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From local hydrological process analysis to regional hydrological model application in Benin: Concept, results and perspectives

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Abstract

This paper presents the concept, first results and perspectives of the hydrological sub-project of the IMPETUS-Benin project which is part of the GLOWA program funded by the German ministry of education and research. In addition to the research concept, first results on field hydrology, pedology, hydrogeology and hydrological modelling are presented, focusing on the understanding of the actual hydrological processes. For analysing the processes a 30 km^2 catchment acting as a super test site was chosen which is assumed to be representative for the entire catchment of about 15,000 km^2. First results of the field investigations show that infiltration, runoff generation and soil erosion strongly depend on land cover and land use which again influence the soil properties significantly. A conceptual hydrogeological model has been developed summarising the process knowledge on runoff generation and subsurface hydrological processes. This concept model shows a dominance of fast runoff components (surface runoff and interflow), a groundwater recharge along preferential flow paths, temporary interaction between surface and groundwater and separate groundwater systems on different scales (shallow, temporary groundwater on local scale and permanent, deep groundwater on regional scale). The findings of intensive measurement campaigns on soil hydrology, groundwater dynamics and soil erosion have been integrated into different, scale-dependent hydrological modelling concepts applied at different scales in the target region (upper Ouémé catchment in Benin, about 15,000 km^2). The models have been applied and successfully validated. They will be used for integrated scenario analyses in the forthcoming project phase to assess the impacts of global change on the regional water cycle and on typical problem complexes such as food security in West African countries.

Keywords: Hydrological process analysis; Runoff generation; Hydrological modelling; Local to regional scale; West Africa

1. Introduction

Climatic and environmental change will lead to shortage in water resources and to uncertainties with regard to food security in many regions of the world in the 21st century. Numerous investigations on global change processes and their impact on the hydrological cycle have shown that global climatic change has a significant influence on the regional water budgets (Gaiser et al., 2003; Bronstert et al., 2002; Menzel and Bürger, 2002; Mimikou et al., 2000; Orange et al., 1997). The national German GLOWA program ('global change of the water cycle') has been set up by the German ministry for education and research (BMBF) to investigate the global

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change effects on the water cycle at regional catchment scales on different continents (Danube, Elbe, Jordan, Volta, Drâa, Ouémé rivers). Thus GLOWA is a complementary programme with regard to international activities such as GEWEX (global energy and water cycle experiment), CLIVAR (climate variability and predictability) and BAHC (biological aspects of the hydrological cycle). One of the five projects funded within the GLOWA program is the IMPETUS project: an integrated approach to the efficient management of scarce water resources in West Africa. In two regional catchments situated north (arid to semiarid Draâ catchment in Morocco) and south (sub-humid Ouémé catchment in Benin) of the Sahara natural and social scientists investigate global and regional change processes and their effects on the water cycle and on the population. The two target catchments of IMPETUS (Oued Drâa and HVO = upper Ouémé valley, Fig. 1) have been chosen as they are assumed to be representative for the region in terms of climate, land cover and anthropogenic influences and therefore also in terms of typical constraints in water related issues. Furthermore, it has been proved that the climate of the regions north and south of the Sahara is connected by atmospheric teleconnection processes (Lamb and Peppler, 1991) and therefore cannot be investigated separately. The integrative, interdisciplinary and application oriented IMPETUS project intends to investigate the whole process chain linking natural and social sciences as well as water quantity and quality. Therefore, feed back mechanisms between different driving forces of environmental change (e.g. rainfall variability depends on land cover change, land cover change depends on population growth and migration process, etc.) have to be considered. Thus the project is structured into several sub-projects for the two regions in Benin and Morocco (meteorology, hydrology, vegetation dynamics, socio-economy, ethnology and medicine) to accommodate the process knowledge required from the different disciplines and the interdisciplinary connections.

In the framework of the IMPETUS project the hydrological research activities and approaches are adjusted to the requirements of the entire project. In addition to the understanding of hydrological processes and their exact representation within hydrological models, the interfaces to the atmosphere, land cover and socio-economy are of central importance in IMPETUS. These driving forces and variables are the main causes and influencing factors for a change in the hydrological cycle. Main objectives of the hydrological sub-projects in Benin and Morocco in the first project phase of IMPETUS (2000–2003) was to describe, to analyse and to quantify the processes of the land phase of the hydrological cycle and to integrate this knowledge into hydrological model approaches applied and validated at local and regional scales. During the forthcoming project phase (2003–2006) these models will be applied for integrative scenario analyses and therefore used as predictive tools. This paper presents the super test site concept, first measurement and modelling results and

