 12.15 the R source code is given for the following roughly described calculations.
The impression that land use does not affect the hydrologic processes in the model is apparent from a short glance on annual mean, variance and sum of discharge, overland-flow, subsurface-flow and evapotranspiration of all realizations depending on what agent was deciding about the cropping. In figure 9.1 and appendix 12.15 these results are given as boxplots of annual data comprising all sub-basins and weather scenarios.

In order to step beyond the reaction to extreme events and hortonic discharge - which is obviously dominant here - a more detailed algorithm is developed: All realizations are compared on daily basis among all unique years - each of the 25 years in each of the 21 weather scenarios - and referred to the mean behavior across all agents in the unique year as reference. In the result every single time series of each agent is assigned the following indicators for discharge, ETP, overland-flow, subsurface-flow and theta in each sub-basin to describe the hydrological behavior:

- absolute deviance from mean
- deviance from mean
- days above bound of mean defined by the standard deviation
- days beyond bound
- deviance from bound (above)
- deviance from bound (beyond)
- max continuous days above bounds
- max continuous days beyond bounds
- mean continous days above or beyond bound
- mean continous days above or beyond bound

In a second phase these indicators need to be embraced removing the effects of the dispersed information towards a more distinct identification of the agent's influence. This shall be achieved by the following algorithm: Each realization of an unique year is respected. According to the distribution of results for each unique subbasin, credits are granted in the following manner:

- $x_i = min(x) \longrightarrow C_i = -2$
- $x_i < Q_1(x) \longrightarrow C_i = -1$
- $Q_3(x) > x_i > Q_1(x) \longrightarrow C_i = 0$

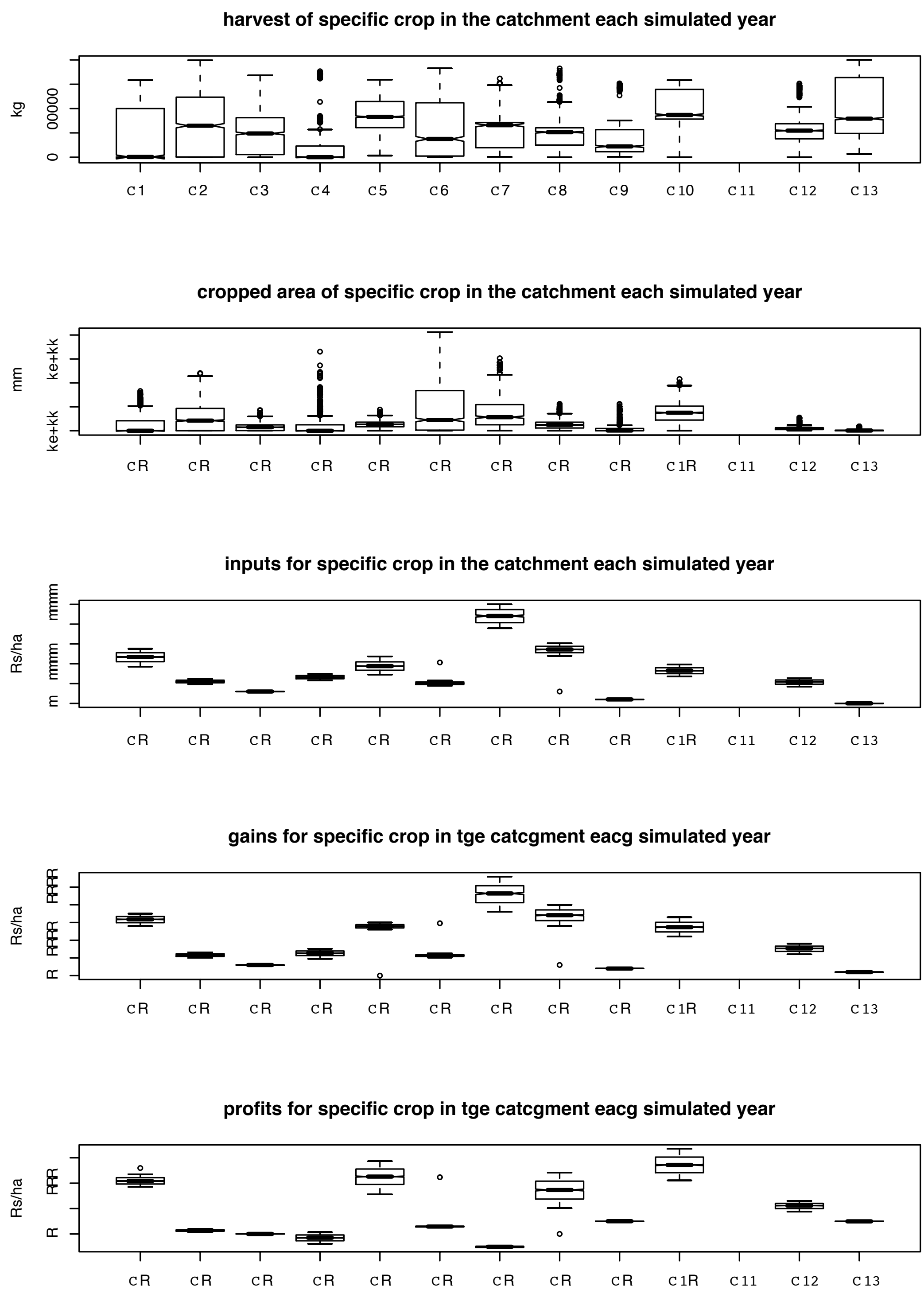


Figure 9.1: Summary of annual data from crop simulations with WASA/WOFOST considering all agents

- $x_i > Q_3(x) \longrightarrow C_i = 1$

- $x_i = max(x) \rightarrow C_i = 2$

where $Q_3(x)$ and $Q_1(x)$ are the upper and lower Tukey's hinge and C_i stands for the credits granted for x_i from the population x. These credits are compiled for all aspects to form an estimator for the whole behavior of the given aspect in all regarded years. E.g. theta: It is defined, that it is positive to have an elevated soil moisture in the subbasin, which is the maximal continuous period above the mean and the shortest continuous period beyond it and which shows the least fluctuation it its performance. Hence the agent performing closest to this ideal will gain the highest credits.
After all credits are assigned the agents are ranked from 1 to 9 for each aspect and finally ranked after the sum of all ranks (without any weights, which might be applicable here). Table 9.1 gives the result. The whole algorithm is given in appendix 12.15 (under section agent assessment of the code).

Table 9.1: Ranking of hydrologic performance of Agents, high rank is hydrologically favorable behavior

Agent No.	Total Discharge	SUB Discharge	SUB Overland-flow	SUB ETP	SUB Theta	$\sum credits$
1	6	6	8	7	6	33
2	4	7	4	9	3	27
3	8	9	9	2	4	32
4	1	5	3	1	5	15
5	2	3	5	5	7	22
6	5	2	2	6	2	17
7	3	8	7	4	9	31
8	9	1	1	8	1	20
9	7	4	6	3	8	28

The results will be discussed in section 10.2.7. It shall be stated here, that even a very integrated analysis of the hydrologic response to certain constraints of agents cannot overcome the fact, that the hydrology of the Mod catchment is highly determined by infiltration access overland flow or to put it the opposite way by infiltration, which is conditioned by land use within given bounds of the soil properties. In the coupled model of WASA and WOFOST this impact has not been simulated since the effect was underestimated and no frame work of field studies about surface structures, cropping techniques and macropore fluxes in decisively swelling soils could be accomplished.
The ranking in figure 9.1 shows contradictory results. E.g. agent no. 8 does gain top score in total discharge from the whole basin and least credits for discharge regarding all subbasins. There is no explicitly well or bad performing agent to be identified.
Still the simulation proposes agent no. 4, 6 and 8 as worst performing in terms of hydrology, while agent no. 1, 3 and 7 get relatively high ranks. Hence weather anticipation and the consideration of not location sensitive arguments might be not applicable for a sustainable and water saving land use practice. Local adaptation and

cropping instead of leaving the land uncultivated promise to have a positive influence in the water retention. The result yet is to be considered as matter of uncertainty. Disregarding any single factor in the overall score of an agent might shift the result. This is especially of importance as all regarded factors are interrelated and of different scope of impact.

