Hydrol. Earth Syst. Sci. Discuss., 8, 7499–7554, 2011
www.hydrol-earth-syst-sci-discuss.net/8/7499/2011/
doi:10.5194/hessd-8-7499-2011

Hydrology and
Earth System
Sciences
Discussions

Applying PUB to the real world: rapid data assessment

C. Jackisch[1], E. Zehe[1], and A. K. Singh[2]

[1]KIT Karlsruhe Institute of Technology, Institute for Water and River Basin Management, Department of Hydrology, Kaiserstr. 12, 76131 Karlsruhe, Germany
[2]Nirma University, Department of Civil Engineering, Sarkhej-Gandhinagar Highway, Ahmedabad, 382 481, Gujarat, India

Received: 19 July 2011 – Accepted: 22 July 2011 – Published: 2 August 2011

Correspondence to: C. Jackisch (gg54@iwk.uni-karlsruhe.de)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

"Predictions in Ungauged Basins" are a challenging task – especially when it comes to meso-scale rural catchments. We present a rapid data assessment scheme based on a functional perspective on the landscape for a hydrological land use decision support model. A hierarchical merging of top down and bottom up approaches combines hydrology, soil physics, agronomy and meteorology in a common nomenclature.

The study at hand is an example to bring PUB to real world application.

1 Introduction

1.1 Motivation

The development of rural areas concerning food security, sustainability and social-economic stability are key issues for the globalised community. Especially in semi arid climates we often find fragile agricultural ecosystems, severe and frequent water shortages and floods together with high production demands and limited land use options.

Facing the big changes in land use, climate and social structures a highly integrated assessment of the human geo-ecosystem is deemed to find solutions to the issues at hand. Yet, this integration is most needed at places where it is most difficult to be realised. On the one hand these areas are periphery and hard to access. On the other hand we have to deal with limited or even absence of data.

1.2 The ungauged catchment problem

The PUB (Predictions in Ungauged Basins) community strives since the initiation of the IAHS decade (Sivapalan et al., 2003) for addressing this misbalanced situation that hydrology is critical to virtually all big challenges we are facing all over the world but is used rather rarely to address them (Beven, 2006).

Limited transferability of findings of one case study to other sites (“uniqueness of place”; Beven, 2000), a lack of catchment classification schemes (Wagener et al., 2007), ad hoc assumptions which need specific calibration to compensate the lack of knowledge about heterogeneity and process interactions (McDonnell et al., 2007) and the unresolved ambivalence of preferential threshold behaviour and continuity approaches (Uhlenbrook, 2006) are only some of the broadly discussed issues of the hydrological community. Although it is aiming at real-world-problems, PUB is primarily a theoretical discourse so far. Our experiment shall contribute to the discussion by asking how to approach ungauged catchments, how to complement the bits and pieces of accessible information and how to validate it.

1.3 Study setup

The present study is as far as we know one of the first missing experiments to assess necessary data for a decision support system (DSS) in a targeted approach that aims on balancing (a) complexity of field methods while (b) being limited to assess a minimal adequate set of information about the landscape structures. Eco-hydrologic system understanding serves as overarching binder.

We allowed ten weeks intensive field work and data collection in the 512 km^2 Mod catchment and some other ten weeks for laboratory analysis of samples – all under particularly limited budget of travel expenses, laboratory contribution and field equipment to be realistic about “real world” applicability. It shall be stressed that the whole data gathering process was basically done by one person alone. Further, we coupled two physically based state-of-the-art models for hydrology and crop dynamics and extended these towards a decision support system (DSS).

1.4 Scale

The scale of our study is of some importance as the setting at hand is neither small enough for proper instrumentation nor large enough for simplified approaches and remote sensing. Yet, this scale – the lower mesoscale – is the level social interaction takes place and cropping – or more generally land use – decisions are taken. It is also the scale of eco-hydrologic structure at system level.

The lower mesoscale is understood as intermediate scale between a singular plot or soil column of some 10^0 to 10^1 m extend and the subbasin with more than 10^3 m extend (e.g. Samaniego and Bardossy, 2006; Uhlenbrook et al., 2002). Hence, we regard the system at a scale above pore-scale physics and below largely integrated system behaviour. The bounds are basically the intersection of the PUB situation with a lack of distributed small-scale data and the degree of heterogeneity of eco-hydrologic structures in the landscape.

As eco-hydrologic systems are structured at all scales and the obtained structures are scale dependent (Schulz et al., 2006; Vogel and Roth, 2003) our focus is set by the regarded processes and entities. From a process perspective Zehe and Sivapalan (2009) argue that major responses of hillslopes and catchments are controlled by dominant emerging structures. The Mod catchment under study is shaped by family run fields of some few hectares and a rather diverse topography. For the question of land use interactions within the water budget, the scale stretches from the local soil-water-atmosphere-plant system over the land-use decision scale of some hectares to runoff generation at the catena of some kilometre length. The catena is also the leading structure for the hydrological behaviour.

1.5 Uncertainty

A sparse data basis makes any modelling approach rather uncertain. However, this is the rule in applied hydrology outside the few heavily instrumented experimental basins. The credo of our study is a synoptic view on the system under study. We believe that consistency with eco-hydrological understanding, a functional description of landscape entities and a framework of a common language will reduce uncertainty much more than some more samples in our data set.

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. A hierarchical approach based on some representative samples will be presented. General plausibility shall be of more importance than any best fit of discharge curves. Moreover the integration of qualitative data and information from several sources will be used to improve the data situation and thus realism of our model.

1.6 Overall target and study questions

By setting up a dynamic eco-hydrological decision support system (DSS) we aspire to answer the overarching question: What is an *optimal* land use strategy for the Mod basin?

We decided to integrate two process based models for semi-arid hydrology and crop development, which will be introduced later, into a common framework of an agent-based DSS. Having these models in mind but still not being limited to them we can point out four key goals:

Goal 1: Compile a *functional* soil map that aids (a) setting up the hydrological model but also provides (b) sufficient information for the cropping issue.

Goal 2: Derive a *functional* map of (potential) land use which uses a compatible nomenclature with goal 1.

Goal 3: Step beyond biophysics: Find linkages between hydrology, pedology, meteorology, economy, politics and the land use decision by the farmers. What information is suitable and accessible for this integration?

Goal 4: Assess hydro-meteorological data for model setup, application and validation.

Along these goals some central methodological questions arise:

- What is the minimum amount of information that is necessary to setup a DSS to assess land use strategies?
- Is it possible to assess this information along a different avenue we call rapid data assessment – compared to more expensive integrated projects and the PUB setting?
- To what degree is coupling of process based models for catchment hydrology and crop production a reasonable way towards a DSS?

Although the modelling is not topic of this paper, it shall be stressed that the decision on the model suite was taken preliminary to the data collection. As basis for the integration we employ the deterministic rainfall-runoff model WASA (model of Water Availability in Semi-Arid environments) (Güntner and Bronstert, 2004), which uses a hierarchical catena based approach and was tested to be applicable virtually without calibration for semi-arid regions. This is extended by the crop simulation module after the de Wit approach as in SWAP (van Dam et al., 2008), which calculates crop stand development and yield based on the degree-day concept and has been successfully applied for agricultural settings also in northern India (van Dam and Malik, 2003).

1.7 Structure of the paper

This paper presents the first part of a comprehensive study. It focuses on the development and realisation of a low budget rapid data assessment scheme. We do not intend to present yet another case-study but to propose a targeted approach based on system understanding, a linkage beyond bio-physical landscape description and to testify its applicability in the face of PUB and decision support modelling.

The coupled modelling of hydrology and crop development utilising the data towards a decision support system will be left to a forthcoming paper. There we will validate the gathered data set and testify the idea of model coupling as one possible answer to the PUB question.

2 The rapid data assessment

We developed and conducted a low budget rapid data assessment using multiple methods with clear focus on landscape functionality, complexity of the problem setting and minimal requirements for the model suite. A very scarce data basis, the "mesoscale" problem setting and urgent issues for the local community settle the study at hand right in the epicentre of the ungauged catchment problem (Sivapalan et al., 2003) – the issue of questionable representativeness of observations (e.g. Liu and Gupta, 2007), short observation periods, limited understanding of specific catchment dynamics, the integration of *soft* and *hard* data, remote sensing and "ground truth", limitation of scenario analysis (Postma and Liebl, 2005) and real-world problem oriented environmental science.

2.1 Scarce data basis and limited assessment resources

Working in data scarce regions requires a revision of standard catchment analytics. As expansively discussed in the PUB initiative (Sivapalan et al., 2003) it appears hardly possible to sufficiently observe virtually all catchments on the planet. At the same time ongoing changes violate the precondition of system stationarity. Fragmented time series, statistics without geographic reference and high uncertainty are the best one can expect. Global data sets and remotely sensed information are hence an important basis for our assessment which brings us back to the challenge of scale and ground truthing.

Clearly one option to approach this was to set up a broad task force bringing together different groups and expertise, which certainly deploys many advantages. The big drawback remains the issue of funds for instrumentation, operation and not least group collaboration on the one hand, so the studies remain largely single site solutions. On the other hand we have to deal with the issue of many cooks striving for a common language (Fenicia et al., 2008).

We propose a different avenue that is much cheaper and has the great charm that the integrated assessment is carried out be a very small team – basically one person. This requires the synopsis of many disciplines and methods and will certainly be an approximation of long term specific investigations. However, we avoid the problem of being lost in translation with scientists from too many disciplines. We aim at the identification of key feedbacks and properties over extensive measurements, which are beyond scope of this study.

2.2 Mesoscale

The Mod catchment under study stretches over some 512 km^2 which is quite large compared to other assessments in data scarce remote regions like e.g. Mallalcahuello, Chile (6.3 km^2) (Blume et al., 2008). Also compared to well instrumented and well analysed experimental basins like e.g. Brugga, Germany (40 km^2) (Uhlenbrook et al., 2002), Weiherbach, Germany (6.3 km^2) (Flury, 1996; Zehe and Flühler, 2001) or Maimai, New Zealand (eight small catchments between 1.6 and 8.3 ha) (McGlynn et al., 2002) the Mod catchment under study is clearly at a different scale and scope. At the same time highly heterogeneous pedology, landuse and topography at this scale require information complementing MODIS or LANDSAT imagery. Yet it is too small to refer to global data sets of large basins with long integration distances. Moreover the catchment is intensely used and decisions are taken at the field scale. Hence, strategies applicable for large regions (e.g. Upper Zambezi in Winsemius et al., 2006) lack the necessary details.

Thus we have to assess structures and patterns that dominate the natural architecture and human interactions. We propose a combination of smart field sampling, which is biased towards leading structures and model requirements, and remote sensing, to bridge scales and data gaps. This is further extended by interviews with farmers and concerned Non-Governmental Organisations (NGOs) and general statistics of the local and regional administration.

Facing this delicate problem setting we still understand the given setting as rather common than exceptional. This is where wise advises are urgently needed, data is scarce and where hydrology needs new avenues to collect adequate information for decision support modelling.