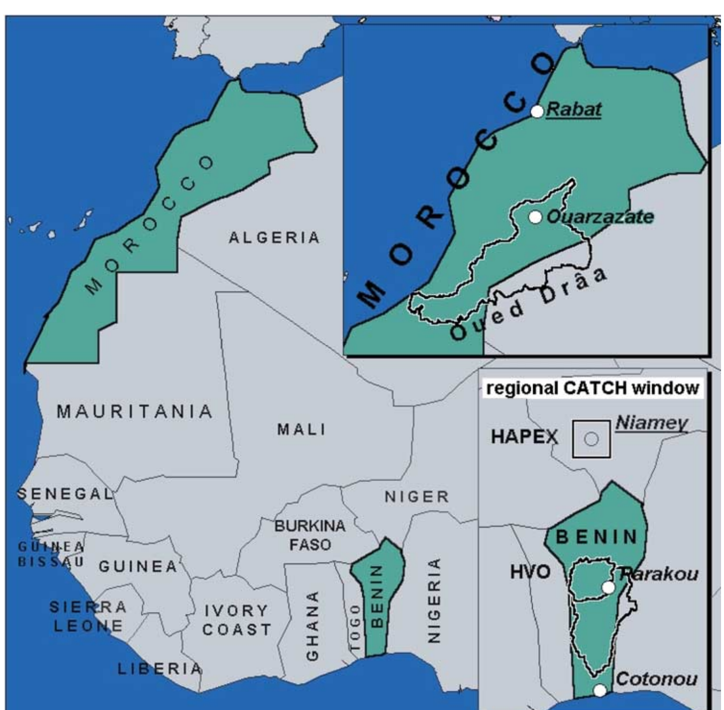

Fig. 1. Overview about the catchments of interest of the IMPETUS project: the Oued Drâa (Morocco) and the upper Ouémé valley (=HVO, Benin).

perspectives of the hydrological sub-project of IMPETUS-Benin. An overview on the socio-economic work within IMPETUS-Benin is given by M'barek et al. (2004) and Hadjer et al. (2004), focusing on water consumption and resource management in Benin.

2. Data base and measurement concept of the upper Ouémé valley

The area of investigation in central Benin (upper Ouémé valley, approx. 15,000 km^2, Fig. 2) can be characterised by a moderate topography (250–550 m a.s.l.), a mosaic of dense savannah vegetation and agricultural fields and fersialitic, partly crusted tropical soils. The climate is dominated by a uni-modal rainy season (about 1100 mm/a rainfall between April and October) whereas the annual rainfall amount varies significantly (coefficient of variation of about 0.19 for the rainfall station Parakou between 1922 and 2001). This variation in rainfall leads to a significantly larger variability in stream flow (coefficient of variation of about 0.63 for the stream flow at the gauge station Ouémé/Béterou).

For the upper Ouémé valley a spatial and temporal data base is available which is comprehensive compared to other West African countries. Basic spatial standard data sets are available for soils, geology, vegetation and topography (Table 1). Temporal data sets on weather, rainfall and stream flow on the regional scale mostly are available in daily resolution whereas one is faced with many gaps in the time series due to malfunction and limited maintenance of measurement devices. Unfortunately these data sets are not comparable to European standards in terms of information provided. As temporal and spatial resolution of regional scale data sets is not sufficient for hydrological process studies, a super test site with intensive measurements was installed to observe, analyse and quantify the hydrological processes.

This concept of one test site being assumed to be representative for the whole catchment was chosen due to the relative homogeneity of the landscape with regard to topography and climate. The super test site covers the different land use types of the upper Ouémé region: "natural" savannah as well as agricultural fields. Most important crops are yams, manioc, maize, cashew, peanut, beans and sorghum. Within the super test site two small subcatchments can be differentiated. The upper Aguima catchment (3.2 km^2) is dominated by natural savannah, and the upper Niaou catchment (3.5 km^2) is mainly used by agriculture. The investigation of these two subcatchments with different land use is essential, because due to population growth a significant change in land cover actually takes place in the northern part of the upper Ouémé region where natural savannah is changed into agricultural fields. The comparison of the two small subcatchments can be used for quantifying the effect of land use change on the hydrological processes. Based on intensive measurement campaigns (soil moisture, soil erosion, infiltration, spatiotemporal

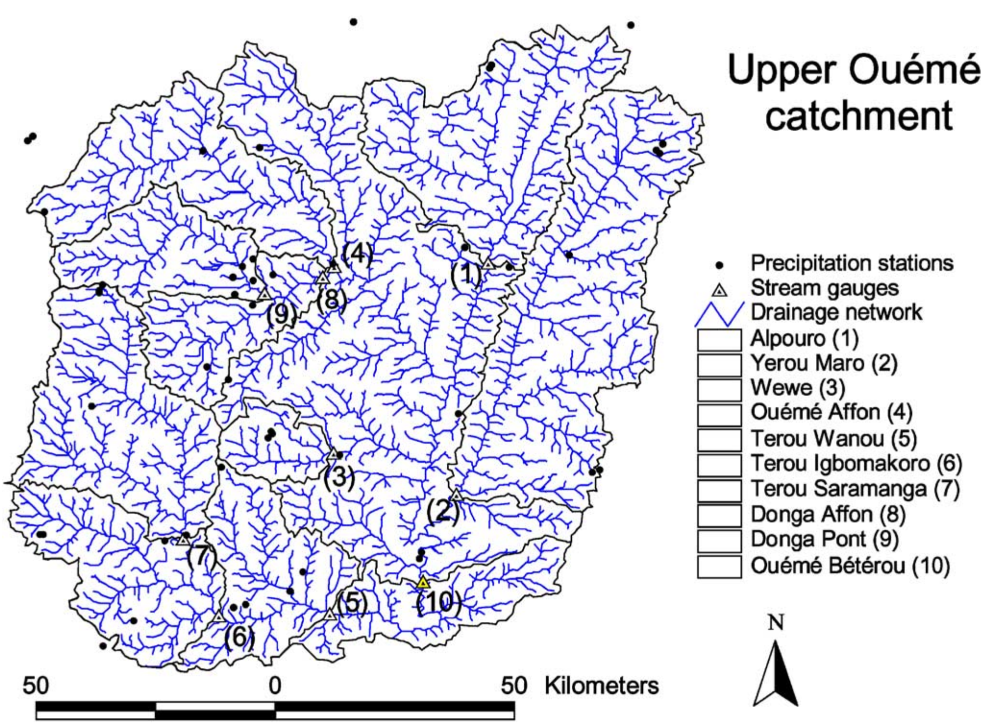

Fig. 2. Upper Ouémé catchment: rivers, stream gauges and rain gauges.