9.1.3 Analyzing Economic Performance under Different Cropping Strategies

In terms of economic benefit and food security the results are much more determined. Figures 9.1 and 9.3 summarizes the realizations of each cropping constraint in terms of harvested amount in the catchment. In appendix/agentprofit.pdf the gained profits of each agent are given.
Although this result is matter of uncertainty too and highly depends on the estimated gains as described in table 8.1, the results allow an insight into the economical performance of the strategies. It shall be pointed out that the strategies differ in their behavior in kharif and rabi season as shown in figure 9.4. Moreover it should be noticed, that the profitability of a strategy is highly conditioned by the given data in table **??** and thus does not reflect on food security and productivity nor does it exhaustively consider labor and market access costs at this stage. It is also of importance to keep in mind, that even a median promising high gains from a cropping strategy does not necessarily represent the most likely realisation of this strategy, as the high inter-annual variance suggests also decreased food security.
Hence the interpretation of the results for a decision about what strategy is performing best needs to be taken under a defined target. E.g. if we are to maximize food security and accountability for cropping under any weather, agent no. 2 and 6 promise to earn good results in kharif and strategy no. 1 and 2 to perform well in rabi. Agent no. 7 and 8 appear to be highly profitable but have a considerable variance. For kharif agent no. 3, 4, 5 and 9 do not gain much profit even if the harvest amounts are considerable. In rabi no. 4, 5 and 9 operate worst, too.

9.1.4 Identification of the Best Land Use Strategy for Jhabua

In the preliminary sections several strategies could be identified to somehow perform good or bad under the aspects of a sustainable agriculture in Jhabua. Comprising all results it becomes striking that weather anticipation does not prove to have great impact in the realization of good harvests and adapted cropping. It also is shown, that cotton is of great wealth if the input costs were rather low, but as input and probable gains are high, it is unprofitable. The agents did not often decide to crop cotton, too. Chickpea, Soyabean and Millet are crops with high production.
Concluding from the results, there is no single best land use strategy to be identified. Yet there is strong evidence for unsuitable policies resulting in reduced food security and disadvantageous hydrologic impacts. Especially as sustainability does include the profitability of every farmer's labor and effort, addressing the costs of cropping appear to be much more remunerative than intensification of agriculture. In chapter 10 there

are more technical remarks on what effects have been regarded in this study and which remained not addressed in this study. One could imagine that additional irrigation from wells or surface storages might alter the results. As infiltration access overland flow is mayor contributor to the catchment's gross discharge, the installation of small local storages[1] - in best case in types of covered cisterns or shaded ponds (see Agarwal et al. 2001, Agarwal and Narain 1997; for details) - could on the one hand increase the retention capacity of the catchment for precipitation water and dispersed fertile top soil in the surface runoff and on the other hand become an alternative source of water saving the scarce ground water resources for drinking purposes.

9.1.5 Autocorrelation of Agents and Weather Scenarios

It shall be proved, that the weather scenarios are not biased and do generate comparable results. Moreover the consistency of the agents' realizations shall be analyzed to estimate the likeliness of the cropping patterns decided upon.
As described in section 8.2 the aim was to generate consistent and plausible weather scenarios which are driven by precipitation on a daily time step. Figure 9.2 gives an overview about the resulting harvest amounts per crop under certain weather scenarios.

In contrast to the unbiased results from any weather scenario, the agents do have a considerable impact on harvest as indicator for land use and land use success. Figure 9.3 shows the resulting harvest amounts per crop under each agents constraint.

In order to compare the realizations of the agents' decisions and the resulting cropping patterns an algorithm was developed to approach the likeliness of these. Its realization can be found in the function *compare:sim* in appendix 12.15. It is based on an indicator, which calculates a sum from all quotients[2] of cropped area for each realization year. It is restricted for realizations where a crop is not cropped at all to definitions given in the algorithms. It also does not prove to be one-to-one unambiguous, as there are special cases where this algorithms returns faulty high likeliness. Still it is used as estimator here. The result is given in figure 9.4.

To conclude the section, it can be stated, that the target of unbiased weather scenarios and decisive agent driven simulations of cropping patterns reacting on several condition was achieved. A comparison of simulated harvests based on real measured time series suggests a general underestimation of the local productivity of local crops but proves that the general behavior of harvested dry mass approximation does represent reality. The underestimation might be a result of the definition of dry mass which is calculated by the model but is not referenced for harvest data by MANDI Jhabua and the statistics offices.

[1] One could also imagine larger reservoirs instead of such small structures. But the disadvantages lie in the very high potential evaporation from an open water surface, long transportation distances of the captured water, vulnerability against pollution and contamination with pathogenic bacteria, accumulation of sediments remote to their origin and a lack of social integrity as it cannot be managed by a village of family community.

[2] in terms of crop1 in year(a) / crop1 in year(b) + crop2 in year(a) / crop2 in year(b) ..., where in x/y $y>x$

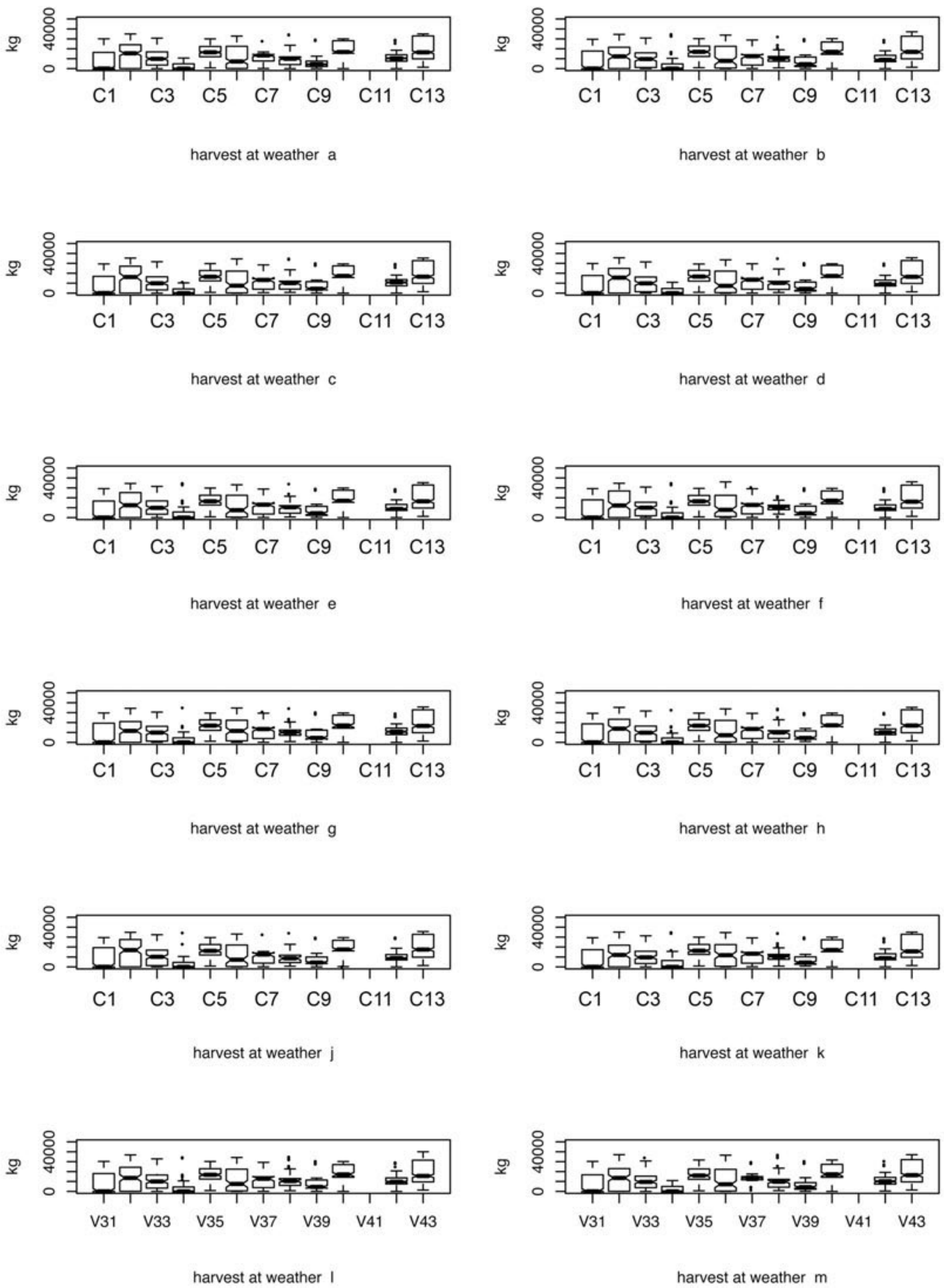


Figure 9.2: Harvest in kg/year for all 13 considered crops in weather scenario a to m from simulations with WASA/WOFOST