2.3 More than a bio-physical problem

A mayor challenge is to balance the necessary degree of detail in bio-physical observations and "synoptic working". We also have to bridge natural architecture and human interactions. What are realistic cropping patterns, land use practices and constraints by soil, water, farmers' believe and economy? How can we measure and account for feedbacks? What knowledge can be transferred from other studies and is feasible to be applied here? How can we integrate this into a setup for decision support?

While goal 1 and 2 (Sect. 1.6) refer to the landscape setting our third goal is much harder to be grasped within the same nomenclature. Yet, wet have to ensure that the functional classes which we can identify under one perspective (e.g. from a pedological perspective) are also suitable for the other aspects (e.g. hydrology and cropping). When approaching our goal 3 we have to find out what drives the farmers' decisions. This aspect becomes even more entangled when we take a look at their mostly desperate situation as Adivasi subsistence farmers and mostly seasonally migrating working poor (Banerjee, 2007; Scholz, 2004) and internal hierachies (Pande, 2003). We interviewed farmers about their regard on cropping, their options, their dependencies, their practices and their timing. The picture becomes complemented by data from the agricultural marketing board (MANDI), the district agriculture office and interviews with related NGOs and authorities.

Moreover, goal 4 opens up an additional challenge: How to join the bits and pieces of hydro-meteorological information to a reasonable data set which is needed to (a) train a weather generator and (b) validate the model suite.

3 Study site and setting

3.1 Study site characterisation

As study area the Mod catchment was chosen. The 512 km^2 large catchment is located in central north-western India in the District of Jhabua, State of Madhya Pradesh, between 22°46′ and 22°30′ N latitude and 74°20′ and 74°35′ E longitude. Figure 1 presents an overview. It is classified as hot semi-arid ecoregion receiving between 350 and 1600 mm of rain per year. The precipitation almost entirely falls in the monsoon season between June and September – basically within a couple of erratic rain spells. The gross water balance is negative with a water deficit of 800 to 1200 mm a^{-1} and above.

Generally, eroded clay and loam soils prevail. The geology of the catchment exposes remarkable heterogeneity of basaltic lava, feldspar-quartzite formations and cretaceous sand- and limestones. The topography is undulating between 500 and 300 m altitude (a.m.s.l.).

The region has encountered drastic deforestation since the late 1960s reducing the once prevailing forest below 5 % of the basin's area. Additionally agricultural practices rely on intensive use of ground water and agrochemicals. Large stretches expose a very meagre, skeletal, thin top soil layer. During dry season the region experiences severe water shortages when water has to be imported by trucks. Many wells have drought or turned salty.

3.2 Horton landscape and Catena as leading topology

This setting already points us to dominating processes: Infiltration excess surface runoff plays an important role in transforming the erratic rain spells into discharge (precipitation driven case). Evaporation and transpiration under strongly water limited conditions are principal during the dry season (radiation driven case).

To characterise this Horton landscape the catena, which is understood as the generic sequence of the whole geologic and hydro-pedologic system along a hill slope, is the structure we can observe and which bridges observation, theory and modelling (e.g. van De Giesen et al., 2000). It is noteworthy that from a functional point of view the catena is not a one-to-one image of base maps and interpolated sample values. We propose the functional catena as sequence of terrain components which are characterised by the dominant processes. The concept bears draw backs in generality but it enables us to comprise relative differences along the leading topology. Moreover, it allows the application of hillslope hydrology process knowledge which does not necessarily need to be specifically parameterised for every single slope.

3.3 The data basis at start

The starting point of the present study is the work of Singh (2004). The available data was basically a set of maps compiled by the Geological Survey of India during the 1970's and 1980's. Namely these are a topographic map 1:50 000; a geological map 1:350 000 and a soil map 1:350 000 (GSI, 1988, 1976). Moreover, some annual and monthly rain records of one station in and a couple of stations near the catchment are given. Luckily some daily water level records between 1992 and 1996 are also available (NCHSE 1993 in Singh, 2004).

Taking into consideration what severe changes in land use and general practice occurred during the last quarter of a century and given the catchment of about 500 km^2 with high variability in all properties, these maps might not be considered as reliable basis of a physical model.

Under a functional perspective the soil map is not only outdated but also not projectable to functional entities. While Singh (2004) could make use of the mapped soil classes as descriptive groups a physical and hydrological soil characterisation is lacking.

During the first weeks we sought for virtually any data available with local and regional NGOs and administration. We were able to get geohydrological, geo-morphological and land use maps 1:1 000 000 and to get an insight into a forest map 1:350 000.

Furthermore we could research in the statistical year books of the Jhabua district Statistical office to gather information about recent land use, population and other data of concern. Unluckily, the data was recorded in Hindi and lacked due geographic reference, which became quite an obstacle. Also an administrative map of the district's sub-divisions as shown in Fig. 2 could not help in projecting e.g. cropping statistics as it obviously serves different purposes.

Besides, we acquired the SRTM digital elevation model (DEM) for the region (USGS, 2004) to extend the manually derived DEM by Singh (2004) based on the topographic map.

4 Balanced assessment strategy

On the one hand it is a virtually infinite demand of data to describe the complex of hydrological properties of all entities in the basin including their linkages, structural information and dominating processes. On the other hand this is faced by accessible information and observable structures which generally will be represented by a set of rather singular samples. Thus to find a balance is an intrinsic challenge where we need to evaluate the contribution of all sample information describing the system and to formulate common nomenclature and comparable units.

In the PUB case we have to compromise the least adequate representation of the system by accessible information. But the data we can access is not necessarily the information needed for the system description or for the model suite. Hence we flexibly merged information from the intersection of needed parameters of the model suite, accessible information about the catchment, general knowledge and system understanding.

Through a synoptic integration of data from diverse sources and a focus on the representation of the dominating processes in the model, we intend to balance the required data with the data we can obtain. This includes the question of parameter sensitivity versus sample representativity and precision, parameter purpose versus the effort to distinctively derive these parameters and the matter of functional classes for the representation in the model which might not have an a priori definition. At the same time the matter of uncertainty and *soft* data arises.

4.1 Assessment strategy

4.1.1 Theoretical concerns

The major divergence of field observation and modelling we find today might be the quest for a common language (Fenicia et al., 2008). While field sampling could concentrate on a large number of infiltrability measurements and excellent pedogenesis description, the modeller might be rather unhappy with this information as van Genuchten parameters and leading soil profiles with distinct *effective* hydraulic conductivities in each layer are needed.

Furthermore, dominating processes and their representation in the model are important proxies for the data needed to describe the system. In our case we highlight Hortonian overland flow and evapotranspiration for the precipitation and radiation driven case respectively.

Definitely, an a priory limitation of the aspects under study risks to miss important factors. Yet a landscape will never be entirely analysed. In practice this has strong implications on the spatio-temporal scale and representativity of observations. And, more importantly, a landscape is not a mere random occurrence.

We hence oppose any random or unconditioned sampling which would lose the information we already can impose from a basic screening and a landscape categorisation. Further, we intend to minimise the number of samples through this. Different structures organise the catchment behaviour at different scales (Schulz et al., 2006). As Zehe et al. (2006) showed in the case for the Horton Weiherbach catchment, we hypothesize that the catena is the leading topology in the Mod catchment. Our survey and our hydrological model WASA (Güntner and Bronstert, 2004) is thus biased along this structure regarding knowledge integration (Wielemaker et al., 2001) and process representation.

4.1.2 Hierarchical synopsis

Consequently, the proposed landscape assessment consists of several intrinsically linked steps. A first landscape categorisation based on recent studies, mapped data and remote sensing images allows the derivation of a classification hypothesis.

In order to (a) test this hypothesis and (b) to find representative samples for all classes, several sampling transects are identified. Along these transects the field samples are oriented. Similar to an optimisation algorithm we start with a broad range of samples with long lag distances. The more we find the hypothesis proven or disproven we adjust the sampling density accordingly. The same holds for the analytical effort: Not every sample is processed for all properties but a hierarchical set shall allow some minimal adequate description.

In a third phase the hypothesis is revised based on the findings from the previous step. We further add a functional aspect to the formerly property-based landscape classification. This aspect avoids both: the effort of parameterising hydrologically very similar classes (with low benefit for the model performance) and the erroneously pooling of functionally distinct classes.

The newly derived functional classes allow the extrapolation of the analytical findings to the catchment (bottom-up) and the regionalisation of general data or spectral properties (top-down). Using remote sensing techniques, the synopsis from several sources of data is performed resulting in a catchment data base.

After defining the catchment (process domain) we also need to find an adequate representation of the weather (driver). The very scarce and vague records do not allow any straight application. Only one station with weekly records of rain and temperature is located inside the catchment. Neighbouring stations contribute valuable information. Still, the only source of continuous daily records of most needed variables is a weather station in Indore – about 140 km away. In the face of contributing to a decision support system not the absolute record but the dynamics should be covered in a weather scenario generator. Hence, again a hierarchical combination of knowledge about monsoon dynamics, local records and the Indore weather time series is key to cope with the PUB situation.

Similarly we have to deal with the research on land use data. The rather subjective but still very comprehensive information from interviews has to be balanced with general agronomic statistics and land use records without due geographic reference.

4.1.3 Practical implications

We decided to afford ten weeks of intensive field investigation. Our eager target was to gather sufficient information to meet our four main goals: Setup of a functional landscape model of soils (goal 1) and land use (goal 2), integrate linkages to the human side (goal 3) and assess sufficient hydro-meteorological data for application and validation (goal 4).

Consequently, our sampling strategy had to hierarchically seek for representative samples at different scales and linkages for their generalisation. This is illustrated in Fig. 3. We place emphasis on relative differences over precision of a single sample. Thus, we divide into disturbed and undisturbed samples. While disturbed samples are much easier to handle and sufficiently precise for several analyses, a set of undisturbed samples is used for precision analysis of hydrologic soil properties. In order to assure representativity, the choice of the latter samples is conditioned by the findings from the former ones.

From a functional perspective the observation-scale needs to be in compliance with the process-scale. While we find our 136 landscape observation points in combination with remotely sensed data sufficient to describe the general situation of soils, erosion and vegetation, they are hardly sufficient for a detailed hydrological soil description. Hence, we recorded additional 25 soil profiles and several outcrops from which samples were analysed for soil mechanical and chemical properties.

Although pedo-transfer functions (Schaap et al., 2001) open ways to derive hydrological properties from the grain size distribution alone, the uncertainty connected to this is too high, as infiltration is a highly sensitive parameter in the Horton situation at hand. We used a double ring infiltrometer with a support of at least about 500 cm^2 in order to take the effects of macro-structures connected to land use practices and the situation of either skeletal or smectitic soils into account.

For the representation of pore scale processes we were able to process five undisturbed core samples of leading soils in a ku-pf and pressure membrane apparatus to derive water retention curves.

While our bio-physical goals 1, 2 and 4 can generally follow this scheme, the integration towards a DSS requires a far more comprehensive combination of various aspects. The overall similarity of the strategy is the combination of bottom-up and top-down approaches guided through a functional, application-oriented perspective on the human-eco-system. Figure 4 illustrates our approach and the different sources and kinds of information which contribute to the functional landscape description, the model setup and overall integration.