Table 1
Available data sets at the super test site Aguima (local scale) and in the upper Ouémé catchment (regional scale)

Data set	Local resolution: Aguima catchment (30 km^2)	Regional resolution: upper Ouémé catchment (15,000 km^2)
Soil	Local mapping (1:50,000)	1:200,000
Topography	1:50,000	1:200,000
Land use	Local mapping	30 m (Landsat based)
Geology	Local mapping	1:200,000
Weather data	10 min (T, h, R, v,...) (three stations) (May 2001–December 2003)	3 h to daily (1 station) (1993–2000)
Rainfall	Break point data (five stations) (May 2001–December 2003)	Daily sums (43 stations) 1993–2001
Stream flow	10 min (five gauges) (May 2001–December2003)	Daily discharges (11 gauges) (until 2000/2001)

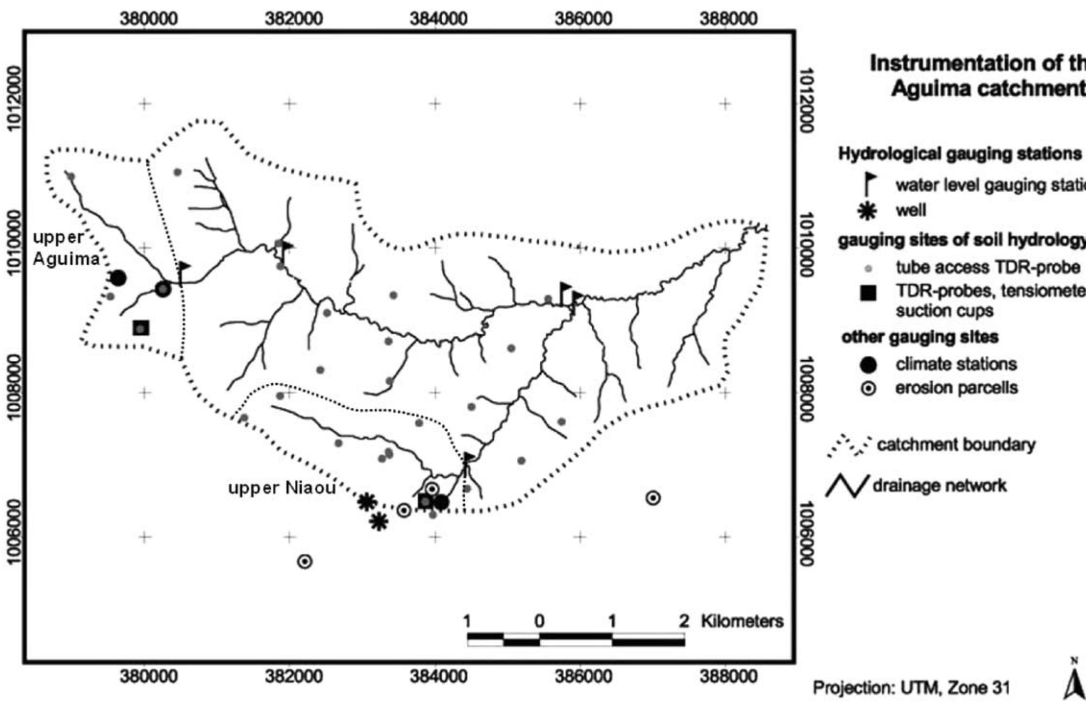

Fig. 3. Instrumentation of the super test site Aguima (central Benin, 30 km^2).

variability of soil properties) and the permanently installed instruments within the super test site Aguima (Fig. 3, 30 km^2) a nested hydrological approach can be applied. The installed instruments (three climate stations, four soil measurement stations (soil content and soil suction), five stream flow gauges and three groundwater wells) gather automatically data since April/May 2001 up to now showing only small gaps due to technical problems. The stream gauges allow the analysis of a set of catchments with increasing size ranging from 3.2 km^2 to 30 km^2.

For the application of process-based models, one important issue of IMPETUS is the improvement of the regional soil map. The regional soil map is needed for a successful regional and process-based hydrological model application. The available soil map focuses on the distribution of soil types instead of the distribution of soil properties which are required for modelling purposes. On the super test site scale (30 km^2) the available soil map has been improved significantly performing drillings and using additional data (topography, vegetation distribution). For the forthcoming project period a similar work on the regional scale is planned, focusing on the derivation of a regional map of soil properties based on the available regional soil map, the vegetation classification derived from satellite images, a digital elevation model and the field investigation of typical catenas.

3. First results of IMPETUS measurement campaigns in the Ouémé valley (Benin)

The main goal of the field work on local hydrology, soils and hydrogeology at the super test site was to provide knowledge and data about the dominant processes and properties for the local model applications. To apply regional hydrological models, model simplifications are required and regionalisation approaches has to be developed to transfer the experience from local to the regional scale.

3.1. Soil hydrology and surface hydrology

During the high rainy season spatial patterns of soil moisture are correlated with topography, resulting in dry upslopes and wet valleys. These patterns do not occur in the dry season and in the beginning of the rainy season because than water content depends mainly on the soil texture (minimal water content). Despite this slope scale pattern at the small scale a very high spatial variability was detected. Applying the nested sampling approach (Webster, 1977) revealed that both, natural savannah and agricultural areas, feature a high spatial variability of soil moisture content and bulk density with 70% of the variability within 100 m being achieved already in 3 m respectively 0.3 m measuring distance.