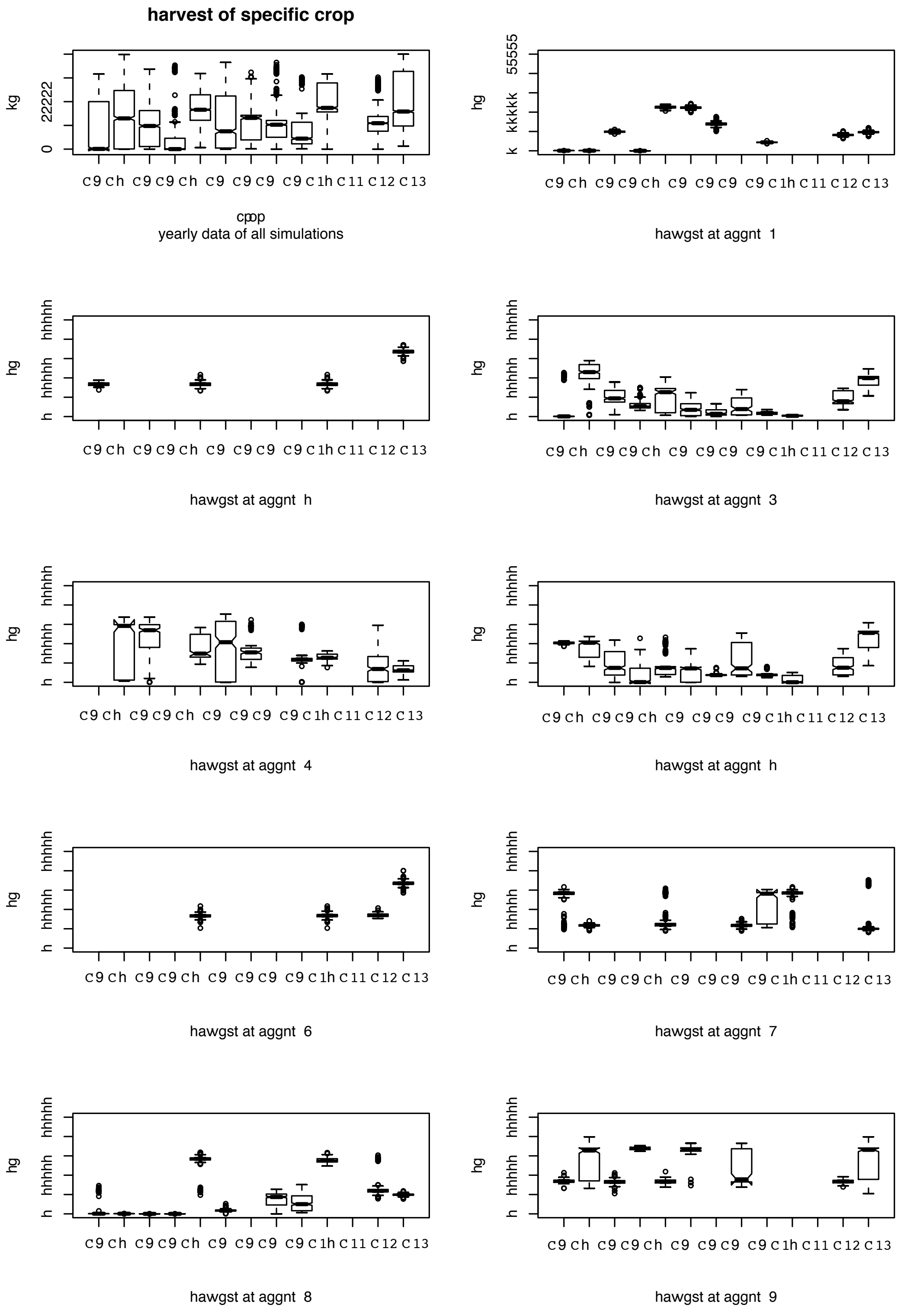


Figure 9.3: Harvest in kg/year for all 13 considered crops under agent 1 to 9 from simulations with WASA/WOFOST

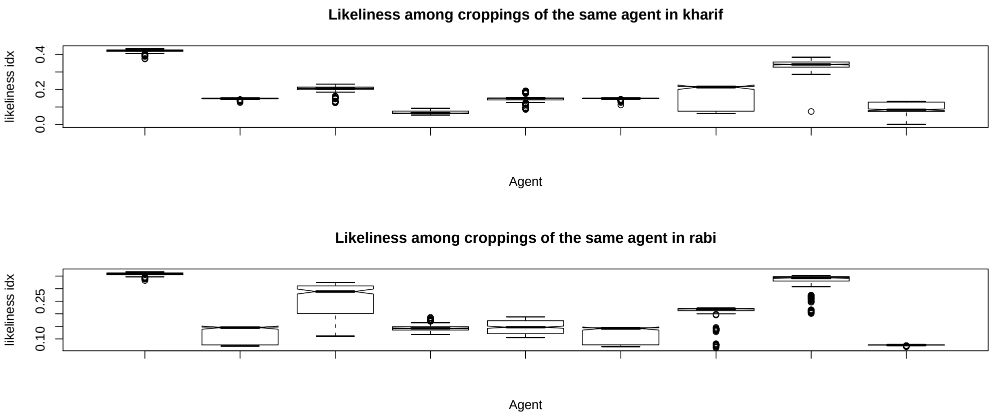


Figure 9.4: Likeliness of agent decided cropping patterns in simulations with WASA/WOFOST

9.2 Ground Water Recharge Assessment

As introduced in section 2.2.4 local authorities expect relatively high groundwater recharge rates for all Jhabua. As field studies on this have not been available to prove the assumed 10% and more of the annual precipitation to sustain the ground water recharge, the model was applied for case studies of different boundary definitions. The following figure 9.5 shows the catchment's discharge behavior as in section 7.3 and table 9.3 holds some of the respective quality indicators.
The definitions of the lower boundary flux maximum, thus maximum groundwater recharge rate, have been chosen to $0.1 mm/day$ for no flux conditions, $5.1 mm/day$ for drained conditions and $15.1 mm/day$ as free drain scenario. The result is on the one hand described as fitting of the simulated time series with the gauge and on the other hand represented as cumulative groundwater recharge versus cumulative precipitation (see table 9.2).

Table 9.2: Groundwater recharge assessment - Sum of Precipitation and Drained Water 1992 - 1996 under Different Boundary Definitions, Mod Catchment, Jhabua, MP, India

Precipitation	Freedrain	Drain	Confined
2496614400 m^3	892649784 m^3	47430666 m^3	3815032 m^3
100 %	35.7 %	1.89 %	0.15 %

The scenarios show a relatively good fit of the catchment's hydrologic behavior in scenario two and three. While the confined groundwater recharge condition overestimates the overall discharge, the drained boundary definition already seems to underestimate this amount of water. Further analysis could be conducted using the model and calculating the most likely fit of the catchment's reaction and the lower

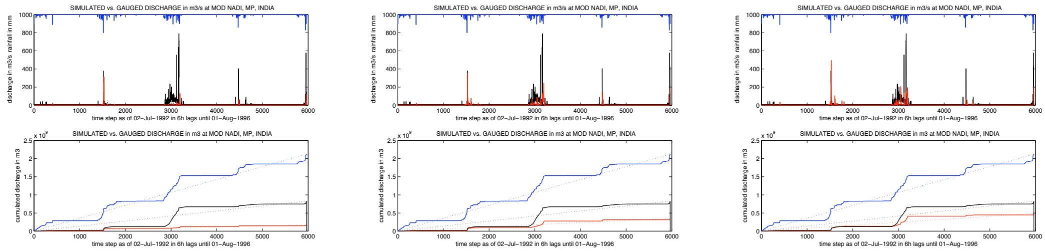


Figure 9.5: Groundwater recharge assessment - Simulation Results of Discharge Behavior under different Draining Scenarios. (a) Free Drain, (b) Drained, (c) Confined