4.1.4 Data synopsis

The synopsis of different sources of information in a comprehensive data framework suitable to parameterise a DSS for land use assessment of the mesoscale Mod catchment is seen as core task to apply hydrological modelling techniques in a PUB situation. Our proposed model suite is based on physical parameters which will be used without calibration. Hence, we are looking for representative samples which we addressed through a functional, catena-based perspective on the catchment. The step from a single weak data point into solid data framework is taken through the a multi-step hierarchical classification, which to some degree is a translation from real world continuous heterogeneity into model world entities. The accepted bias is that large scale patterns and relative differences are deemed to be more important than exact parameters at some singular monitoring stations. As we represent the landscape based on catenas (rel. differences) and as a Horton situation prevails (large scale patterns) we find the assessment strategy and model structure quite in accordance with the system's characteristics.

With regard to hydrometeorological data we are faced with one manual weather station inside the catchment at Ranapur, recording only temperature and precipitation with limited quality, weekly resolution and without temporal overlap to the gauge data. This PUB situation makes a reference to stations near the catchment necessary. Unluckily, close by stations have also rather limited observations. The weather station at the College of Agriculture, Jawaharlal Nehru Krishi Vishwavidyalaya, Indore is the closest station with a detailed record of all needed parameters at a daily time step. Although it lies some 140 km east from Jhabua we find the records quite adequate to capture the heavily externally driven situation during wet and dry season.

Besides the meteorologic forcing most data on land use, crop dynamics, landscape evolution, erosion etc. had to be transferred from other studies or neighbouring regions. With a strong focus on functional accordance this might be the best one can get in a PUB situation.

4.2 Field sampling and analytical methods

The analytical methods reflect on the stated strategy. Table 1 provides an overview about the gathered data. It is apparent that the balance consists in combining rather simple field techniques (double ring infiltration experiments), basic laboratory analytics (core soil parameters, not all samples tested for all parameters), on site mapping (soil vegetation components, representative catenas), remote sensing (generalisation of singular samples and mapping) and more sophisticated exploration where needed (e.g. the soil hydraulic property determination).

4.2.1 Sampling design

Identification of transects

In order to find representative catenas a preliminary analysis of all available data (Landsat Imagery, DEM, maps of Geologic Survey of India) (Singh, 2004; Tomar et al., 1995; GSI, 1976, 1988) identified five transects. They where identified manually to cover the diversity in the catchment and "repesentative" catenas at the same time. Consequently we sought for transects which follow the general topography across several of the major preliminary classes of land use, soil and geology. It is assumed, that (a) topography does represent most of the bias of the landscape, (b) that the needed data is representative for "similar" catenas, (c) observations at different 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.

Along these transects we concentrated our samplings. For further reference and to account for a possibly erroneous bias some additional random sampling points have been assigned.

Although the general sampling design is developed in the preface of the field trip, the actual sample position along the transects and close to the random points was left to be decided during the field trip. Additionally we used any opportunity of wells and outcrops to gather information about the deeper subsurface.

An overview about the transects and sampling and observation points is given in Figs. 1 and 5.

4.2.2 Sampling objectives

An overview about the employed analytical methods to assess the bio-physical system is presented in Table 1.

To describe the landscape and in order to recognise leading soils and their hydrological properties we recorded in total 136 observation points of land cover and soil characteristics.

At 24 points we examined detailed on-site soil outcrops and collected 81 soil samples.

Soil profiles

Since soils in the Mod catchment are generally rather shallow, we excavated soil pits down to the bedrock to also collect data about the lower boundary of the soil domain. At each profile we examined:

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

Outcrops and wells

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.

Within the catchment several large wells for water supply were under construction allowing a more detailed examination of the geology at these place. In the study at hand, only the stratification profiles have been recorded without further analysis of the formations.

Infiltrability

As infiltrability is a crucial parameter in the Horton setting and 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. Due to very limited transportation capacity, local inaccessibility of other equipment and the robustness of the method the standard double ring infiltrometer was chosen.

At 20 locations we measured rates in the order of $\pm 10^{-5}\,\mathrm{m\,s^{-1}}$. Similarly to the soil samplings, the measured rates were regarded as representative for the respective soil class.

Laboratory analysis

Out of 81 samples, 39 were processed for grain size distribution, bulk density and organic carbon. Some 16 of these were analysed for cation exchange capacity, too.

Additionally we were able to bring five undisturbed soil samples of leading soils to our lab at Potsdam University and to analyse the samples for the water retention curve using a Ku-pf apparatus and a pressure membrane apparatus by UGT GmbH Müncheberg.

4.3 Remote sensing

In our study remote sensing (RS) is used in several phases and different manners. On the one hand we use it as mapping tool before the transect identification and during the functional landscape classification procedure. On the other hand we use it as spectral analyser of top-soil properties. Apart from that, near field RS in the form of photographs from local hill-tops are used for mapping and validation.

4.3.1 Spectral analysis

Due to absence of almost any kind of living vegetation at the end of dry season after about eight months with hardly any precipitation and high evapotranspiration, the analysis of soils based on its spectral reflectance is of great potential in the study area. We employed a comprehensive approach to identify soil types and properties from its spectral characteristics after Baumgardner et al. (1985), Goldshleger et al. (2004) and Huete and Ustin (2004).

4.3.2 Spectral top-soil properties

The spectral composition of reflected energy from soils mainly depends on its clay and organic components, surface structure and moisture condition (Baumgardner et al., 1985) (in Huete and Ustin, 2004). As the analysis of samples states, most soils of the catchment have relatively high content of clay and loam. 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. (1985) 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 strong influence on soil reflectance and is a regulator for nutrient condition and biological activity in the soil (Blume et al., 2002). Additionally a broad number of physical and physiological processes are closely connected to the content of organic matter. Mathews et al. (1973) (in Baumgardner et al., 1985) found organic matter to be highly correlated to the reflection band between 0.5 and 1.2 µm. Stoner (1979) (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 effect occurs in the visible wavelengths. This shall be represented through band 3 of a landsat ETM+ image.

Montgomery (1976) and Baumgardner et al. (1985) found silt content to be the single most significant parameter in explaining spectral variations in soils. Although effects can be found in all visible and near infrared bands, reflectance bands between 0.52 and 0.62 µm are stressed to be the best identifier for fine silts. This shall be represented through band 2.

4.3.3 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.

Landsat ETM+ imagery composites of bands 2, 3 and 4 are used for this purpose. This is in compliance with the Normalized Difference Vegetation Index (NDVI) (e.g. Tucker, 1979) and its numerous modifications which are based on the differences in the vegetation's reflection properties of near IR and red light (band 4 and 3 of ETM+ images). ETM+ band 2 is additionally used as greenery index. Moreover, a simple subtraction approach using the spectral properties of bare soil after dry season and vivid vegetation after the monsoon shall serve as estimator for vegetation and land use.

4.4 Extension beyond bio-physics

In Table 2 we give an overview about research extending the domain of eco-hydrology. As we are not dealing with any pristine ecosystem human interaction, cropping practices and decision making processes are principal controls.

Some information can be found in specific studies of NGOs and GOs. Yet most of the needed data is no result of a straight forward analysis. Contributing reports, data collections and interview partners are compiled in Table 3. Our focus is set by our goals and the hydrological frame of the study. Without understanding the farmers' concerns and practices we could impose some more or less unsuitable scenarios, which leaves any applicability out of scope. It was most revealing to discuss our analysis with the farmers and to directly ask them about setting, options, risks, demands and dependencies. How do the farmer organise? Whom do they believe? What crops do they find suitable for their fields? How do they till and schedule? What are their experiences with extreme events?

Of cause this will not present any van Genuchten parameters but suits very well with our functional perspective on the landscape. These interviews lead to the structure of the knowledge base for a decision agent in our model suite. It gets filled with statistical data from concerned GOs and agencies.

All dates and samples of course remain an approximation of what could be achieved in specific long term investigations. The strength of this study clearly lies in the synopsis of data from several aspects.

4.5 Hydro-meteorological data

After having discussed the approaches to meet goals 1, 2 and 3 – the environmental and socio-economic setting – we will present the hydrometeorological data domain which is part of goal 4 of our study.

4.5.1 Meteorological records

Inside the Mod catchment we only find one meteorological station in Ranapur (Fig. 1). This station and the stations close to the catchment in Jhabua, Megnaghar, Udaigarh, Thandla, Rama, Paplawad, Jhobat and Alirajpur are manual stations with records of temperature and precipitation dating back to the mid 1960's. The records are of monthly, weekly and in the best case daily resolution. Unfortunately, the standard for the data quality is rather low.

In order to unify the meteorological data and to extend information beyond weekly and daily precipitation and average temperature, we gathered a copy of records at the College of Agriculture, Jawaharlal Nehru Krishi Vishwavidyalaya, Indore from 1992 to 2001. This station is still incomparable with western standards and manually driven, but holds a precious record of daily maximum and minimum temperature, precipitation, air humidity, soil temperature, pan evaporation, wind speed and wind direction.

In order to use this data, the sparse weather records get paired with general knowledge about monsoon dynamics (e.g. Keshavamurty and Rao, 1992; Singh, 2001). Their findings led to a great simplification for the transfer of weather records to the catchment which is presented in Sect. 5.5.

Moreover, the Horton landscape situation allows the application of a modified Hargreaves method (Droogers and Allen, 2002) for potential evaporation estimation under inaccurate data. This step dramatically shortened the list of needed critical data to solar radiation, temperature and precipitation - compared to the method by Shuttleworth-Wallace (Shuttleworth and Wallace, 1985) which additionally requires a real-time status of wind velocity and air humidity.

4.5.2 Gauged discharge

Although some four years (1992–1995) of daily water level data exists we find it applicable to speak of a ungauged basin. Singh (2004) presents the poor water level-discharge relationships of the gauge which add uncertainty to the also modest gauge record. It was out of scope for our study to contribute with own measurements as our field work was limited and took place in the beginning of dry season.

5 Results and discussion

5.1 Soil classification on the basis of field samples

Table 4 presents the resulting soil parameters for identified functional soil classes. In addition to these values we can describe the classes as follows:

5.1.1 Deep clay montmorillonitic black

This fine-grained clayic black soil occurs in local depressions and alluvial depositions close to the stream network. It corresponds very well with the characterization of Black Cotton Soil in Tomar et al. (1995) and Jain et al. (1993). 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 m 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.

This soil presents low infiltration rates (altered by cracking structures), high water storage capacity and can be regarded as highly suitable for cultivation of rather demanding crops like cotton. Nevertheless, cultivation of this soil is very laborious.

5.1.2 Alkalic dark brown loam

This soil can be regarded as 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. It is a rather silty soil. The clay minerals appear to be both, kaolinitic and smectitic origin. The effects of swelling and shrinking are minor. The upper horizon of about 0.2 m shows a share of skelettal gravels of about 16.5 %, while the lower body is rather homogenous and slightly more clayic. Infiltration rates are moderately low. Due to its position on uplands and slight slopes, and due to the moderate water retention capacity these sights are rather dry lands with medium fertility. At sufficient water availability or irrigation it is well suitable for crop and vegetable cultivation.