In order to examine the influence of land use on soil surface permeability, infiltration experiments using hood, double and single ring infiltrometers were carried out on different land cover types (agricultural fields, savannah, forest). The infiltration experiments revealed that the permeability of the soil surface is strongly dependent on land cover. While for the different types of natural vegetation (sparse woodland, dense tree savannah, grass savannah within inland valleys) only small differences between the mean saturated conductivities were observed, a significant difference between natural vegetation and cultivated land was measured (Fig. 4). The main influencing factor for the saturated conductivity is the macroporosity of the soil, which strongly depends on the soil biologic activity. While the water conductivity of the upper soil layer is mainly dependent on land use, the saturated conductivity (k_s) of deeper soil horizons is more related to soil type and texture of the horizon. Concerning the predominant flow paths within the soils on the hillslope, the decrease of the saturated hydraulic conductivity k_s with depth, which was determined on Lixisols (saprolithic horizon), and the impermeability of the plinthitic crust of Plinthosols forces lateral flow processes.

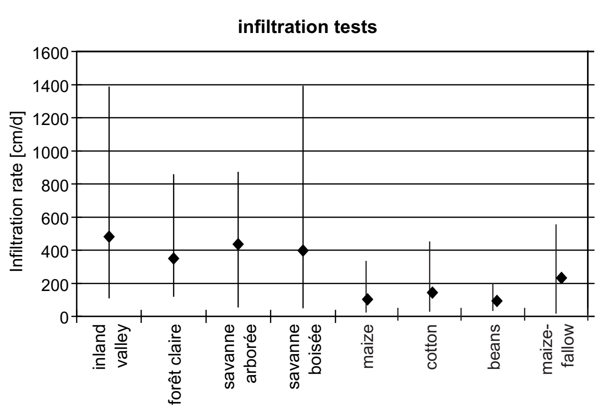

Fig. 4. Infiltration rates depending on land use, measured within the Aguima super test site (*bas fond* = swampy inland valley without trees; *forêt claire* = forest with 50–75% tree coverage; *savanne arborée* = savannah with 20–50% tree coverage; *savanne boisée* = savannah with 5–20% tree coverage).

The effect which dominant land use has on the hydrological behaviour of small catchments was investigated by delimitating the two small subcatchments (3.2 and 3.5 km^2) with different land use (natural savannah versus agricultural fields) by stream flow gauges and electric conductivity probes. The measurements revealed that in a dry year the agricultural catchment showed a six times higher discharge than the savannah catchment while in a wet year the difference was significantly smaller (Table 2). In both periods the agricultural catchment showed high soil water contents earlier in the rainy season than the savannah catchment which could not be explained by the variability of the soil texture alone. Thus the savannah catchment shows higher evaporation and interception losses and has a higher water storage capacity due to thicker soil horizons because erosion is less pronounced on these areas as a consequence of low surface runoff (Giertz and Diekkrüger, 2003).

Main implications of the field hydrological investigations with regard to modelling are:

- The high small scale variability of soil hydrological properties needs to be considered by process oriented models (subgrid variability within each simulation unit).
- The high small scale variability of soil moisture must be taken into account during model validation based on measurements of soil water content and soil water potential.

Table 2
Surface runoff generation during a dry (2001) and a wet year (2002): runoff contribution of Aguima catchment (savannah) versus Niaou catchment (agriculture)

Seasonal water balance	Aguima catchment (3.2 km^2, savannah)	Niaou catchment (3.5 km^2, agriculture)
Rainfall 2001	809 mm	809 mm
Runoff contribution 2001	32 mm (4% of rainfall)	136.5 mm (17% of rainfall)
Rainfall 2002	1145	1145
Runoff contribution 2002	109.2 mm (9.5% of rainfall)	161.7 mm (14% of rainfall)

- Soil parameters are strongly dependent on land use. This interdependency must be taken into account for modelling purposes, especially if pedotransfer functions are used to derive soil hydraulic parameters from basic soil properties.

3.2. Soil erosion and soil degradation process

Measurements of the current soil loss by runoff plots (16 m^2) indicate a significant influence of different growing systems on soil loss (Fig. 5). The highest loss was found on cotton fields cultivated in furrows in the direction of the slope. In comparison, there was less erosion in fields with yam planted on mounds and crops on furrows parallel to contour lines. In the savannah soil erosion also occurs, but to a significantly lower extend. Measurements with erosion pins on differently prepared soil surfaces confirmed these findings. Summarized, soil loss in agricultural used fields always was higher (mean 40 t ha^{-1} a^{-1}) than in the savannah (mean 3.9 t ha^{-1} a^{-1}). Extrapolating these conditions to the future the expected erosion would lead to a significant decrease of the thickness of the top soil layer and therefore also to a decrease in the maximum rooting depth and field capacity. Drillings on agricultural fields close to the super test site already show this reduction of hillwash thickness on farm land (hillwash = allochthonous small-grained upper sediment layer).

