Comparative discharge prediction from a small artificial catchment without model calibration: Representation of initial hydrological catchment development

H. Bormann, H. M. Holländer, T. Blume, W. Buytaert, G.B. Chirico, J.-F. Exbrayat, D. Gustafsson,
H. Hölzel, P. Kraft, T. Krauße, A. Nazemi, C. Stamm, S. Stoll, G. Blöschl and H. Flühler

Vergleichende Abflussvorhersagen eines kleinen, künstlichen Einzugsgebiets ohne Modellkalibrierung

Introduction

Due to recent environmental change and subsequent hydrological change, there is an increasing demand for hydrological predictions, as well as improved understanding of processes (SIVAPALAN et al., 2003). Hydrological models can serve as useful tools for both purposes. Conceptually different models have been developed and applied for prediction and scenario analysis. Previous model comparison studies revealed that conceptually different models showed similar sensitivities to environmental change scenarios (HUISMAN et al., 2009), while the modeller often made the difference between each model application, rather than the choice of the model (DIEKKRÜGER et al., 1995). The question remains to which degree the influence of the modeller depends on data availability and whether a gradual improvement of the data base reduces differences between predictions based on different models.

Within the framework of the Transregio-SFB 38 “Structures and processes of the initial ecosystem development phase in an artificial water catchment”, this study addresses the issue to test a model’s ability to make hydrological predictions without any calibration. In agreement with the PUB initiative (Predictions in Ungauged Basins; Sivapalan et al., 2003), different models were applied based on sparse data of catchment characteristics, while hydrological fluxes (e.g., discharge) and state variables (e.g., soil moisture, groundwater table) were unknown to the modellers. There-

Zusammenfassung

Zehn konzeptuell unterschiedliche Modelle wurden im Testeinzugsgebiet Hühnerwasser in der Lausitz (Nordostdeutschland) angewandt, um den Abfluss aus dem 6 ha großen Gebiet, einem ehemaligen Tagebauareal, abzuschätzen. Der Modellvergleich erfolgte in drei Stufen, wobei die Zielsetzung eine Anwendung für unbeobachtete Einzugsgebiete darstellte. Zuerst wurden nur Angaben über Bodentextur, Topographie, Bodenbedeckung und Klimadaten bereitgestellt, wobei hydrologische Daten (Abfluss, Bodenfeuchte, Grundwasserstände) zurückgehalten wurden. Dadurch konnte die Modelleignung bei begrenzter Datenverfügbarkeit getestet werden. Die Ergebnisse der Modelle variierten stark, wobei sämtliche berechnete Wasserbilanzgrößen innerhalb der dreijährigen Beobachtungsdauer von den beobachteten Werten stark abwichen. Aufgrund der hochdurchlässigen Böden berechneten die Modelle vorwiegend unterirdischen Abfluss. Die Beobachtungen zeigen jedoch eine Dominanz des Oberflächenabflusses. Im zweiten Bearbeitungsschritt erfolgte eine Gebietsbegehung, bei der visuell sichtbare Prozesse wie Grabenerosion und Bodenverkrustung in die Berechnung Eingang fanden. Dadurch verbesserten sich die Modellergebnisse nennenswert und der Oberflächenabfluss wurde deutlich besser wiedergegeben. Im dritten Schritt wurden Modellverbesserungen durch Parameteroptimierung und verbesserte Schätzung der Anfangsbedingungen und Speicherkapazitäten erzielt. Dabei spielte bei der Erreichung verbesserter Berechnungsergebnisse die persönliche Erfahrung und Beurteilungskompetenz der Modellanwender eine wichtige Rolle.

Schlagwörter: Künstliches Einzugsgebiet, initiale Ökosystementwicklung, Modellvergleich, A-priori-Vorhersage, Prozessverständnis, Datenverfügbarkeit, unbeobachtete Einzugsgebiete.