5.1.3 Clay loam red Kaolinit

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 m deep and very homogenous in its composition without any stratification. Despite the lower CEC and pH values these sites are used for crop cultivation in kharif (first cropping period starting with the onset of the monsoon). With moderate water retention capacity sufficient precipitation and fertilisation is prerequisite.

5.1.4 Meager brown loam

This prominent soil class can be found on gentle slopes all across the catchment. It is referred to as "normal" soil by the local farmers. Thus, cultivation has adopted to the moderate fertility and water retention capacity. Low infiltration rates point to the issue of weathering and erosion. Cultivation in rabi (second cropping period starting in dry season) is rarely possible.

5.1.5 Meager red

This prominent class describes heavily eroded meager and very shallow soils. Thus, water retention is very low. It can only be used as grassland.

5.1.6 Acidic red brown feldspathic

These loamy soils develop above feldspathic bedrock. It presents a moderate water retention capacity and good infiltrability. As the class name imposes, these soils tend to be slightly acidic lowering its agricultural suitability. Still, it is cultivated in kharif.

5.1.7 Skeletal brown

This class is similar to the meager brown loam with high content of rocks. The physical and chemical properties are assumed to be the same like meager brown loam.

5.1.8 Skeletal hill

This class is conspicuous at the heavily eroded steeper hill slopes. It is very shallow with hardly any water retention capacity or nutrients. Potential reforestation programs will be challenged by this, as a whole pedogenesis has to be recovered against floods and droughts.

These soil classes prove our first hypothesis of Horton discharge. Most soils are strongly degraded with limited agricultural and water retention capacity. Additionally the functionally contrasting classes (arable clays/eroded stony loams) prove our proposition, that soil analytics are key to the understanding of the hydrological behaviour of the landscape. Not surprisingly, land use follows the soil patterns.

5.2 Remote sensing soil analysis

Based on three Landsat 7 ETM+ and two Landsat 5 TM images we conducted a remote sensing approach to top soil properties to translate point information from the field survey into areal information. The recorded field observations and analytical results are too few to allow any sound spatial statistics. They serve as ground references for a maximum likelihood supervised classification approach (e.g. Richards, 1994) based on bands 2, 3 and 5 of the landsat ETM+ scene of 1 April 2000 having a resolution of 30 m. The algorithm has been applied without threshold definition based on an iteration of different training regions of interest (ROIs) based on a subset of the topsoil samples.

5.2.1 Cross-validation of classified entities

The high variability of soil classes in this region on a very small scale results in mixed pixels of the RS images. Thus there are two problems: (a) the taken 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 might not be distinguishable from the spectral properties of the used bands.

As a detailed soil mapping survey lies far out of scope of the project, panorama photographs from all major elevations in the catchment were taken. These were used as additional intermediate scale qualitative validation. For plausibility control of the classification results, they were compared with respect of the representation of local structures.

5.2.2 Resulting soil map

To remove the remaining noise in the classification result a five pixel moving window calculating the median was applied using r.neighbor in Grass GIS. The 30 m grid is thus smoothed to a 150 m median, which is proposed as reasonable scale to decrease overfits due to local variance.

Figure 6 presents the identified soil classes and assigned samples in the central catchment. The cross-validation reveals a reasonable compliance with the samples and areal panorama photographs taken from local elevation points.

5.3 Land cover, monsoon rains and potential vegetation

Figure 7 illustrates post-monsoon vegetation (purple colours) depending on a minimum of precipitation during the monsoon season.

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

Hence, the landsat ETM+ image of 18 October 2001 was used for (potential) land cover analysis to derive a realistic approximation of the situation in the basin. Moreover a landsat TM image of 9 October 1989 (after a monsoon spell of about 800 mm) is used for the same supervised maximum likelihood classification to validate the results.

5.3.1 Land cover classes

Floodplains

Mainly in local depressions and at shallow river banks sufficient water is received and more importantly not quickly drained which enables 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 even a third cropping can be possible.

Dryland agriculture

This can be regarded as most common type of agriculture in the region. Generally two cropping seasons are possible, while the second 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 or a lack of irrigation facilities results in much lower productivity than at other patches.

Meager grassland

Large plains were found that turn into greenery during monsoon. Yet the soils are very shallow and gravelly such 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 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.

5.3.2 Land cover classification result

In Fig. 8 the resulting land cover classifications are presented. Both maps 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, there still is a high dynamic in land use because of deforestation, erosion and infrastructural development.

Generally the results are plausible compared to the observations during the field work and hill-top photographs. Although a high uncertainty about the identified classes remains, an extensive land use mapping campaign had not been feasible in our rapid data assessment. Moreover, during the field work only dry-season conditions could be directly observed. Comparing the two results with the in situ findings, the land cover map resulting from the supervised classification of the ETM+ image of 18 October 2001 is accepted as best guess for the further analysis.

5.3.3 Cross validation of land cover analysis

The result of the cross validation of the land use classification is presented in Table 5 and Fig. 8. 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 kinds of dryland agriculture is only roughly possible using this method.

5.4 Additional data collection

In order to reduce uncertainty in the bio-physical data base and especially to extend our findings to enable a land use related decision support assessment, we move beyond classical bio-physical landscape analysis.

5.4.1 Soft data on hydrologic behaviour

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 sciences developed a considerable methodology for that (e.g. Seidman, 2006). Although, people will not present the van Genuchten parameters of their fields' soils or a detailed sketch of subsurface heterogeneity, they are source of vast information about landscape development, preferential processes and process paths or decision patterns. They reported about wells turning salty, what conditions are likely to produce surface runoff, irrigation demands and possibilities, their experiences with certain crops, decision structures, economic aspects, etc.

In such interviews we learned a lot about how the farmers decide on a crop to plant and the tillage timing. We were explained how the water retention of their fields behaves compared to neighbouring farmers. Further, their reports on recent land use changes, extreme events and general long-term changes is invaluable when compiling a data set like this, although the subjectivity needs to be considered.

Further consultations with concerned professionals at Governmental Organisations (GOs) and NGOs revealed critical insights into landscape properties and anthropogenic interactions which would have been unaddressable through own investigations.

5.4.2 Statistical data of land use, agriculture and population

The Census Office of Jhabua Distict publishes an annual Statistical Year Book of the district. Despite the fact that clear geographic references could not be reconstructed, these records presented general land use and population data at sub-district (Tehsil) level. The District Collectorate and Land Records Office could add further information to this aspect.

Very interesting information could be gained from the District Agriculture Officer Jhabua. The GO provided quite detailed information about crops and cropped area, yields and timings which were essential for the decision support system. In connection with the District Agricultural Marketing Board, which committed data on agricultural costs and gains per cropping season and even expenses for fertilisers and seeds, this formed a solid basis for estimates on economic feedbacks of cropping efforts.

5.4.3 Social dependencies and decision structures

For the development of a DSS in addition to a sound representation of the bio-phyical system, social dependencies and decision structures are of equal relevance (Pallottino et al., 2005). While other crop DSS (e.g. Jones et al., 2003) deal with pests or fertiliser optimisation for large scale industrial agriculture, the issue at hand demands assessment of cropping options under limited resources and within the given social framework. When is the cropping decision taken by whom and for what reasons? Certainly when it comes to strategy evaluation, we have to make sure to project the strategies as realistic as possible. Our findings are contained in a rule system for a decision taking agent routine.

5.5 Hydrometeorological data

Jain et al. (1993) present a long record of monthly data for temperature and precipitation at nine stations in and around the catchment lasting from the 1950s to the 1980s. Singh (2004) could obtain daily precipitation records at six of these stations for the period of 1980s to 2000. Although this is a great data set for such a remote area, it does not suffice to drive our physical process models.

About 140 km from the basin under study exists the well-maintained weather station of the College of Agriculture, Jawaharlal Nehru Krishi Vishwavidyalaya, Indore. Here we could gather a record of the atmospheric conditions between 1992 and 2001. Of special importance we regard the time series of daily pan evaporation.

Moreover, the State Water Data Centre Bhopal collected water level records at about daily interval between 1992 and 1995 for the Mod river. The water level-discharge relationship was reported to be rather weak (Singh, 2004) which is due to considerable alternations of the river bed during floods, potential backlog effects from the junction with the Anas river near the gauge and due to the fairly unconfined bounds of the river. The gauge was managed at a highway bridge.

5.5.1 Condensing the fractals

Under highly convective weather conditions no-one would think of using data from a 140 km distant station. But since TRMM satellite products are only available since 1998, data quality at the nearby stations is low and most importantly because the monsoon rains propagate in bands, we believe that data from this station is a reasonable choice. As shown in Fig. 9, the correlation is fairly acceptable under the given constraints. The lagged cross correlation points out the timing error of less than two days at the Indore station.

In addition to the climate which allows our approximation, also the landscape processes will be described much better with a well established potential evaporation relationship and a close handle on the latent heat flux through air humidity compared to slightly less uncertain precipitation records. Furthermore, the targeted DSS cannot rely on singular weather realisations. Hence the multiple weather records will be used to train a weather generator.

Moreover, it needs to be kept in mind that we neither can nor intend to carry out any model calibration but that we need data for validation of our process model. Thus, beyond discharge some information about soil moisture and crop production is of great value which we derive from satellite images and agronomic statistics.

Figure 10 presents a rough overview about the hydrometeorological data. We would like to point out that the very high discharge measurements in 1994 are likely to be erroneous. A water balance assessment reveals that the proposed discharge is 72 % of the precipitation compared to the far more plausible ±20 % during the other years.

5.5.2 Remaining fractals

A further aspect we investigated but could not resolve in a satisfactory way is ground water recharge, where we obtained records for several observation wells. Unfortunately a precise geographic location was missing and could not be reconstructed through other means which made the data obsolete. Similarly most statistical data like crop production per administrative unit, irrigation application, population etc. could not be used in the required spatial resolution because of unclear geographic reference.

5.6 Feasibility – how far did we get?

As presented, we could establish a sound data basis for a hydrology-based DDS of the sparsely analysed Mod catchment. The major step forward can be found in the compatible nomenclature of all aspects of our study and the hierarchical assessment. Yet, there is only little proof that the description through the found parameters is correct and sufficient. The forthcoming publication on the modelling part of this study will compare model results to the four years of gauge records and three top-soil moisture maps derived from Landsat images for validation.

Although this a success, uncertainty is rather high. One major draw back is the weak link of field observations and a modelling reality. As discussed by Wagener et al. (2007) and Blöschl and Zehe (2005), among others we still lack a clear concept translating landscape into processes and vice versa.

5.6.1 Real world PUB

We believe that a clear concept of dominating processes, scales and sample representativity is a feasible answer to the PUB issue. The presented hierarchical landscape assessment allows a condensation of information respecting this. Despite that, our study remains a case study and as such does not yet establish a general PUB data assessment strategy.

Nevertheless, we did not only find parameters for a certain model. We showed that a multi-perspective data assessment is one possible answer to uncertainty. The synergies of system understanding and implicit observations elevate the weak singular samples to a system parameterisation. On the other hand, the mismatch of availability of data with our concepts and models is apparent. Our approach needed to stick to classical hydrological landscape representation schemes through van Genuchten parameters and distributed communicating soil columns. If one thinks of a consequent extension of a landscape data assessment to entire hydrology, we have to revise many links.