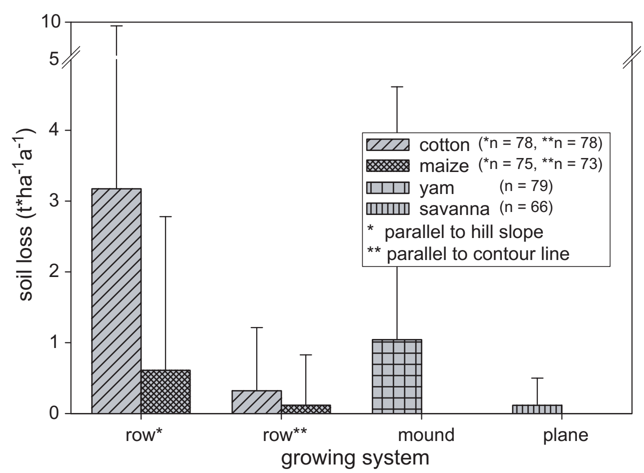

Fig. 5. Erosion rates measured on erosion plots at the super test site Aguima.

Analyses of grain size distribution and quantities of organic carbon and nitrogen of the eroded material compared to the A-horizon of the soils point out that in addition to a physical degradation a chemical degradation is observed. The comparison of chemical parameters of savannah soils and agricultural fields also show an intensified nutrient leaching in the agricultural fields compared to the savannah soils. The estimation of soil erosion rates is required for the quantification of environmental change scenarios considering the implications of land use change (savannah to agriculture) on soil water storage characteristics which will be performed in the next step.

3.3. Conceptual model of hydrogeological processes

A first conceptual, hydrogeological model (Fig. 6) was developed based on the field activities on geological mapping, geochemical and hydrochemical analyses, environmental labelling with ^{18}O, ^{2}H and ^{3}H, local and regional piezometric mapping and pumping tests

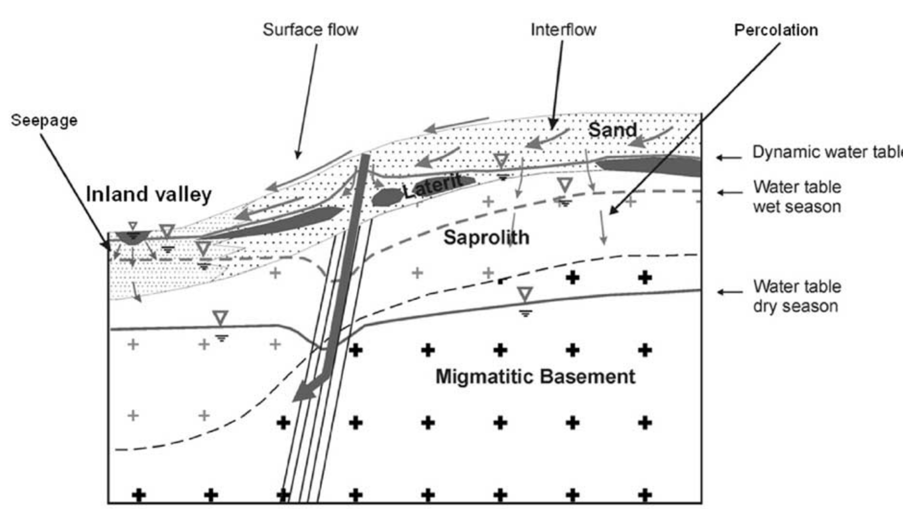

Fig. 6. Conceptual hydrogeological model for the Aguima super test site in central Benin; dynamic water table = perched water table only during the rainy season; the big vertical arrow in the centre represents the importance of preferential flow paths for groundwater recharge. Groundwater recharge only occurs along preferential flow paths and not over the entire catchment area.

as well as tracer experiments. The fractured basement aquifer is characterised by a transition towards a quasi-porous aquifer in its overlaying weathering zone. This vadose zone is structured and consists of a saprolithic weathering zone above the migmatitic basement followed by a lateritic strengthened horizon which is overlaid by mostly highly permeable sandy topsoil. The saprolithic weathering zone has a mean thickness of about 12 m and is only partly saturated due to the high variability of the water table between dry and wet season. Pumping tests proved the reaction of the vadose zone as a leaky (semi-confined) quasi-porous aquifer with the lateritic strengthened zone as a low permeable upper boundary. The development of the soil water content in the vadose zone can clearly be explained with respect to geology and lithology. Both a clear dependence of the soil moisture content on the substrate as well as a strong influence of low permeable horizons on the percolating water is evident. The lateritic strengthened horizons act as aquitards, where percolation of the infiltrating precipitation water is redirected. While this part of the percolate contributes to the surface water (interflow), another part is able to pass the nearly impermeable lateritic horizons through preferential flow paths (thick arrow in the centre of Fig. 6) and thus contributes to the groundwater recharge. This local groundwater recharge only can take place in periods with high soil water content (about mid-August to mid-October in central Benin). Significant differences between groundwater and soil water chemistry engage that the deeper aquifer is replenished mainly by lateral inflow from outside and that the upper aquifer and the lower aquifer are disconnected to a large extent.

From the hydrogeological analysis it can be concluded that on the local scale fast surface and subsurface processes are dominant, local scale groundwater recharge occurs by preferential flow, but is quantitatively of minor importance. Analyses on environmental tracers indicate that groundwater does not directly take part in the local scale water cycle, but is much more importance on the regional scale. Therefore hydrological models on different scales have to consider groundwater processes in different ways. Interactions between groundwater and surface water (streams) need to be considered for modelling purposes, especially in the beginning of the rainy season (seepage from streams to groundwater) as well as in the mid and the end of the rainy season (base flow).