Table 9.3: Groundwater recharge assessment - Quality Indicators for Fit of Simulated Discharge to Measured Discharge from Catchment

WASA Model Quality Indicators for Discharge from Catchment									
Run	MSE	$\sum \Delta Q$	$\sum$ abs(ΔQ)	R	bias	C2	ISE	RS2	E
Scenario 1: Free Drain at 15.1 mm/day									
WASA all TS	853.65	-29875.7	37054.4	0.36	-5.11	0.00	4.53	0.98	0.10
rain season 1	43.24	-769.4	1134.9	0.36	-1.78	0.00	2.99	0.99	0.95
rain season 2	136.46	-1586.4	4138.2	0.41	-2.46	0.01	1.69	1.00	0.87
rain season 3	1191.64	-22862.8	25183.8	0.30	-32.29	0.00	0.97	1.00	0.25
rain season 4	52.06	-2293.1	3867.2	0.35	-3.59	0.00	1.37	1.00	0.95
Scenario 2: Drained at max. 5.1 mm/day									
WASA all TS	748.94	-21702.2	35706.3	0.48	-3.72	0.00	4.25	0.98	0.21
rain season 1	41.76	-708.0	1102.3	0.48	-1.63	0.00	2.94	0.99	0.96
rain season 2	62.65	-672.2	3415.7	0.53	-1.03	0.01	1.15	1.00	0.94
rain season 3	1020.75	-16809.5	24047.0	0.44	-23.74	0.00	0.90	1.00	0.36
rain season 4	62.00	-1745.5	4154.1	0.47	-2.73	0.01	1.49	1.00	0.94
Scenario 3: No Drain at max. 0.1 mm/day									
WASA all TS	769.99	-15699.5	37120.0	0.49	-2.67	0.05	4.31	0.98	0.19
rain season 1	47.98	-584.1	1130.1	0.49	-1.35	0.05	3.15	0.99	0.95
rain season 2	307.50	728.0	5305.7	0.50	1.30	0.09	2.54	0.99	0.70
rain season 3	945.83	-12483.2	23981.3	0.48	-17.63	0.03	0.86	1.00	0.41
rain season 4	42.14	-1749.3	3717.5	0.49	-2.74	0.04	1.23	1.00	0.96

boundary flux parameter. But already these three scenarios propose, that groundwater recharge is lower than two per cent of the precipitation (compare tables 9.3 and 9.2 and figure 9.5). Hence further investigation on water availability in Jhabua is urgently needed. If the groundwater recharge proves to be gravely overestimated by the local authorities and the development of its exploration continues or even remains at the current level, the whole fresh water supply of the region is at risk.
During the field work massive groundwater consumption for irrigation was encountered at some villages, where even in the post-rabi season maize was cropped. Even without any study of available groundwater resources it is ridiculous to waste scarce fresh water to evapotranspiration and (cash)crop production in this semi-arid region.

A local development will always be hampered if basic needs of all people are not accessible to everybody.

10 Synopsis & Discussion

The work at hand did rush through many aspects of modern applied environmental science: From appropriate field work and remote sensing over a broad range of modeling approaches to sound process oriented modeling and strategy analysis as basis of a decision support system - many of the currently discussed restrictions of hydrological and environmental modeling had to be addressed. As the scope of this work as a master thesis without a broadly funded collaborative consortium did not allow exhaustive and detailed methodology development, there remains a high degree of uncertainty and arguable concepts which will be pointed out in this chapter.
There are also important results for the region's development and the scientific progress in hydrologic modeling of complex human-eco-systems which will be summarized here.

10.1 Synopsis

The project's target was to develop, setup and apply a hydrological model for decision support in a semi-arid sub-catchment which is able to analyze land use strategies independent of anticipated scenarios determining the results to some degree.
On the one hand the aim was accomplished, as the modified WASA/WOFOST has been successfully applied for the catchment of the Mod river in Jhabua, Madhya Pradesh, NW India. It was shown, that local adaptation of land use patterns are of much more benefit than knowing precisely the monsoon's precipitation in advance (see section 9.1.4). From the economical point of view, the question of production costs proved to be of major relevance over the rewards and harvest amount a farmer can achieve. This fact is certainly striking with regard to potential losses to droughts and erosion. Moreover the assumed groundwater recharge rate has been addressed and found as probably more than five times over-estimated by the authorities. There is further assessment and immediate action towards water saving practices and small scale water harvesting structures advised.

On the other hand the proposed model complex did not overcome most restrictions of the mechanistic bottom-up paradigm in hydrological modeling. As always some aspects and processes will be approximated or remain not respected in such models and as uncertainty cannot be clearly appointed to each compartment of data, parameters and process descriptions, the need for a unified hydrological theory at the catchment scale (e.g. Sivapalan 2005) has to be emphasized. Nevertheless the study employed plausibility over stiff data devoutness and presented a methodical framework to identify landscape patterns and representative properties from field survey and remote sensing. Especially with regard to ungauged basins, which includes catchments of high dynamics regardless of installed gauges (Bloeschl 2005), this could serve as one part in system description through a more comprehensive approach.

Yet it has to be stated that the soil-water-atmosphere-plant-system with the given interactions of land use and the region's water household is not entirely represented by the model. Many compromises and simplifications had be accepted. The dream of a real comprehensive simulation of the interactions in a human-eco-system, which e.g. could account for the influence of different cropping practices and certain small scale water harvesting structures, was by far not fulfilled. Although the following discussion might appear rather pessimistic, it shall serve as critical argumentation to be able to distinguish a new unifying hydrological paradigm on catchment scale from misleading mechanization of environmental processes.

10.2 Discussion

10.2.1 Field Work

Few Samples and Biased Sampling Sites

The whole 512 km^2 catchment was represented by some 81 samples and 136 recorded observation points. In order to have a statistically representative set of samples for each soil and land use class a multiple of this actually was needed. Most samples could not even be examined for all properties. The analytical methods bear lots of possible errors, too. The transects or regions of major interest are biased by a priori data given by soil and geology maps, by accessibility and subjectivity. The analysis of the hydrologic soil properties had to rely on benchmarks from only five samples from "subjectively" selected "representative" sites.
At this point the whole study already needs to be rejected as inappropriate, isn't it. It hopefully was possible to argue and show, that expert knowledge and a holistic approach is able to overcome some of the today's standards, which negate any knowledge before concluding from some investigations. The presented framework of course bears a high degree of uncertainty, but this might not only be due to few samples but rather due to the single sample's representativeness for the catchment's behavior.

Selected Parameters

It should be of question why it was chosen to represent the catchement's hydrologic behavior with grain size distribution, van Genuchten/Mualem parameters, and organic content. Why have cropping practice, swelling and shrinking behavior of the soil, altered infiltrability and fertilizer application not been of major concern? Why was soil moisture not measured during the field campaign?
The answer lies clearly within the proposed modeling approach based on WASA and WOFOST which do not (directly) employ these parameters. It is matter of uncertainty too, if the chosen indicators are able to represent reality on the appropriate scale.

Infiltration Measurement with Double Ring - a Bad Infiltration Estimator but a Good Interview Technique

Infiltrability on site can be considered as very realistic parameter. At the same time it reacts sensitively on every kind of macropore resulting in a high variability of consequent measurements at one site. The double ring infiltrometer is a standard method. It also proved to be highly inaccurate. In can also not really be assumed to reach any kind of steady-state flux at saturation when *three successive readings show the same flux rates.* It must be presumed, that neither the actual infiltrability of the soil surface was measured, nor that it represents any flux rate of the soil at saturation. Especially considering the high content of smectitic clays, the hydraulic conductivity might drop far below rates of 60 mm/h. Other methods, e.g. the hood infiltrometer, could have been employed. Long-term observations on larger scale could have delivered more reliable information. Moreover it should be pointed out, that the measurements were mostly taken without repetitions.