5.6.2 Technical implications

Virtually any single piece of analysis could have been done better – from infiltration assessment over soil moisture monitoring to weather and discharge gauging. But under the limited resources and time frame we allowed for the study we present a PUB-feasible strategy.

In a following study one might seek for a more general iteration procedure to find a minimal adequate data set for the landscape description. One can imagine a much more integrated system of multi-perspective data assessment and hydrological modelling, where the model is rather a learning tool (compare Beven, 2007) triggered by system understanding and guiding the sampling.

6 Conclusions

We could show that through a functional and hierarchical assessment of a poorly gauged, remote catchment it is possible to set up a comprehensive data base for hydrologic properties and land use decision support modelling. Although a high degree of uncertainty remains, we have great confidence that approaching a landscape as generic and organised system rather than any random occurrence can bridge the PUB issue to real world applications. The study at hand could set up a comprehensive data base within 10 weeks of field work, 10 weeks of laboratory analytics and 15 weeks of data compilation with almost no budget. While many details can be improved, the big picture was captured.

A big draw back is the still weak link of landscape properties and field measurements to model reality and pore-scale hydrological concepts. Even though our functional, catena based approach could already set a guide line for relating structure and general findings to parameters of landscape entities, todays eco-hydrologic models miss to embrace a landscape as system which is shaped by the processes we aim to mimic. Hence the development of assessment strategies needs to be in close connection to the development of concepts and models avoiding ad-hoc mechanistic descriptions.

Acknowledgements. We like to express our gratitudes to all the people in Jhabua who helped during the fieldwork and research for data. The study highly benefited from the generous resourcing of laboratory facilities at the College of Agriculture, Jawaharlal Nehru Krishi Vishwavidyalaya, Indore where we could process all 39 disturbed soil samples. We also deepling thank the colleagues at the Institute of Geoecology at Potsdam University, Department of Hydrology at Technische Universität München and Department of Hydrology at KIT Karlsruhe. The project was sustained through the reliable scholarship of the Heinrich-Böll-Foundation and the German Academic Foundation.

References

Banerjee, R.: Struggles of the Bhil Indigenous People in Jhabua for Access to Water, SANDRP. Dams, http://www.sandrp.in/drp/April_2007.pdf, last access: July 2011, Rivers & People, 5, 7–12, 2007. 7507

Baumgardner, M. F., Silvall, L. F., and Biehll, L. L.: Reflectance Properties of Soils, Adv. Agron., 38, 1–44, doi:10.1016/S0065-2113(08)60672-0, 1985. 7519, 7520

Beven, K. J.: Uniqueness of place and process representations in hydrological modelling, Hydrol. Earth Syst. Sci., 4, 203–213, doi:10.5194/hess-4-203-2000, 2000. 7501

Beven, K.: Searching for the Holy Grail of scientific hydrology: $Q_t = (S, R, \Delta t)A$ as closure, Hydrol. Earth Syst. Sci., 10, 609–618, doi:10.5194/hess-10-609-2006, 2006. 7500

Beven, K.: Towards integrated environmental models of everywhere: uncertainty, data and modelling as a learning process, Hydrol. Earth Syst. Sci., 11, 460–467, doi:10.5194/hess-11-460-2007, 2007. 7534

Blöschl, G. and Zehe, E.: On hydrological predictability, Hydrol. Process., 19, 3923–3929, doi:10.1002/hyp.6075, 2005. 7533

Blume, H. P., Brümmer, G. W., Schwertmann, U., Horn, R., Kögel-Knabner, I., Stahr, K., Auerswald, K., Beyer, L., Hartmann, A., Litz, N., Scheinost, A., Stanjek, A., Welp, G., and Wilke, B.-M.: Lehrbuch der Bodenkunde – Scheffer/Schachtschabel, Spektrum/Springer, Heidelberg, 2002. 7519

Blume, T., Zehe, E., Reusser, D. E., Iroume, A., and Bronstert, A.: Investigation of runoff generation in a pristine, poorly gauged catchment in the Chilean Andes I: A multi-method experimental study, Hydrol. Process., 22, 3661–3675, doi:10.1002/hyp.6971, 2008. 7506

Droogers, P. and Allen, R. G.: Estimating reference evapotranspiration under inaccurate data conditions, Irrig. Drain. Syst., 16, 33–45, doi:10.1023/A:1015508322413, 2002. 7522

Fenicia, F., McDonnell, J. J., and Savenije, H. H. G.: Learning from model improvement: On the contribution of complementary data to process understanding, Water Resour. Res., 44, W06419, doi:10.1029/2007WR006386, 2008. 7506, 7511

Flury, M.: Experimental evidence of transport of pesticides through field soils – A review, J. Environ. Qual., 25, 25–45, 1996. 7506

Goldshleger, N., Ben-Dor, E., Benyaminil, Y., and Agassil, M.: Soil Reflectance as a Tool for Assessing Physical Crust Arrangement of four Typical Soils in Israel, Soil Sci., 169, 677–687, 2004. 7519

GSI, Geological Survey of India: Geology and Mineral Resources of the States of India – Part XI – Madhya Pradesh, 30, 1976. 7509, 7516

GSI,Geological Survey of India: District Resource Map – Jhabua District, Madhya Pradesh, 1988. 7509, 7516

Güntner, A. and Bronstert, A.: Representation of landscape variability and lateral redistribution processes for large-scale hydrological modelling in semi-arid areas, J. Hydrol., 297, 136–161, doi:10.1016/j.jhydrol.2004.04.008, 2004. 7504, 7512

Huete, A. and Ustin, S.: Remote Sensing of Soils and Soil Processe, in: Manual of Remote Sensing, Remote Sensing of Natural Resources Management and Environmental Monitoring: Manual of Remote Sensing, edited by: Ustin, S., vol. 4, Wiley Inc., 3–52, 2004. 7519

Jain, H. K., Khanna, A., Saraf, V., Dwivedi, H. B., Tiwari, J., Pendharkar, V., and Shrivastava, K.: Sustainable Utilization of Natural Resources in Jhabua District, NCHSE, Bhopal, 1993. 7523, 7531

Jones, J. W., Hoogenboom, G., Porter, C. H., Boote, K. J., Batchelor, W. D., Hunt, L. A., Wilkens, P. W., Singh, U., Gijsman, A. J., and Ritchie, J. T.: The DSSAT cropping system model, Eur. J. Agron., 18, 235–265, doi:10.1016/S1161-0301(02)00107-7, 2003. 7530

Keshavamurty, R. and Rao, M. S.: The Physics of Monsoons, Allied Publishers Ltd., New Delhi, 1992. 7522

Liu, Y. Q. and Gupta, H. V.: Uncertainty in hydrologic modeling: Toward an integrated data assimilation framework, Water Resour. Res., 43, doi:10.1029/2006WR005756, 2007. 7505

McDonnell, J., Sivapalan, M., Vaché, K., Dunn, S., Grant, G., Haggerty, R., Hinz, C., Hooper, R., Kirchner, J., Roderick, M., Selker, J., and Weiler, M.: Moving beyond heterogeneity and process complexity: A new vision for watershed hydrology, Water Resour. Res., 43, W07301, doi:10.1029/2006WR005467, 2007. 7501

McGlynn, B., McDonnel, J., and Brammer, D.: A review of the evolving perceptual model of hillslope flowpaths at the Maimai catchments, New Zealand, J. Hydrol., 257, 1–26, doi:10.1016/S0022-1694(01)00559-5, 2002. 7506

Pallottino, S., Sechi, G., and Zuddas, P.: A DSS for water resources management under uncertainty by scenario analysis, Environ. Model. Softw., 20, 1031–1042, doi:10.1016/j.envsoft.2004.09.012, 2005. 7530

Pande, M.: Stepping Out – Life and Sexuality in Rural India, Penguin Books, New Delhi, 2003. 7507

Postma, T. J. B. M. and Liebl, F.: How to improve scenario analysis as a strategic management tool?, Technol. Forecast. Soc., 72, 161–173, doi:10.1016/j.techfore.2003.11.005, 2005. 7505

Richards, J.: Remote sensing digital image analysis: an introduction, 2nd Edn., Springer, Heidelberg, 1994. 7525

Samaniego, L. and Bardossy, A.: Simulation of the impacts of land use/cover and climatic changes on the runoff characteristics at the mesoscale, Ecol. Modell., 196, 45–61, doi:10.1016/j.ecolmodel.2006.01.005, 2006. 7502

Schaap, M. G., Leij, F. J., and Genuchten, M. T. V.: Rosetta: A computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions, J. Hydrol., 251, 163–176, doi:10.1016/S0022-1694(01)00466-8, 2001. 7514

Scholz, F.: Geographische Entwicklungsforschung, Gebr. Borntraeger, 2004. 7507

Schulz, K., Seppelt, R., Zehe, E., Vogel, H., and Attinger, S.: Importance of spatial structures in advancing hydrological sciences, Water Resour. Res., 42, W03S03, doi:10.1029/2005WR004301, 2006. 7502, 7511

Seidman, I.: Interviewing as qualitative research: A guide for researchers in education and the social sciences, Teachers College Press, New York, 2006. 7529

Singh, A. K.: Towards Decision Support Models for an Ungauged Catchment in India, the Case of Anas Catchment, Mitteilungen des Instituts für Wasserwirtschaft u nd Kulturtechnik der Universität Karlsruhe, vol. 225, 2004. 7509, 7510, 7516, 7522, 7531

Singh, C. V.: Probabilities and distribution of monsoon rainfall in normal, flood and drought years over India, Meteorol. Atmos. Phys., 78, 205–214, doi:10.1007/s703-001-8174-7, 2001. 7522

Sivapalan, M., Takeuchi, K., Franks, S. W., Gupta, V. K., Karambiri, H., Lakshmi, V., Liang, X., McDonnell, J. J., Mendiondo, E. M., O'Connell, P. E., Oki, T., Pomeroy, J. W., Schertzer, D., Uhlenbrook, S., and Zehe, E.: IAHS Decade on Predictions in Ungauged Basins (PUB), 2003–2012: Shaping an exciting future for the hydrological sciences, Hydrolog. Sci. J., 48, 857–880, 2003. 7500, 7505

Shuttleworth, W. and Wallace, J.: Evaporation from sparse crops-an energy combination theory, Q. J. Roy. Meteorol. Soc., 111, 839–855, doi:10.1002/qj.49711146910, 1985. 7522

Tomar, V., Gupta, G., and Kaushal, G.: Soil Resources and Agroclimatic Zones of Madhya Pradesh, 1995. 7516, 7523

Tucker, C. J.: Red and Photographic Infrared Linear Combinations for Monitoring Vegetation, Remote Sens. Environ., 8, 127–150, doi:10.1016/0034-4257(79)90013-0, 1979. 7520, 7526

Uhlenbrook, S.: Catchment hydrology – a science in which all processes are preferential, Hydrol. Process., 20, 3581–3585, doi:10.1002/hyp.6564, 2006. 7501