4. First results of hydrological modelling on local scale (super test site)

On local scale the TOPLATS model concept was applied to evaluate the suitability for a hydrological process analysis and regional model application in the research area. TOPLATS (Famiglietti and Wood, 1994) is a grid-based spatially distributed model, which combines the physically based simulation of spatially distributed, single SVAT schemes (soil vegetation atmosphere transfer) with the lateral TOPMODEL concept. The SVAT scheme is based on the Penman–Monteith equation for the calculation of potential evapotranspiration, a two-layer soil module based on the Brooks–Corey parameterisation and on both, infiltration excess and saturation excess runoff generation. Main focus besides the water balance is set on the solution of the energy balance of the earth's surface. The validation of the simulation results revealed that the water balance and the discharge of the Aguima catchment were well reproduced by the model after calibration (Fig. 7). Comparing the observed and simulated hydrographs a model efficiency of 0.62 for daily discharges was obtained. Additionally the surface runoff simulated by the TOPLATS model was validated by comparing the model results to measured surface runoff data from erosion plots. The average values of several runoff plots considering all main land use types were used. The correlation of the simulated (58 mm/a) and the observed (50 mm/a) runoff for the year 2002 was fairly good.

As the vertical discretisation of the soils in the TOPLATS model is restricted to two layers, a second process-based model concept was applied. To overcome this limitation, a quasi-3D approach was achieved by dividing a catchment into many slopes which are representative for subcatchments, calculating the water fluxes of all slopes by applying the SIMULAT-H model and aggregating the water fluxes of all slopes for the catchment. SIMULAT-H is a in lateral direction coupled version of the one-dimensional SIMULAT model (Diekkrüger and Arning, 1995) which is able to calculate the water fluxes in soils for unsaturated and saturated conditions including water logged profiles. SIMULAT is based on the Penman–Monteith equation for the calculation of

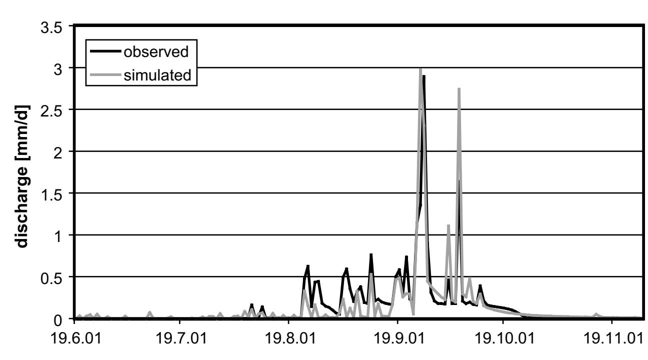

Fig. 7. Comparison of measured and simulated discharge (application of the TOPLATS model) at the local scale Aguima catchment (30 km^2) for the year 2001.

Table 3
Quality measures of the application of the SIMULAT-H model in the Aguima catchment

Catchment, period	Model efficiency	Coefficient of determination	Simulated stream flow (mm/a)	Observed stream flow (mm/a)
Upper Aguima (3.2 km^2) calibration period, 2002	0.82	0.78	117.2	109.2
Aguima (16 km^2) validation period, 2002	0.86	0.87	132.5	139.6

Calibration: upper Aguima, validation: Aguima.

potential evapotranspiration and the approach of Smith and Parlange (1978) for infiltration. The computation of the soil water flow is based on the Richards' equation, and therefore the soil can be vertically discretised in as many layers as needed.

The results of the SIMULAT-H application are satisfying. The water balance is well reproduced as well as the seasonal structure of the hydrograph and most flood events. Due to the dynamics of the river bed, the inundation during flood events and the temporal malfunction of measurement devices a perfect correlation of simulation and observation cannot be expected. Nevertheless SIMULAT-H could be validated by applying the model after calibration for the upper Aguima catchment to the Aguima catchment without further adaptation (Table 3). The statistical quality measures are better than the results obtained by the TOPLATS model.

Finally also the comparison of simulated and measured soil moisture values gathered by the automatic soil water stations led to reasonable soil moisture time series of the simulations (Fig. 8) despite the small scale spatial soil variability (Giertz and Diekkrüger, 2003). As a result of the better representation of the vertical distribution of soil physical properties the same dominant water fluxes were calculated (surface runoff and interflow) as derived from the hydrogeological measurements and observations.

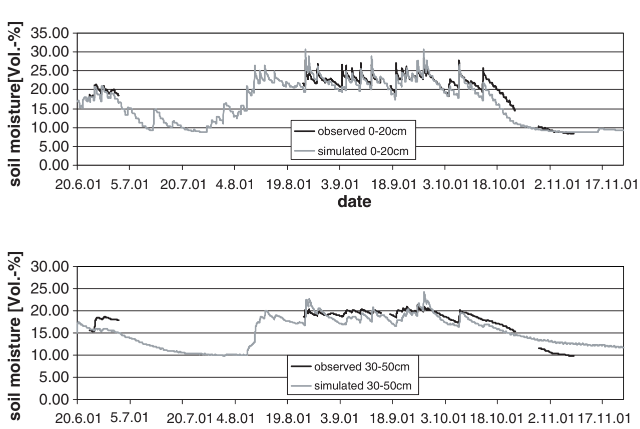

Fig. 8. Comparison of simulated (SIMULAT-H) versus observed volumetric soil moisture at the savannah site (0–30 cm depth, $R^2 = 0.95$; 30–50 cm depth, $R^2 = 0.86$).