The double ring yet is a very simple instrument, which could be produced in a local welding shop. The concept is to some degree self-exlanatory, which enables the involvement of local farmers in the investigations. In order to collect information about the catchment a participatory approach can be the best way to learn to ask the right questions and to be understood. It is of absolutely no value to pose highly sophisticated inquiries to locals and authorities which cannot be comprehended. People who live from the fields of the region since generations, can best explain the landscape's development. And as the landscape's history is part of the current and future processes and conditions, this will enlighten a comprehensive understanding of drivers, thresholds, steady-states and overall behavior of the catchments compartments.

Local Heterogeneity vs. Generalization

It was introduced how many difficulties persisted to determine the high heterogeneity of the landscape of the catchment. The heterogeneity is manifold in the space-time-domain: the distribution of rainfall, soils and geology, crops and natural vegetation and many more. The decision for a daily time step simulation is justified as a day is not an administrative (or arbitrary) sequence, but represents a natural phenomenon. But rain events and harvests do not take place in daily steps. Hence it has to be rescaled which is connected to an elevated degree of uncertainty.

It is the same problem concerning the delineation of the landscape into the catena concept of WASA, where as a matter of fact highly heterogeneous toposequences are arranged into quasi-homogenous entities. The whole delineation process is based on a probably faulty classification referring to questionable parameters determined by unrepresentative samples analyzed with doubtful methods. But still the results have a quite high degree of plausibility because the presented framework did respect the interrelatedness of all compartments and emphasized realistic best guesses over single point measurements.

No Process Observations in the Field

Unluckily the project could not use parallel observations from remote sensing, field measurement and landscape observation of the processes. Although in the face of climate change it will become more probable to experience extreme events, which could not be observed before, a holistic approach identifying a catchment's behavior would surely benefit from records about dynamics in contrast to singular conditions. On the other hand one has again to point out, that a landscape has been formed during its history and lots of traces of this history can be found. Those are partly mapped in geomorphologic maps but mostly need expert knowledge about formation processes from a geo-ecological point of view and their scale in time and space. It appears rather likely that leaving the reductionist paradigm in hydrological modeling will need to develop a new standard for landscape analysis and new analytical aspects, which incorporate the information about organizing principles.

10.2.2 Laboratory Analysis

Precision of Laboratory Inventory and Methods

Many of today's laboratory inventories use in any way electricity. For all analytical methods samples and chemicals had to be balanced. Due to fluctuations in the electric current these weights are by far less precise than the electric display proposed. Additionally volumetric measurements could not always regard the expansion of water at higher room temperature. Thus considerable uncertainty is implicit in the sample processing.
An other aspect of precision is the used method itself. As different analytical procedures result in different results, the detailed description is given in section 4.1. The hydrometer method for grain size distribution analysis is internationally not accepted as standard. In the face of inaccurate balances and rather limited time for processing the samples, this method still appeared to be appropriate. But as settling times of suspended particles is crucial for this method, the rather short settling time of two hours for the silt fraction might have caused an overestimation of the clay content. Additionally the soil has been suspended in $(NaPO_3)_6$-Solution and organic matter was destroyed by H_2O_2. This will have some influence in the soil's structure which as a matter of fact has not been addressed.

ku-pf Apparatus and Clayey Soils

Addressing the behavior of the soil under unsaturated conditions is considered key to understand and simulate water flux. The ku-pf apparatus enables an analysis of almost undisturbed samples for their ku-pf response. For a sample of homogeneous sandy soil, the method might be very insightful because the major dynamic of the ku-pf-curve takes place around or above 2 pf. Clayey soils have a different water retention behavior, which becomes dynamic at much higher pf-values. Additionally shrinking causes cracks on the surface which of cause will most likely appear near the tensiometers inside the sample. Hence the validity of the observations are strongly reduced to the period until the cracks reach the tensiometers during the drying process. In contrast the pressure membrane apparatus revealed to be of much higher precision of its results.

10.2.3 Remote Sensing

Based only on 3+2 Landsat Images

For the analysis only three Landsat ETM+ and two Landsat TM images have been freely available. As introduced, the resolution of Landsat images in terms of spectral and spatial discretization is not suitable for every applications. In a highly heterogeneous system all pixels have to be regarded as a mélange of surface inventory below this scale. It was also shown, that similar supervised classifications of different images produced different results, which both might be wrong.
The images are singular "snap shots" of the earth's surface. There was no ground "truth" information for the day of the image available, which elevates uncertainty about results drawn from these images. Studies addressing the water content of a landscape cannot draw results from singular conditions of the top most soil layers and vegetation on incomparable points in time. Because of that it was proposed to use remote sensing as tool for a geographically explicit landscape analysis contributing to observations in the field. In every case the relative distribution of water and not any absolute indicator was basis for the classification.

Supervised Classification Using Maximum Likelihood

A supervised classification algorithm is conditioned by the user's input of identified region of interest (ROIs) as training sets with spectral properties. These identified classes might appear to the user as easily distinguishable but might prove to bear rather similar spectral properties. The maximum likelihood comparison of every pixel to the training set cannot decide on structures and plausible toposequences but only on mathematical compliance with any of the ROIs.
On the one hand this is an objective and comfortable method. On the other hand it is highly dependent on the classified ROIs and its geographic reference. The method does not consider knowledge about self-organization of landscapes. It can also not ask for contributory information in cases of low compliance to any of the ROIs. Remote sensing still appears as a suitable tool to analyze the behavior of landscapes and natural systems. A method stepping beyond structure analysis based on single point reference (in space and time) which considers self-organizing principles might overcome the given restrictions.

10.2.4 Base Data

Quality, Temporal Resolution and Assumptions of Gauged Discharge

For validation in the study at hand an almost five year time series of generally 6h gauge measurement was used. It was provided by the State Water Data Centre Bhopal in Singh (2004). A review of this data does conclude no good quality of the

data and high measurement error under intermitted runoff conditions (Singh 2004). In the calibration of water table height to discharge, a number of assumptions are again part of the algorithm. Mainly the determination of a flow by measuring only one dimension (the height) and estimating the cross-section but not having any information about velocity presumes a free flow downstream. As such any alternation of water tables in river stretches below the gauge must not influence the gauge-discharge relationship.
For the Mod catchment as part of the Anas and further the Mahi River Basin with rather gentle terrain this supposition might not apply in events of repeatedly high discharge from the whole basin due to back lock at junctions or weirs.
Further the temporal resolution of the data is of relevance. A highly dynamic system deserves much shorter time steps to represent the processes, especially when one can assume heavy rainfalls to last only few hours but generating major discharge of a whole season. Without knowledge about every rain event and its intensity - as implicit in daily precipitation data - there are statistical downscaling options but the process representation cannot be assumed as certain. In case of the gauge measurement, the single water level event within six hours is even more uncertain. One might determine a value far apart from a representative mean of the period without knowledge of the overall time span in a kind of cumulative parameter like the collected rain of a day.
Moreover the moment of measurement is of relevance. The quantification of rain of the last 24 hours might only consist of the precipitation almost 24 hours ago or be just the precipitation at this very instant. The assumption about the distribution of the collected rain over the time span will be the same.
Summarizing this excursus, aside of uncertainties of the measurement itself, there is much reason for disbelieve in the given data. Hence a statistical quality assessment must not only focus the fit of the model to measurements but critically address the plausibility of both time series.
To come back to the analysis at hand there are mainly two results from this excursus. First, the gauged discharge of the 1994 monsoon is overestimating reality. A comparison of the rainfall-discharge-reaction as simple linear models of rainfall and discharge delivers somehow comparable parameters for 1993, 1995 and 1996 but a much higher intercept and median for 1994. It is thus in doubt, that the gauged base flow did exist in reality and that the discharge from the catchment during 1994 has been 72% of the fallen rain, while in 1993, 1995 and 1996 only between 17% and 23% of the precipitation has derived to discharge. (See Appendix 12.12 for this analysis.)
Second, the statistical algorithms need to be modified to meet their assumptions. This could be a moving window approach averaging a time-span of three to seven days and delivering floating means to which then the algorithms can refer. The interpretation of each rainy season on its own is proposed, too. One might even think of a kind of boot strapping to treat even existing values as NaNs and revise their plausibility.