Uhlenbrook, S., Frey, M., Leibundgut, C., and Maloszewski, P.: Hydrograph separations in a mesoscale mountainous basin at event and seasonal timescales, Water Resour. Res., 38, 1096, doi:10.1029/2001WR000938, 2002. 7502, 7506

USGS: Shuttle Radar Topography Mission, 1 Arc Second scene SRTM u03 p147r044, Unfilled Unfinished 2.0, Global Land Cover Facility, University of Maryland, 2004. 7510

van Dam, J. C. and Malik, R. S.: Water productivity of irrigated crops in Sirsa district, India, WATPRO final report, http://www.waterfoodecosystems.nl/content.php?page=1871 (last access: July 2011), 2003. 7504

van Dam, J. C., Groenendijk, P., Hendriks, R. F., and Kroes, J. G.: Advances of Modeling Water Flow in Variably Saturated Soils with SWAP, Vadose Zone J., 7, 640–653, doi:10.2136/vzj2007.0060, 2008. 7504

van De Giesen, N., Stomph, T., and de Ridder, N.: Scale effects of Hortonian overland flow and rainfall-runoff dynamics in a West African catena landscape, Hydrol. Process., 14, 165–175, oi:10.1002/(SICI)1099-1085(200001)14:1%3C165::AID-HYP920%3E3.0.CO;2-1, 2000. 7509

Vogel, H. and Roth, K.: Moving through scales of flow and transport in soil, J. Hydrol., 272, 95–106, doi:10.1016/S0022-1694(02)00257-3, 2003. 7502

Wagener, T., Sivapalan, M., Troch, P., and Woods, R.: Catchment Classification and Hydrologic Similarity, Geogr. Compass, 1, 901–931, doi:10.1111/j.1749-8198.2007.00039.x, 2007. 7501, 7533

Wielemaker, W., de Bruin, S., Epema, G., and Veldkamp, A.: Significance and application of the multi-hierarchical landsystem in soil mapping, Catena, 43, 15–34, doi:10.1016/S0341-8162(00)00121-1, 2001. 7512

Winsemius, H. C., Savenije, H. H. G., Gerrits, A. M. J., Zapreeva, E. A., and Klees, R.: Comparison of two model approaches in the Zambezi river basin with regard to model reliability and identifiability, Hydrol. Earth Syst. Sci., 10, 339–352, doi:10.5194/hess-10-339-2006, 2006. 7506

Zehe, E. and Flühler, H.: Preferential transport of isoproturon at a plot scale and a field scale tile-drained site, J. Hydrol., 247, 100–115, doi:10.1016/S0022-1694(01)00370-5, 2001. 7506

Zehe, E. and Sivapalan, M.: Threshold behaviour in hydrological systems as (human) geo-ecosystems: manifestations, controls, implications, Hydrol. Earth Syst. Sci., 13, 1273–1297, doi:10.5194/hess-13-1273-2009, 2009. 7502

Zehe, E., Lee, H., and Sivapalan, M.: Dynamical process upscaling for deriving catchment scale state variables and constitutive relations for meso-scale process models, Hydrol. Earth Syst. Sci., 10, 981–996, doi:10.5194/hess-10-981-2006, 2006. 7511

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 1. Applied analytical methods for rapid data assessment of the bio-physical setting in the Mod catchment, Jhabua, India.

in situ assessment	Mapping of Soil-Vegetation-Units (SVUs)	identification of mayor SVUs, manual mapping based on topological maps, hilltop based areal photographs
	Topographic Mapping	GPS with barometric altimeter (calibrated each day)
	Characterisation of Soils and Soil Hydrology	field assessment at outcrops along transects, assessment of existing exposures, soil sampling for further analysis, site characterisation at 136 observation points (top soil)
	Infiltration Rate	double ring infiltrometer
	Depth to Bedrock and Bedrock Characterisation	outcrops, well profiles
laboratory analysis	Grain Size Distribution	Hydrometer Method
	Organic Matter Content	Titration with Diphenylamin-Indicator & Sodium Dichromat
	pH Value	glass-electrode pH-meter
	Cation Exchange Capacity	Sodium acetate method
	Water Retention Curve	Ku-pf apparatus with 5 undisturbed ring samples and pressure membrane apparatus

Table 2. Overview about sampling objective beyond bio-physical representation.

bio-physical system	consolidation of mapped data
	ground truth for remote sensing
	find representative catenas
	soil hydrologic properties
	collection of further existing data
human interaction	what crops are planted
	for what reasons
	reaction on monsoon
	social problem setting
	and possible constraints
decision support system	constraints of agricultural practice
	farmers' conception of decision making
	knowledge about forcing (weather/hydrology)
	costs and market values

Table 3. Contributing GO and NGO Reports and Consulted Stakeholders.

NGO reports	National Centre for Human Settlements & Environment (NCHSE), Jhabua
	Gramine Vikas Trust (GVT), Jhabua
	Krishi Vigyan Kendra (KVK), Jhabua
	Centre for Science and Environment (CSE), India
GO data	Census Office Jhabua Distict (Statistical Year Books)
	District Geohydrology Officer Jhabua (Geohydrological Maps)
	District Collectorate and Land Records Office (Admin. Units)
	District Agriculture Officer Jhabua (Cropped Area, Crops, Yield Statistics, ...)
	District Groundwater Survey Unit (Groundwater Records)
	District Agricultural Marketing Board (Mandi) (Agricultural Costs and Cains, Fertiliser and Grain Expenses...)
	MP Council of Science and Technology (Map Products)
interviews	Farmers
	NGOs
	local GO authorities
	regional GO authorities

Table 4. Overview about the resulting functional soil classes and the mean values of all analysed samples of a class not deeper than 0.6 meters. *skel* describes the mass-percentage of stones [%], *sand, silt & clay* are given as mass-percent of the sieved sample hence without the skeletal fraction [%], Δ gives the USDA texture class **c**lay / **l**oam / **s** and, *cation exchange capacity* (CEC) is given in mol(+) per gram of soil [$\text{mol}^+ \, \text{g}^{-1}$], *organic carbon* content in per cent of mass [%], *depth* in meter [m], *bulk density* (BD) in [$\text{g}\,\text{cm}^{-3}$], saturated water content Θ_s, residual water content Θ_r, van Genuchten parameters α [cm^{-1}] and n and infiltration rate as *saturated conductivity* k_s in [$\text{mm}\,\text{h}^{-1}$].

soil class	cover	skel	sand	silt	clay	Δ	CEC	Corg	depth	ph	BD	Θ_s	Θ_r	α	n	k_s
Deep Black	8.74 %	0	20.1	23.9	56.0	c	750.1	0.6	2.5	8.34	1.7	0.383	0.073	0.944	1.21	60
Alkalic Dark	11.83 %	16.5	39.77	30.99	29.24	l	475.7	0.49	1.2	8.05	1.8	0.305	0.0662	0.21	1.4	90
Red Kaolinit	1.57 %	14	45.47	27.85	26.68	l	342	0.51	1.0	7.43	1.8	0.45	0.105	0.205	1.37	80
Meager Brown	18.18 %	29.7	36.69	33.18	30.13	cl	309	–	1.2	8.5	1.8	0.48	0.050	0.18	1.32	50
Meager Red	24.53 %	35.1	39.28	38.17	22.58	l	330	0.37	0.2	7.69	1.9	0.49	0.043	0.205	1.37	115
Acidic Red	8.15 %	23.2	39.24	36.6	24.2	l	215.8	0.48	1.0	6.8	1.7	0.48	0.050	–	–	156
Skel. Brown	18.88 %	64.5	36.69	33.18	30.13	cl	–	–	1.2	8.5	1.8	0.48	0.050	0.18	1.32	50
Skel. Hill	6.1 %	77.8	48.24	26.6	25.2	scl	–	–	0.2	6.69	1.8	0.49	0.043	0.205	1.37	85

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◄ ►
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 5. Land Cover Classification Area Shares. (A) October 1989, (B) October 2001.

No.	Class	A	B	certainty
1	water bodies	0.72 %	0.36 %	1.00
2	floodplains	7.48 %	8.44 %	0.86
3	dryland agriculture	13.08 %	36.11 %	0.50
4	dryland meager agri.	39.57 %	9.93 %	0.38
5	meager grassland	27.59 %	9.23 %	0.63
6	wasteland	11.56 %	35.94 %	0.44

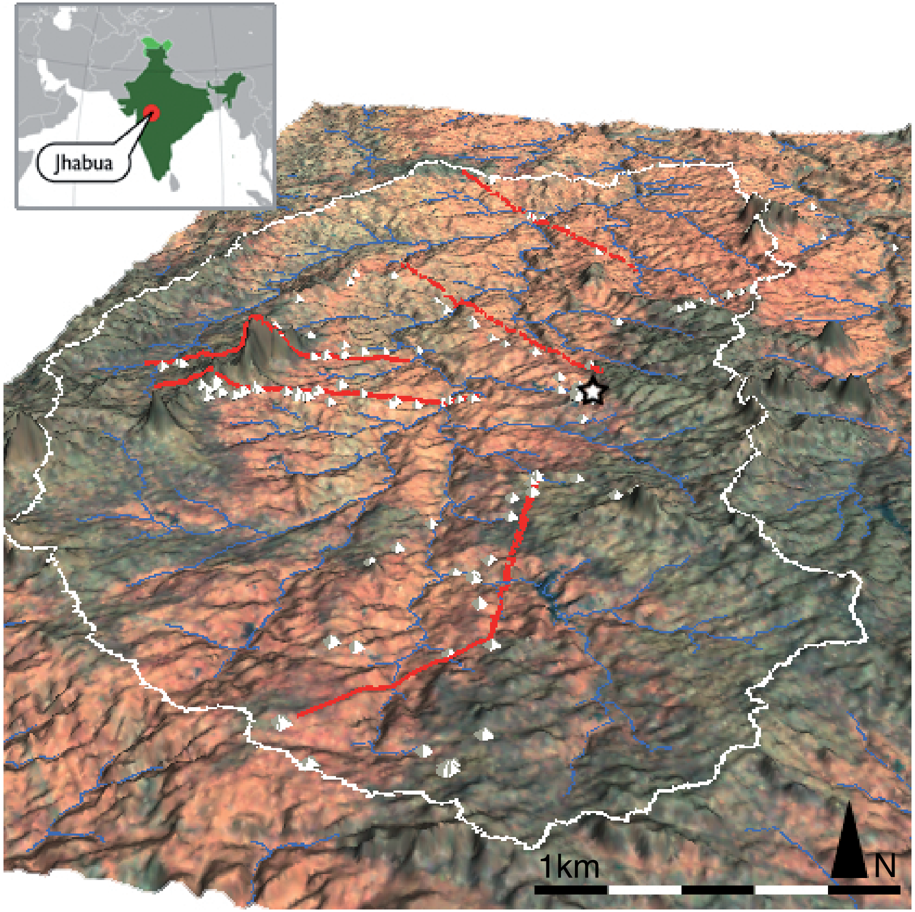

Fig. 1. Mod Catchment, Jhabua, Madhya Pradesh, India. Base: Band 2, 3 and 5 of Landsat ETM+ 1 April 2000 draped to SRTM. Transects (red lines), Sampling Poins (white dots) and Ranapur weather station (star).