Summary

Ten conceptually different models were applied to predict the discharge from the 6 ha artificial Chicken Creek catchment in Lausatia, North-East Germany, which has been created in an open cast mining area. The study consisted of three steps to make a model intercomparison with the objective of *a priori* prediction of the water balance and the discharge dynamics. In order to test the ability of each model and modeller to predict water flows in an ungauged catchment, only soil texture, topography, vegetation coverage and climate data were provided to the modellers in the first step. Hydrological data on discharge, soil moisture and groundwater levels were withheld. This enabled us to assess the predictive capabilities of the models under sparse data conditions. The predicted components of the water balance varied in a wide range. None of the model simulations came close to the observed water balance for the entire 3-year study period. Discharge was mainly predicted as subsurface flow with little surface runoff. In reality, surface runoff was a major flow component despite the fairly coarse soil texture. In the second step, additional process knowledge was gained during a joint field visit. The occurence of gully erosion and surface crusting was detected and implemented into the models. Consequently, model predictions changed considerably. The previous simulations dominated by subsurface flow changed to surface flow-dominated simulations. Additional data, provided in the third step, mainly confirmed the parameterisations and assisted in a better definition of initial conditions and subsurface storage. The comparison indicates that, in addition to model philosophy, the personal judgement of the modellers was a major source of the differences in the model results. The model parameterisation and choice of initial conditions depended on the modeller's judgement and were therefore a result of the modellers' experience in terms of model types and case studies.

Key words: Artificial catchment, initial ecosystem development, model intercomparison, a priori prediction, process understanding, additional quantitative data, ungauged catchments.

fore, this study combines the advantages of an artificial catchment, characterised by well defined lower and lateral catchment boundaries, with the task of the prediction of hydrological fluxes for catchments where model calibration is not feasible. Based on the model intercomparison approach, the ability of conceptually different models to predict catchment water flows can be tested for the conditions of an initial ecosystem development that is characterised by a gradual change in catchment properties in terms of vegetation, small scale topography and catchment saturation. Based on this first stage of model intercomparison, another important question is addressed: to what extent does the predictive model performance rise by acquiring additional qualitative and quantitative information on processes (2nd stage) and catchment characteristics (3rd stage)?

Chicken creek artificial catchment

The 6 ha Chicken Creek catchment is currently the largest artificial catchment worldwide. It was built in 2005 by Vattenfall Europe Mining in scientific cooperation with the Brandenburg University of Technology (Gerwin et al., 2009). It is located in an open pit mining area in Lusatia, Germany. The catchment base is a 2 m thick clay layer, forming a 450 m long and 150 m wide catchment. A sand layer of 2 to 3 m depth has been put on top of the clay basement (Figure 1). It consists mainly of sand with varying fractions of 2–25% silt and 2–16% of clay. The longitudinal slope is 1–5%. After five years of catchment development, the depression at the catchment outlet has become a small lake which collects the outflow from the catchment. The catchment boundary is defined by the high edges of the clay layer. The climate is temperate and humid. Annual precipitation in the past decades varied from 335 mm (1976) to 865 mm (1974), the mean annual temperature was 9.3 °C (1971–2000). The catchment remained unplanted after construction, and the establishment and further development of the natural vegetation is being closely monitored. Continuous hydro-meteorological measurements are taken on climate, soil moisture, groundwater and discharge since 2005 while only climate data were provided to the modellers in the first modelling stage.

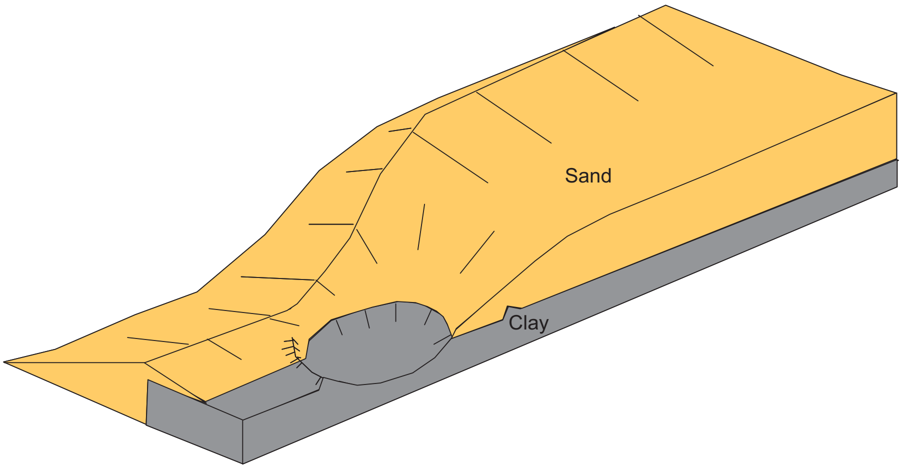

Figure 1: Cross section through the Chicken Creek catchment (Transregio-SFB 38, changed)
Abbildung 1: Querschnittsdarstellung des Testgebiets Hühnerwasser (verändert nach Transregio-SFB 38)