10.2.5 Hydrologic Modeling with WASA

Process Oriented Modeling and Tomographic View on the Environment

WASA actually is a very nice model which tries to represent organization patterns and presents an approach to regard the processes on the effective scale. It is highly transparent and allows changes in the process representation to a relatively high degree. Its strength might at the same time be also a restriction as the classic process description remains on equations which have been developed for homogenous laboratory conditions. The good approach of water fluxes on SVC-scale becomes arguable precise on LU-scale, as subsurface-flow and inter-flow revealed to be still improvable. Hence it is one example where based on a broad database small scale processes are simulated which cannot entirely be recombined to realistically represent the runoff of the whole catena. Generally the interfaces of all compartments appear to deserve improvement to follow the ambition of a catena approach. -static topographic domain

Static Topographic Domain for a Changing Surface

Hydrologic modeling of the human-eco-system mainly is bound to a static framework of its "sandbox". Many water driven processes are to some degree determined by topography which is represented in a digital elevation model derived from topographic maps, surveying or remote sensing. But landscapes are developing. A single rain event might change a plateau into a gully. Or a land slide might shift the river bed. Hence the topographic domain is not static.
The task to identify thresholds and principles in the combination of processes on completely different scales will be matter of environmental science for further development.

10.2.6 Modeling of Crop Development with the WOFOST Approach

Physicalization of Concepts

The approximation of a crop development through the accumulation of temperature quanta is impressive. It is also imposing how the self-shading of leafs, the photosynthetic activity and the creation of organic matter is actually reduced to a concise algorithm of radiation and plan specific parameters. Even interactions with the local water (and originally nutrition) conditions are considered.
At the same time none of the parameters does really have a measurable physical expression. The phenotypic behavior of a plant is highly dependent on interactions with other plants and micro-organisms. Studies showed that inter- and multi-cropping can elevate harvest amounts by 40% and more. Among a wast number of factors the whole cropping technique is not respected in the model. Moreover optimal or disadvantageous conditions like water logging or certain special circumstances during any development stage are completely ignored. The soil type too does not influence the crop's development in WOFOST.

For standardized conditions of large scale industrial agriculture in defined homogenous and flat terrain, the approach is probably a very good tool for production assessment as SWAP has been applied in several studies. The transfer of the reductionist concept into a dynamic hydrologic model needs to stress the limitations. It is advised to develop theories which can make use of long term experiences of farmers and which do respect cropping practices and vegetative patterns. For the representation of natural ecosystems even more investigation is needed.

Limited Degree of Freedom

As mentioned e.g. water stress, water regime, preferred conditions, micro-climate and other site related crop specific aspects have not been included in the WOFOST concept. The results from the simulations surprised with relatively low variance for unique years and crops throughout the catchment. Because of the determination based on very few parameters, one should reconsider the applicability of the de Wit - approach for dynamic crop modeling.
Although the algorithms use very detailed figures about local radiation, diffusion of light within the stand, temperature scaling etc. under the conditions of a rural human-eco-system the approach fails to employ driving factors. Possibly the theory presented by (Ursino and Contarini 2006) could be a good starting point for further development of tools which are applicable at the places and scales of need for food security estimation.

Limited Interaction within the Soil-Water-Atmosphere-Plant-System

As the model application showed, the hydrologic interactions of crops are rather unidirectional. While water stress is limiting the plant's development, stomatal resistance, water uptake and other factors do not feed back. The feed back is only relying on leaf area index, stand height and with some restrictions rooting depth. The water which is taken up by the plant is only estimated through these parameters. Additionally altered albedo was not yet implemented in the model.

10.2.7 Predictions of the Model

One might ask, what worth is the model if the hydrology is not really precisely simulated - which might have been also addressed through a water balance estimation - and the crop development routine appears to be somehow inappropriate for the given task of rural development assessment. One might also point out soil fertility, erosion and community organizing as much more important drivers of the human-eco-system at hand. Factors like migration, patriarchy and capitalistic economy drop out as core of the development problems.
And yes, the WASA/WOFOST model is not at all capable to calculate answers to all the questions. It might not even be capable to identify good land use strategies because of the restrictions presented earlier. But it can and did simulate hydrology and crop production under certain constraints. The proposed results are still considered as valuable advices. It more attention is given to adapted crops and to low

production costs for the farmers, this might elevate the farmers situation to be able to actively contribute to other projects as proposed in section 10.3.
Moreover it was pointed out, that the groundwater recharge might be overestimated. Hence the model might warn local stakeholders before it is too late. Nevertheless all results have to considered as uncertain in some degree, hence further observations are appropriate.
In terms of further development of hydrology-based environmental modeling the study at hand could be seen as preliminary study for a broader integrated project. As many restrictions of state of the art modeling were tackled a consecutive study can address the tasks differently. It was also possible to show what can be done from the scratch and what indicators from the field can be used for a system description. It hopefully was also convincingly shown, that comprehensive fieldwork and extensive research at local authorities and NGOs can provide an expedient data base for process modeling.

Strategy Analysis based on WASA/WOFOST

Section 9.1 introduced the results from simulations of different agent constraints under different weather realizations. It had to be concluded, that the combined model WASA/WOFOST was only able to account for some effects of land use-hydrology-interaction in a semi-arid human-eco-system.
It will not be discussed that there is considerable uncertainty in all assumptions, estimations and technical realizations of the model as introduced in section 1.2 and earlier in this chapter. The concept of simulating the plant's physiology in a relatively detailed and dynamic hydrologic framework proved not to respect all interactions, which could be regarded as drivers. Certainly for erratic monsoon rainfalls a representation of the complex dynamics of infiltration, which is influenced by the type and time of cultivation, by the moisture and swelling status of the soil and by the plant and cropping patterns. Hence WOFOST or SWAP as models for large-scale homogenous agriculture production estimation to some aspect cannot reckon processes on plot or even plant scale.
One might think, that a new subroutine respecting cultivation patterns and infiltration/surface dynamics, including cracking, siltation, different crops etc., might overcome the mentioned restrictions. But still there actually is no data about infiltation at this scale. There is also no interactive erosion-deposition of top-soil simulation. There will also be no subroutine accounting for irrigation and the groundwater withdrawal or water harvesting structure. There are many more aspects on different scopes and scales which all need to be integrated and could be considered by the proposed agent or a multiagent system, enabling also community interactions. But in the end the system will still be uncertain and mainly driven by infiltration access overland flow. The need for data would be tremendous and one still was not really able to incorporate expert knowledge and long term experiences of the people. As (e.g. in Klemes 1983, Sivapalan 2005, Nash and Sutcliffe 1970) discussed, the restrictions of mechanistic determinism and uncertainty demand a more integrated approach to catchment ecology and hydrology.

10.2.8 Overall Strategy of this Project

Focus of the study at hand was to develop a decision support tool focussing the rural communities of the Mod catchment in Jhabua, Madhya Pradesh, India. In every step a deep concern for the needs of local people to decrease their vulnerability to droughts and insolvency has been carried. The presented approach of a comprehensive landscape analysis and its representation in an eco-hydrologic model is proposed to be developed further and to enable everybody to contribute and benefit from it.
It has to be admitted, that the way towards a due decision support model which can be distributed freely is still long. Some steps could be done in this study. Besides the proposed options for land use strategy development, possibly science itself might be major beneficiary of the project at this stage. But in the long run, hopefully tools will be developed which will serve the people's desires and to help us finding sustainable solutions for our future.

Resources

The study at hand did also present methods without expensive and highly-sophisticated equipment. The emphasis should lie on expert-knowledge to be able to identify structures and organizing patterns. The project did not exhaust any funding because most of the used data and software is publicly available as open-source. But it had to exhaust investigative power and creativity.

Focus of the Study

In the face of obstacles in process description in available models, weak data and unexplored methodology the study gave one example to set up and adjust a model from the scratch. The lack of theories for organization principles and overall catchment behavior had to be compensated with plausible data and parameter sets. The interactions of social, environmental, infrastructural and economical processes had to be reduced to land use. Market access, mobility, knowledgeability and access to information, labor time, food demand, healthy nutrition needs, fresh water supply, sanitation, migration and many more factors have not been integrated.
A really integrated model should consider at least some indicators of these. Yet already the identification of any best land use policy proved to be not unambiguous. A reduction of uncertainty through the interrelatedness of processes towards plausible bands of behavior is imagined to address this dilemma.