5. Hydrological modelling at the regional scale (upper Ouémé catchment, Térou)

The applicability of two different model concepts for regional hydrological modelling has been compared in the Térou basin (3133 km^2, a subcatchment of the upper Ouémé valley): a process and physics-based model (TOPLATS) and a conceptual model (UHP). The process-based TOPLATS model (see Section 4, Famiglietti and Wood, 1994) requires a number of spatially distributed model parameters (in this case on a grid size of $100 * 100$ m) and therefore needs detailed input data on soils, vegetation and topography. The conceptual and lumped UHP model (Bormann and Diekkrüger, 2004), similar to the HBV model (Bergström, 1995), consists of four storages generating the different (fast and slow) flow components on the subcatchment level. The catchment water fluxes are calculated by a superposition of the subcatchment water fluxes. As the process description of this model is simple, the data requirements are significantly smaller. Model parameters have to be determined only on the subcatchment level. Both models were tested using standard data sets of the Térou catchment.

The TOPLATS model has been applied and validated successfully at the super test site scale (see Section 4). For the application at the regional scale further data sets are required containing information on soil physical properties and spatial distribution on rainfall intensities. A comparison of the TOPLATS model with the conceptual approach showed that based on the data actually available on the regional scale a model validation is not feasible (Bormann and Diekkrüger, 2003). The main reason is the high sensitivity of the model results to the soil physical model parameters and the limited knowledge concerning the spatial availability of the boundary conditions (rainfall intensities in particular) and model parameters. Thus a validation of TOPLATS at the regional scale can be performed only if these data sets are available (earliest at the end of the second project phase of the IMPETUS project).

Due to the described limited data availability at the regional scale the simplified model concept was applied (UHP model, Bormann and Diekkrüger, 2004) which is robust with regard to data uncertainties. The UHP model was calibrated using a 7 years data set of hydrometeorological data (1993–1999). For model validation up to now only data for the year 2000 are available. So the model validation at the moment is limited to the year 2000 (Térou river, split sample test), to results of the uncertainty analysis (see below) and to model applications in several other catchments in the upper Ouémé basin (Donga river, Affon river, upper Ouémé river, proxy basin test). The 7 years water balance is simulated exactly (25.2 m^3/s mean observed discharge compared to 25.1 m^3/s mean simulated discharge) for the Térou river with a model efficiency of 0.76 (weekly stream flow data). The seasonality as well as the slow runoff component (base flow) is simulated well (Fig. 9).

The uncertainty analysis focused on the uncertainty of model parameters using the Latin Hypercube method (McKay et al., 1979) and on the comparison of the effect of decreasing knowledge about catchment precipitation (decreasing number of rainfall stations considered). Model efficiency directly depends on the density of rain gauges. The better the variability of rainfall can be reflected by the model input data the better simulation results can be expected. The coefficient of model efficiency increases from 0.77 using four rain gauges to 0.91 using six rain gauges for the years 1998–1999 (Térou river, weekly stream flow). Applying the Latin Hypercube method the model parameter uncertainty (described by statistical distributions of the model parameters) was transformed into a reliability measure of the simulated hydrograph. A confidence interval of 80% was calculated. If the observed hydrograph lies within the uncertainty band, then the model can be assumed to be useful as a predictive tool. In the case of the Térou catchment the uncertainty band was narrow for most of the simulated years, and the observed hydrograph was lying mostly (85% of the values) within the 80% confidence interval (Fig. 10). Further results of the uncertainty analysis are shown by Bormann and Diekkrüger (2004).

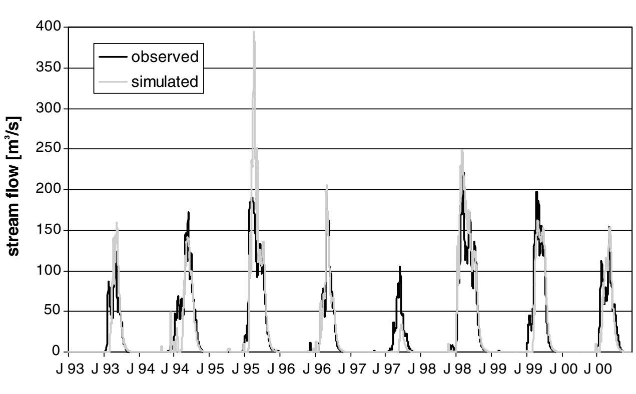

Fig. 9. Model application of the conceptual UHP model on the regional scale Térou catchment (3133 km^2) for the years 1993–2000; weekly values.

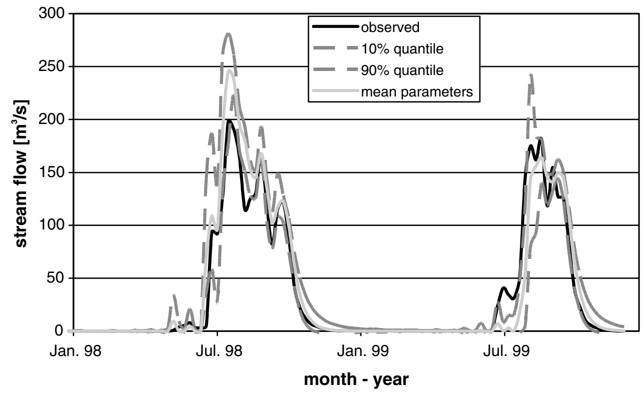

Fig. 10. Confidence interval around the simulated stream flow of the Térou (gauge Wanou, 1998/1999), calculated according to the Latin Hypercube method.

6. Conclusions and perspectives

From the results presented here it can be concluded that the process studies carried out essentially increased the knowledge about the hydrological processes in the sub-humid tropics. Hydrological processes were analysed and quantified, and the knowledge gained was applied in the hydrological modelling at different scales. In addition to the hydrological models mentioned, erosion and groundwater models will be applied in the forthcoming project phase of IMPETUS to consider all processes which are relevant for the assessment of water quality and quantity as well as soil fertility.