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

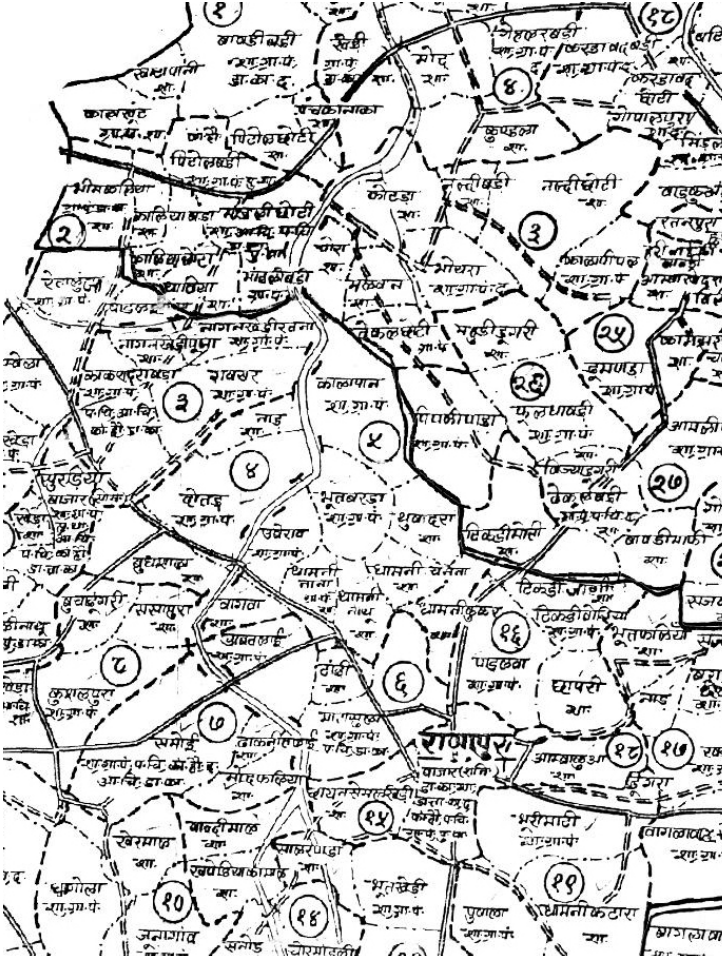

Fig. 2. Administrative map of the lower Mod catchment, Jhabua District, MP, India.

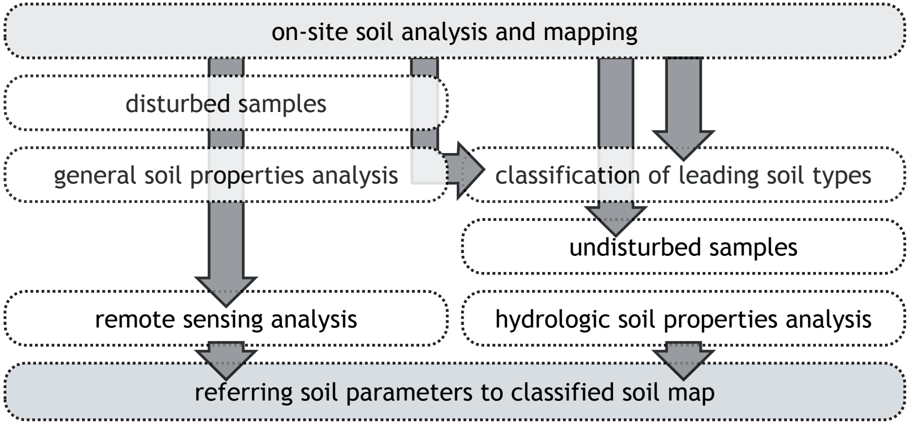

Fig. 3. Hierarchical sampling strategy for catchment representation with a minimum of samples in a multi-step classification approach.

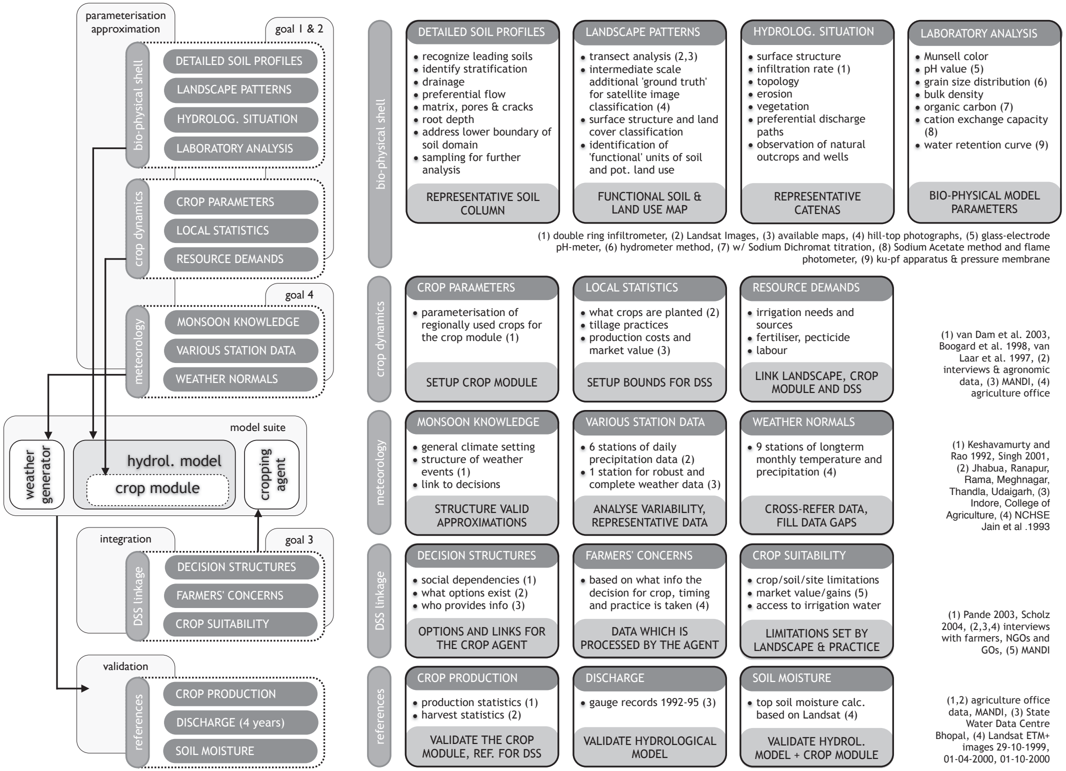

Fig. 4. Data Assessment Strategy Overview and Analysis Aspects, Linking Elements and Sources.

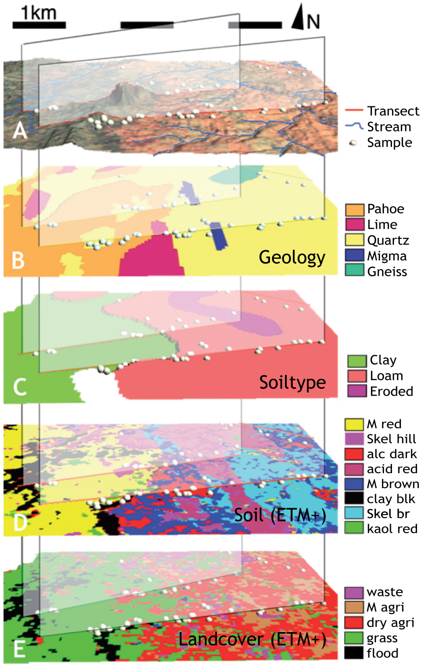

Fig. 5. Detailed view on Transects in the central western part of the Catchment: **(A)** Topography: Landsat ETM+ on SRTM with river network, transects and sampling points; **(B)** Geologic Setting: Pahoe = Vesicular Pahoehoe Flow, Lime = Nodular Limestone, Quartz = Muscuvite Quartzite, Migma = Migmatite, Gneiss = Gneissose, Feldspathic Formations; **(C)** Soils: Clay = Clay, moderate erosion, Loam = Loam, kaolinitic, erosion, Eroded = Loamy, skeletal, erosion; **(D)** Soil Description from Remote Sensing: M red = meager red, Skel hill = skeletal hill, alc dark = alkalic dark brown loamy, acid red = acidic red brown feldspath, M brown = meager loamy brown, clay blk = deep clay montmorillonite black, Skel br = skeletal brown, kaol red = clay loam kaolinite red; **(E)** Land Use Classes from Remote Sensing: waste = wasteland, M agri = meager agriculture, dry agri = dryland agriculture, grass = grassland, flood = floodplain agriculture.

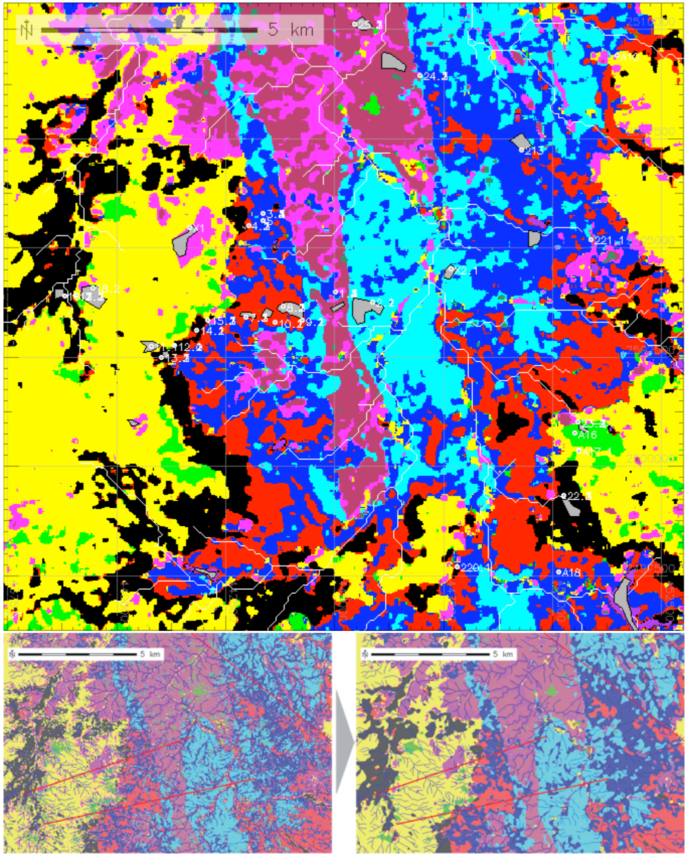

Fig. 6. Soil classes in central catchment of mod river, result from maxlik classification smoothed using 5 pixel median in GRASS, training ROIs for classification are marked in grey, soil samples are marked with white labels. Deep clay black – black, alkalic dark – red, red kaolinitic – green, meager brown – blue, meager red – yellow, acidic red – maroon, skelettal brown – cyan, skelettal hill – magenta, skelett – sea green, water body – purple. Lower panel: basis and result of smoothing procedure.