Driver Identification for Land Use - Hydrology Interaction Modeling

It might be a weak point of the study at hand that there has been no due analysis of main drivers in the human-eco-system conducted before deciding for a model and process simulation approaches. Exemplarily infiltration shall be named here. It is obvious that different cropping practices have a high impact on infiltrability of the soil. It was found that the soil was prepared at the end of rabi season to be able to absorb as much water as possible when the monsoon is approaching. Effects on crusted cracked surfaces are also dependent on vegetation, soil matrix, its shrinking and swelling

behavior and other factors. In face of rather unascertainable representation of water movement in unsaturated soils these (not regarded) drivers might have strong impact on the overall water household.
Generally the driver-pressure-state-impact-response (DPSIR) framework could serve as base for such identification process. In any case, the interconnectedness of processes in the time-space domain has to respected.

10.3 Further Findings during Fieldwork

As mentioned earlier several ideas for an analysis of land use related aspects to the water household of the Mod catchment could not be realized. It shall be shortly addressed now, what ideas have been developed during the two months in Jhabua based on experiences and interviews.

The Erased Forest

Degraded shallow soils and severe risks of flash floods near hill sides are common. The steep slopes of the hills elevating some 200m above the mean level cannot capture much precipitation. The waste lands are only sparsely vegetated by grasses. At the same time eager projects started to replant some trees and to construct small traps to decrease surface runoff and erosion. Many of these structures have been found demolished. Replanted trees were drought or eroded because the soil layer was too shallow.
A proposal is to reproduce a natural evolution of an forest or bush eco-system. Thistles or special grasses could be used as pioneer species which prepare a fertile and reinforced soil layer. Then successively larger plants are introduced which are capable of very dry conditions and produce rather roots then heavy leaves and other organs, which amplify the risk of land slides. After an initial period the induced eco-system could develop further on its own and form a big water storage. Of cause such a process will not be accomplished within a few years. It might take more than a decade to reach a somehow stable state.

Besides, approaches of agro-forestry could help to reduce evapotranspiration losses from the fields. It is matter of further investigation to find a structure and suitable project areas for that. A highly transpiring tree species might be even disadvantageous. Yet agro-forestry proved to be a valuable approach to minimize erosion and soil degradation in many regions in the south.

Small-scale Water Harvesting Structures

The whole catchment lacks water harvesting structures. The very few open reservoirs can only be accessed by farmers nearby and have high evaporation losses. As presented in (Agarwal and Narain 1997) many traditional, easy to build techniques exist and should be employed to preserve ground water for drinking purposes. It is also imagined that clever systems of water harvesting structures on communal level can enhance the overall productivity and decrease erosion and harvest losses. For a detailed compendium about projects and structures it is referred to publications of the *Centre for Science and Environment, New Delhi, www.cseindia.org* (e.g. Agarwal et al. 2001) and (Agarwal and Narain 1997).

Further arguments and findings are compiled in the executive summary.

11 Executive Summary

The work at hand tried to always focus its practical applicability to the problems Jhabua and other semi-arid regions are faced with. Although intensive work had to be given into theoretical development of the methodical framework this chapter shall give a brief summary of the analysis and findings from the model application and field work. It is meant for locals, NGOs, GOs and other policy-makers.

11.1 Setting of Jhabua and the Mod Catchment

The Mod catchment and Jhabua district was found as rather typical example for the tropical rural world at the beginning of the 21st century. Although relatively well connected to the major infrastructure connecting the country's centers it is very much periphery in many senses. Typical problems of desertification, degradation of soil and water quality and quantity, erosion and a generally difficult social-economical situation are characteristic.
As to be observed at many places of the world with deforestation and intensification of agriculture the drastic shift of the whole complex of energy, matter and nutrient household at the earth's surface began. The result today are deserted landscapes with shallow skeletal infertile soils, relatively low capacity for water retention from the erratic monsoon rains, fast infiltration excess overland flow generation, erosion of the top soil etc. Additionally a shift in the social structure can be observed in terms of relatively high population pressure accompanied by low accessibility to education, healthcare and economic participation[1].

11.2 Topic of this Study

In order to find ways towards sound hydrology based decision support modeling, the study at hand presents a methodical framework of data acquisition, data analysis, model setup and its application for strategy analysis. Its major perspective deals with general land use constraints, the identification of possible controllers of the water household to influence and an assessment of additionally possible policies for a sustainable development of the region.
The presented approach had to deal with several limitations of current state of the art

[1] One outstanding reason to this can be found in persisting social exclusion of adivasi (aboriginal) groups such as the Bhil which account for 97% of the population here. While language barriers, inherited patriarchy and other hierarchies restrict access to participate on administrative level, foreign induced agriculture and capitalistic structures to some degree force the locals to seasonally migrate for labor, to seek their survival in cash crop farming and to abandon sustainable methods in favor for "modern" intensive agricultural techniques.

hydrologic modeling, data processing and geostatistics. The many technical notes will be excluded from this summary, yet it shall be pointed out, that far more development in the field of applied theoretical environmental science is aspired. The work at hand did not exhaust any high donated budget, hence it shall serve also as example for other low-budget projects by NGOs and GOs.

11.3 Findings During the Fieldwork

Before the results of the model will be presented attention shall be drawn to some aspects which could not be included in the model until now but which became apparent during the investigations on site.

11.3.1 Deforestation and Reforestation programs

The fact that deforestation is one of the major drivers of the whole complex of desertification is acknowledged (e.g. Falkenmark et al. 1989). Some of the heavily eroded bare slopes of the hill sites in the catchment have been addressed with reforestation projects. Even erosion protection was given, many of the nursery trees unluckily still have fallen to drought and erosion. It can be assumed that these trees do hardly get sufficient water and nutrients to endure the long dry period. Situated at the (steep) slopes on shallow skeletal soils if some water can be captured by the soil it soon will be drained or evaporated.
It is proposed to develop strategies to reproduce natural succession starting with some pioneer plants which could be thistles or grasses with low water requirement, deep strong roots and moderate biomass production. For income generation safflower could serve this purpose which can besides stabilizing the slopes and initiating some organic matter produce oilseeds and flowers for further processing on local scale (e.g. Kar et al. 2007). From this start more and more large plants can be associated to initiate a self-stabilizing ecosystem. Special concern should always lie on the delicate equilibrium of plants needed to sustain this ecosystem and to retain enough water and nutrients for own metabolism and the carrying capacity of the site, in order to avoid landslides caused by too heavy above ground vegetation, intercepted water, water pressure at high moisture conditions and insufficiently firm cohesion of bedrock and soil (e.g. Chen 2006).

11.3.2 Small-scale Water Harvesting Structures

The whole catchment lacks water harvesting structures. The very few open reservoirs can only be accessed by farmers nearby and have high evaporation losses. As presented in (Agarwal and Narain 1997) many traditional, easy to build techniques exist and should be employed to preserve ground water for drinking purposes. It is also imagined that clever systems of water harvesting structures on communal level can enhance the overall productivity and decrease erosion and harvest losses. For a detailed compendium about projects and structures it is referred to publications of the *Centre for Science and Environment, New Delhi, www.cseindia.org* (e.g. Agarwal et al. 2001).

11.3.3 Just Groundwater Conservation

As introduced the high pressure of any profit from the meager farm lands to sustain a living can be seen as one major driver of decisions and actions in the region. Most of the previous shifts in land use and the deforestation can be regarded under the paradigm of personal profits over public commodities. That this happens not due to evil will but to economic pressure and wrong planning shall not be addressed further here.

This paradigm did not change until now. Who is able to access water will use it - independent of any social considerations. Certainly for groundwater resources it is irresponsible to use the scarce good for maize production in late rabi season while at the same time many of the public tube-wells are drought already. It will be showed later, that the groundwater recharge is a severe topic for the region (see section 11.4.2).