The investigations indicate that the local scale water balance very sensitively reacts to changes in vegetation and soil degradation. According to Falkenmark and Widstrand (1992) Benin is not yet affected by water stress, but water stress is already forecasted for the year 2025 taking into account the population development (UNEP, 2003). Land degradation and climate change can accelerate this process. Therefore it is necessary to develop management instruments to govern water consumption and water distribution to avoid conflicts and shortages.

At the actual state of the project validated hydrological modelling instruments are available on local and regional scales in the upper Ouémé catchment to reproduce the main processes of the water cycle. These models will be used as part of the future scenario analysis. For the regional model application the regionalisation of the process knowledge gained at the local scale is required. In particular the regional soil information needs to be improved with regard to physical and chemical soil properties determining the soil fertility. Coupling the hydrological models with validated models for plant growth (crops), economic development and predictions with regard to the water demand of population, industry and agriculture, this model chain can calculate change scenarios and quantify the effects on the regional scale.

For the final aim of IMPETUS, the development of management strategies, the precise definition of scenarios is required. Starting from global scenarios (e.g. SRES scenarios of the IPCC, 2001) the knowledge about regional driving forces and the results of local investigations will be included in the scenario definition. Thus an assessment of regional effects on water availability and food security (by balancing availability and demand) caused by regional and global change processes is feasible. On this basis a development of management tools is planned within IMPETUS. Therefore two important links need to be emphasised: the link between water availability and crop production and the link between the abiotic water cycle, the population and the society. The realisation of these interfaces including the feedback mechanisms will be one major challenge of the project.

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References

Bergström, S., 1995. The HBV model. In: Singh, V.P. (Ed.), Computer Models of Watershed Hydrology. Water Resources Publications, pp. 443–476.

Bormann, H., Diekkrüger, B., 2003. Possibilities and limitations of regional hydrological models applied within an environmental change study in Benin (West Africa). Physics and Chemistry of the Earth 28 (33–36), 1323–1332.

Bormann, H., Diekkrüger, B., 2004. A conceptual hydrological model for Benin (West Africa): Validation, uncertainty assessment and assessment of applicability for environmental change analyses. Physics and Chemistry of the Earth. 29 (11–12), 759–768.

Bronstert, A., Niehoff, D., Bürger, G., 2002. Effects of climate and land use change on storm runoff generation: present knowledge and modelling capabilities. Hydrological Processes 16 (2), 509–529.

Diekkrüger, B., Arning, M., 1995. Simulation of water fluxes using different methods for estimating soil parameters. Ecological Modelling 81 (1–3), 83–95.

Falkenmark, M., Widstrand, C., 1992. Population and water resources: A delicate balance. Population Reference Bureau, Population Bulletin, Washington, DC.

Famiglietti, J.S., Wood, E.F., 1994. Multiscale modelling of spatially variable water and energy balance processes. Water Resources Research 30 (11), 3061–3078.

Gaiser, T., Krol, M., Frischkorn, H., de Araújo, J.C. (Eds.), 2003. Global Change and Regional Impacts, Water Availability and Vulnerability of Ecosystems and Society in the Semi-Arid Northeast of Brazil. Springer, Heidelberg.

Giertz, S., Diekkrüger, B., 2003. Analysis of the hydrological processes in a small headwater catchment in Benin (West Africa). Physics and Chemistry of the Earth 28 (33–36), 1333–1342.

Hadjer, K., Klein, T., Schopp, M., 2004. Integrated approach of water consumption in Benin embedded in its social context. Physics and Chemistry of the Earth, this issue.

IPCC, 2001. Climate change 2001: The scientific basis. Contribution of the working group I to the third assessment report of the intergovernmental panel on climate change. Cambridge, 882pp.

Lamb, P.J., Peppler, R.A., 1991. West Africa. In: Glantz, M., Katz, R.W., Nicholls, N. (Ed.), Teleconnections Linking Worldwide Climate Anomalies. Section 5, pp. 121–188.

M'barek, R., Behle, C., Mulindabigwi, V., Schopp, M., Singer, U., 2004. Sustainable resource management in Benin embedded in the process of decentralisation. Physics and Chemistry of the Earth, this issue, doi:10.1016/j.pce.2005.06.016.

McKay, M.D., Beckmann, R.J., Conover, W.J., 1979. A comparison of three methods for selecting values of input variables in the analysis of output from a computer code. Technometrics 21 (2), 239–245.

Menzel, L., Bürger, G., 2002. Climate change scenarios and runoff response in the Mulde catchment (Southern Elbe, Germany). Journal of Hydrology 267 (1–2), 53–64.

Mimikou, M.A., Baltas, E., Varanou, E., Pantazis, K., 2000. Regional impacts of climate change on water resources quantity and quality indicators. Journal of Hydrology 234 (1–2), 95–109.

Orange, D., Wesselink, A.J., Mahe, G., Feizoure, C., 1997The Effects of Climate Changes on River Base Flow and Aquifer Storage in Central Africa, 240. IAHS Publication, pp. 113–123.

Smith, R.E., Parlange, J.-Y., 1978. A parameter-efficient hydrologic infiltration model. Water Resources Research 14 (3), 533–538.

UNEP, 2003. Availability of Freshwater in West Africa. Available from: <www.unep.org/aeo166.htm>, date of access: 15.7.04.

Webster, R., 1977. Quantitative and Numerical Methods in Soil Classification and Survey. Clarendon Press, Oxford, 269pp.