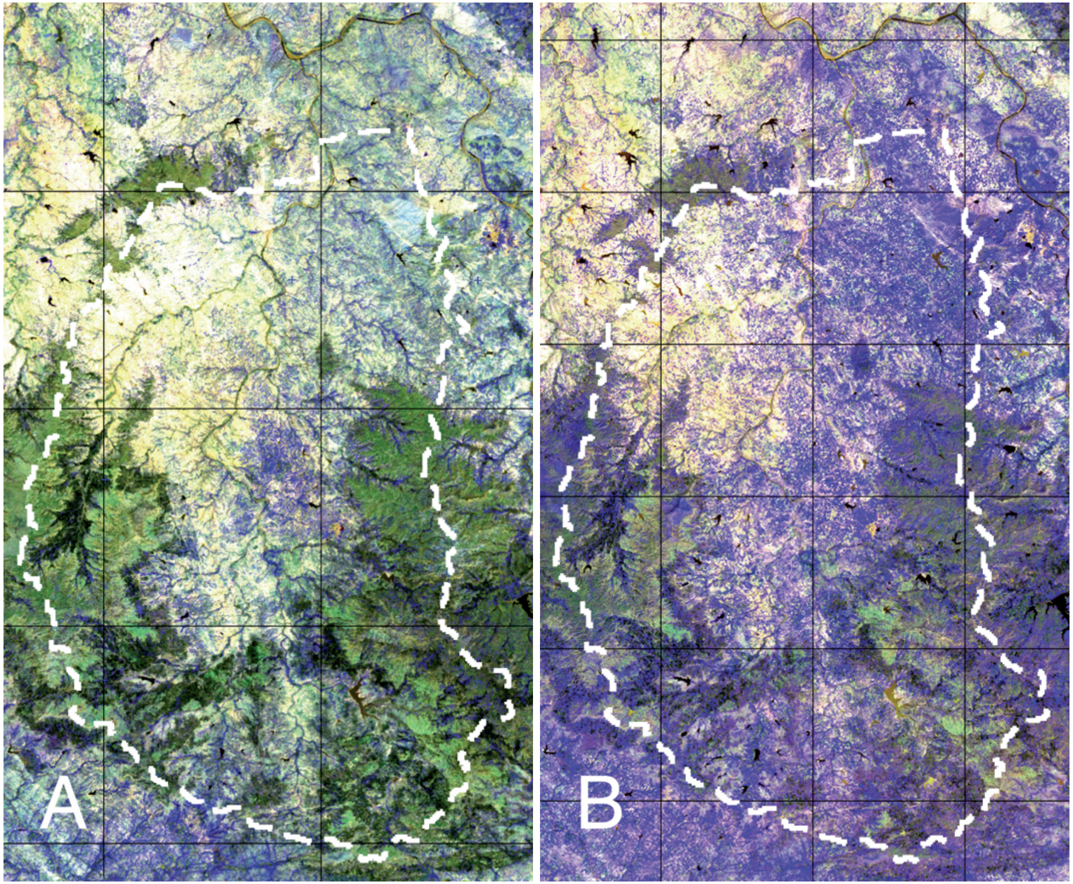

Fig. 7. Landsat ETM+ Band 2, 3 and 4 (rgb) Composite after Monsoon Spell **(A)** 2000 (±400 mm) and **(B)** 2001 (±700 mm), Mod Catchment, Jhabua, Madhya Pradesh, India. Purple colours indicate vegetation.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◀I | ▶I

◀ | ▶

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

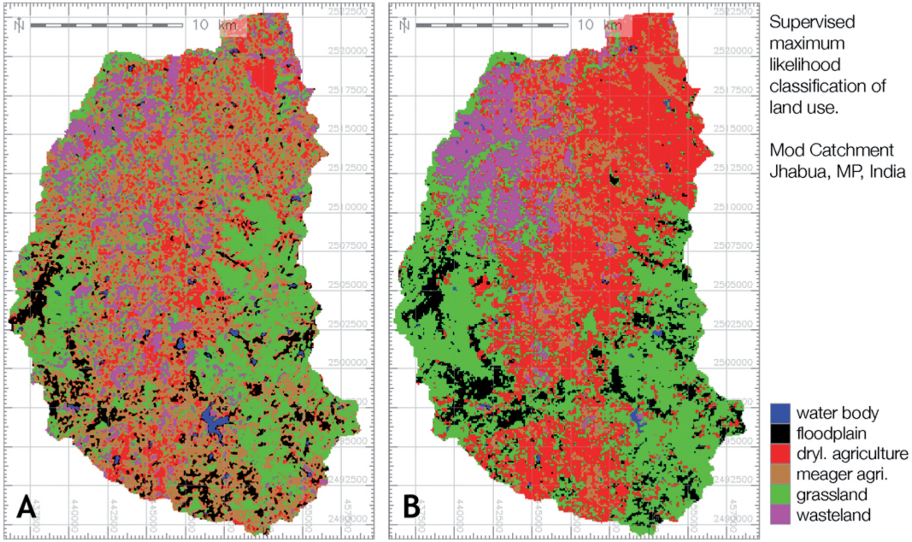

Fig. 8. Land Cover Classification of Mod Catchment, Jhabua, Madhya Pradesh, India. Result generated using supervised maximum likelihood classification based on ground data. **(A)** Basis is Landsat TM of 9 October 1989 **(B)** Basis is Landsat ETM+ 18 October 2001.

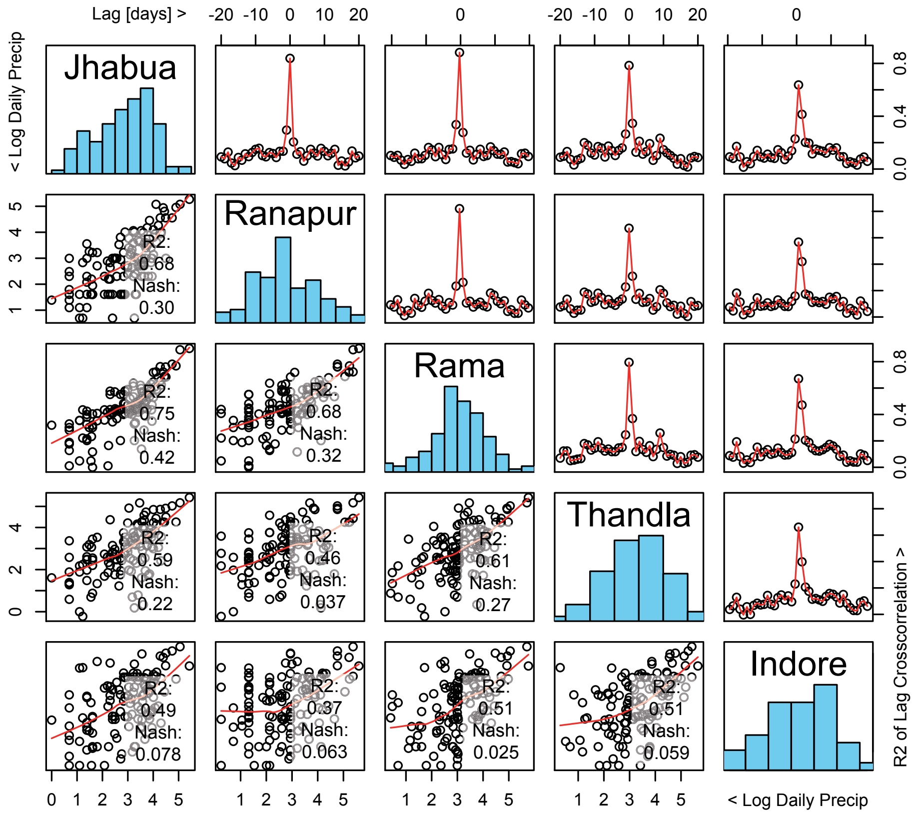

Fig. 9. Correlation of in and near catchment rain records and the records at the College of Agriculture, Indore. Lower Panel: Logarithmic values without zeros and limited to pairwise complete observations as Scatter with smoothed lowess regression line, R^2 and Nash; Diagonal Panel: Histogram of Logarithmic Data Set; Upper Panel: Lagged Cross Correlation of full pairwise data sets, ±20 days in lag steps of 1 day.

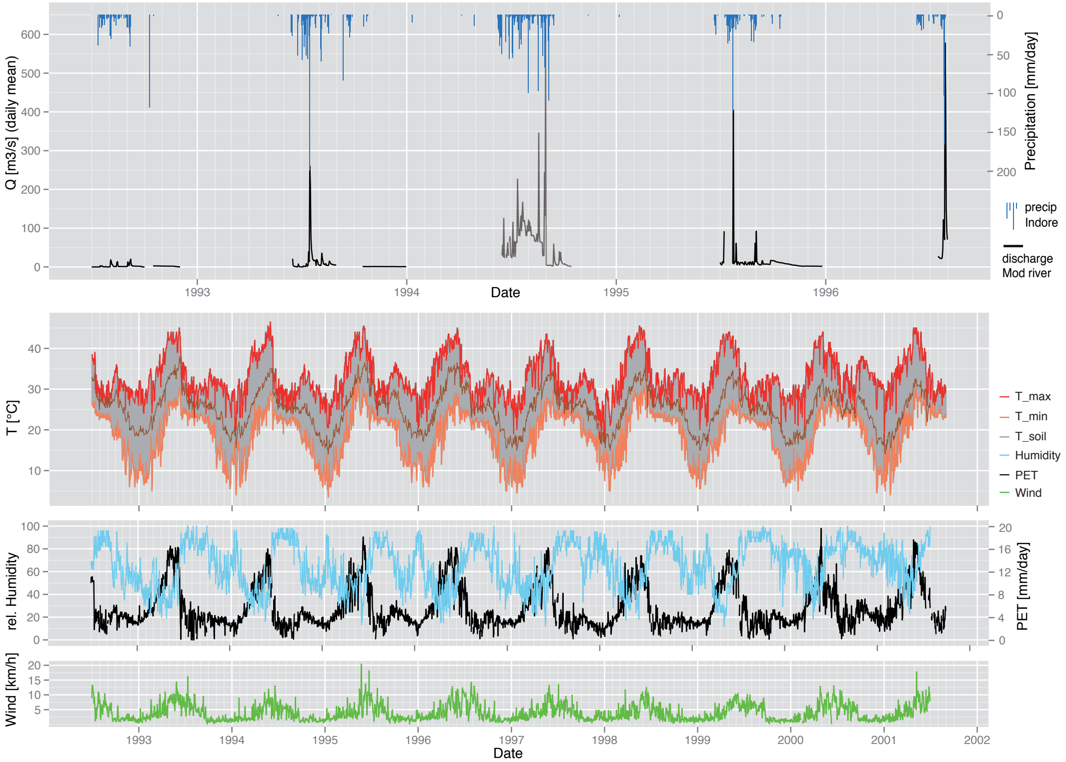

Fig. 10. Hydrometeorological Data. Daily Values for Mod River Discharge and Meteorological Records, College of Agriculture, Indore.