11.3.4 Community Organizing

A comprehensive approach to cope with the problems could start with a step backward. One has to realize that it is impossible to turn Jhabua into a prosperous region of wealth within some years and with the same attitude of export production of valueless agricultural products. Certainly the communities will fall apart when local problems and social differences amplify. At the same time projects will need to be soundly developed within local structures. A reforestation program which is not maintained fails due to the same reason as larger reservoirs cannot make a difference. If the communities are given some degree of sovereignty in decisions, in land use planning, in water harvesting and in funding of cropping, construction, maintenance and distribution coupled with information and assistance, future projects might fall on fertile ground (e.g. Gala 1997, Albert 2004).

The subsistence of the communities stands in first place. Seeds can be nursed free of charge and locally adapted. Water harvesting takes place on small scale and is distributed to the benefit of the whole village and not exploited for the profit of few. A local adaptation of the crops (see also section 11.4.1) will also be much easier, if the community decides based on its needs and options instead of a single farmer.

An organization on village scale can also create new options for exportable products which are processed and hence can achieve much higher gains compared to the raw material. Here GOs and NGOs should assist with trade networking.

11.3.5 Agro-Forestry and Multi-Cropping

Several studies exist which present highly improved cropping and water household conditions in agro-forestry and multi-cropping systems (e.g. Young 1989). Even it will be a long way to re-establish an intact system of trees and fields beyond and one will need to assess which species are appropriate for the region, a system elevating the canopy, increasing interception, decreasing erosion and retarding overland flow will be very favorable.

11.4 Findings from the Model Application

11.4.1 Land Use Strategy Assessment

An agent based simulation of different land use strategy was developed and applied. Even only a small set of possible cropping constraints was examined (see chapter 9) the following conclusions are drawn.
In contrast to the common belief weather anticipation proved not to be key to high productivity and profits. Although highly water demanding crops will be lost to drought in years with insufficient rain. Major positive impact on productivity and gains is to be expected from local adaptation. Moreover it has to be pointed out that production costs are far more influential on benefits from agriculture than any other factor. Further it is to be pointed out that the water household is positively effected by any cropping (except of irrigated cultivation) compared to fallow or barren lands. As discussed these findings are matter of further assessment because the developed model has not been validated under many circumstances. They shall give arguments for further development and pilot projects.

11.4.2 Groundwater Recharge

Groundwater as source for drinking and fresh water supply and irrigation is further explored by local authorities and individuals. Based on findings from well observations the State Water Data Centre Bhopal issued figures of about 30% development of groundwater utilization. The model was also used to recursively estimate the groundwater recharge rate within the catchment. While super-ordinate contributions to the groundwater household have be neglected[2] a recharge rate of about 2% of the precipitation is estimated. If the groundwater recharge proves to be gravely overestimated by the local authorities at about 10% and the development of its exploration continues or even remains at the current level, the whole fresh water supply of the region is at risk.
In dry season groundwater is virtually the only on-site source of drinking water. If it is wasted for irrigation and overexploited aquifers might suffer salt water intrusion or irreversibly fall dry.

11.4.3 Inter-seasonal Hysteresis

In compliance with observations precipitation and water storage during rainy season does influence the conditions of the whole year. Certainly on deeper clayey soils of smectitic type even the surface dries up completely considerable amounts of water can be stored within greater depth.

[2] This might be valid assumption because the Mod catchment is a headwater of the whole Anas and Mahi River Basin and the conditions within the wider region appear mainly rather similar.

Hence on the one hand it is worthy to address this characteristic by opting for crops with low transpiration and deep roots and by increasing the soils storage capacity on degraded sites - which undoubtedly is a longer development process. On the other hand one should be careful when addressing the state of the catchment's hydrology and vegetation from singular remote sensing or ground observations (compare Agarwal et al. 2001). As infiltration excess overland flow accounts for the most prominent path of the water even higher annual rain sums might not completely recharge the catchment's water storages, when the sum of precipitation is only due to few erratic events

11.5 Final Remarks

Addressing a complex system like a landscape within its generic history, processes, scale and interacting framework is no linear action and reaction mechanism after the Newton principle. Nor can such a system be merely described as sum of its compartments determining its behavior for any future.
The study at hand could find some ways to include process and experimental knowledge in order to understand and represent the system. But by far it was not able to comprise all imaginable and unimaginable factors contributing to the system. Hence I would like to end this thesis with two conclusions:
The qualitative knowledge about the landscape based on long term experiences might be superior to any sophisticated measurement. Hence the combination of experiences of local people and knowledge about driving processes might together develop to suitable solutions to the current problems.
The presented methodical framework, analysis and findings are matter of further development, critical challenge and possibly disapproval, if more appropriate approaches are able to represent the human-eco-system more realistically.

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12 Appendix

Because most of the material which shall be provided as appendix is more interesting on file than on paper, all relevant files are linked here. The hardcopy version holds a DVD with these files and all related source code for further improvement and application. All provided files are given under Creative Commons License. The DVD also holds a folder of supplemental material where a selection of data from the study and other developed routines are assembled.

12.1 Soil Pits - Data Sheets

Link to Data Sheets of all Soil Pits as pdf-File: soilsamples.pdf

12.2 Ground Water Recharge and Development

The State Water Data Centre Bhopal gives the following Evaluation about the Groundwater Resources in Jhabua District: GroundwaterDevJhabua.pdf

12.3 Well Observations of Pre- and Post-Monsoon Water Table

Link to Graphs of Water Table in some selected Wells (H.K. Jain et al. 1993): wellgraphs.pdf

12.4 Mechanical and Chemical Soil Analysis

Link to Table of Grain Size Distribution Analysis as pdf-File: grainsize.pdf
Link to Table Summarizing all Soil Data as pdf-File: samples_summary.pdf

12.5 Van Genuchten Parameter Fitting

Link to Matlab-Script for Van Genuchten Parameter Fitting Routine: pf_fit.m

12.6 Preprocessing of WASA Inputs

Link to MS Access Database holding the Parameters of the Catchment: wasadata.mdb
Link to Matlab-Script Meteorological Input Data Preparation: metoanalysis.m

12.7 Modified Hargreaves for Evapotranspiration

Link to Matlab-Script of Hargreaves Potential ETP Calculation: ep_hargreaves_2_2.m

12.8 Result details of original and modified WASA application

Simulation Results using (a) original WASA and (b) modified WASA for Mod catchment data. Each provided for all four covered rainy seasons 1992 - 1996: a) detailgraphsimorig.pdf, b) detailgraphsimnow.pdf

12.9 Cropcontrol

Link to Fortran90 File Controlling the Cropping: /wasa/hillslope/cropcontrol.f90

12.10 Crop Development Routine

Link to Fortran90 File Holding the Crop Development Routine after WOFOST: /wasa/hillslope/cropdev.f90

12.11 Post-processing of WASA outputs

There are several scripts given as supplemental material which all serve different aspects to analyze the results from simulations of the modified WASA. Some selected post-processing tools are given here:
wasa_interpretation.m
wasa_stats.m
wasasimulationanalysis.m

12.12 Statistical Precipitation-Discharge Analysis

This is the R-Script using R (R Development Core Team 2006) for a statistical analysis of precipitation and the catchment's reaction in form of discharge. It refers to the explanations in Section 10.2.4. Link to R-Script as pdf File: appendix_rscript_temp.pdf

12.13 Weather Generator

Link to Matlab-Script of Weather Generator: weathergenerator.m

12.14 Cropping Agent

Link to Fortran90 File of the Cropping Agent: /wasa/hillslope/cropcontrola.f90

12.15 WASA Simulation Analysis

Land Use - Hydrology - Interactions: Simulation Results and Environmental Parameters

Link to pdf File with Statistics of Environmental Parameters of the Simulation Results: simulationresults_environpara.pdf

Simulation Analysis and Parameter Estimation

Link to R-Script for Simulation Result Assessment and Parameter Preparation: wasa_XXL_analysis2.

Agent Performance Beyond the Scope of Annual Averages

Link to R-Script of Simulation Result Analysis: r_wasaout_x.r

Declaration on Honor

I herby declare to have conducted the study and to have written this thesis on my own. All external sources and references are marked in the text. No other means than mentioned have been utilized.

Ich versichere hiermit die vorliegende Arbeit eigenständig verfaßt zu haben. Alle benutzten Quellen und Hilfsmittel sind im Text genannt und referenziert. Weitere Mittel wurden nicht verwendet.

Potsdam, March 27, 2007

Conrad Jackisch