Simulation models and modelling steps

Four modelling stages are planned in this model intercomparison initiative from which results on the first three stages are presented in this paper:

1. The *a priori* model application based on a sparse data set, comparable to operationally available data sets (gridded information on elevation, clay basement, soil texture and soil depth, mean annual vegetation cover; hourly climate data; initial groundwater heads; aerial photo; shape file of the gully-network) without having visited the catchment;
2. A model application after having discussed the model results of the *a priori* model application during a workshop and having visited the catchment;
3. A model application based on additional data available (soil hydraulic data, soil physical data, soil moisture, infiltration rates, extended vegetation data, new digital elevation model, new aerial photo),
4. A model calibration based on event based stream flow data provided for a subcatchment (1.8 ha).

In order to compare the ability of hydrological models to predict water flows of an "ungauged" catchment, ten different models were applied to the Chicken Creek catchment in each modelling stage. The overall 12 models conceptually differ in spatial dimensionality, spatial representation of heterogeneities and process representation. Table 1 provides an overview on the models (for details see Holländer et al., 2009). While most modellers selected process

Table 1: Applied catchment models, their dimensionality and representation of the most important processes. (Penman-M. = Penman-Monteith)
Tabelle 1: Verwendete Modelle, ihre Dimensionalität und die wichtigsten, erfassten Prozesse (Penman-M. = Penman-Monteith)

Model-dimension	Infiltration	Surface runoff	Unsaturated flow	Saturated flow	Potential ET
Catflow-2D	Richards'	St. Venant	Richards'	Richards'	Penman-M.
CMF-3D	Richards'	Mass balance	Richards'	Darcy	Penman-M.
CoupModel-3D	Darcy	– (switched off)	Richards'	Hooghoudt	Penman-M.
GSDW-Lumped	Green-Ampt	Storage based	Bucket approach	Storage based	Penman
Hill-Vi-3D	Rain	– (switched off)	Gravity flow	Dupuit-Forchheimer	Turc
Hydrus-2D-2D	Richards'	– (switched off)	Richards'	Richards'	Penman-M.
Mike-SHE-3D	Richards'	St. Venant	Richards'	Darcy	Penman-M.
Net-Thales-3D	Rain	Mass balance	–	Kinematic flow	Penman-M.
SIMULAT-1D	Richards'	Time delay	Richards'	Darcy	Penman-M.
SWAT-3D	SCS	Muskingum	Soil function	Hooghoudt	Hargreaves
Topmodel-3D	Green-Ampt	Time delay	Exp. Function	Time delay	Penman-M.
WaSiM-ETH-3D	Green-Ampt	Kinematic wave	Richards'	Darcy	Penman-M.
WaSiM-ETH-2D	Green-Ampt	Storage based	Richards'	Linear storage	Penman-M.

based models, they rated differently the importance of representing spatial heterogeneity. Additional criteria of model selection, mentioned by the modellers, were model availability, being familiar with a model, and having confidence in the model. An important boundary condition of this initiative was the fact that no modeller had any time allocation for this modelling task in their budgets.

Results

A priori model application

The model comparison revealed that there is huge variability among the models with respect to simulated discharges. Expressed as percentage of the observed annual discharge, the discharge predicted by the models ranged from 10 to about 330%. Similarly, the frequency distribution of the simulated discharge varied significantly between the models (Figure 2). These differences could be mainly attributed to different model parameterisation and conceptualisation (for details see HOLLÄNDER et al., 2009). One important problem was the initial soil-water content, which was not defined by the data. Most modellers neglected the relative dryness of the dumped soil material; instead, some modellers performed warm-up runs to initialise their models, resulting in wet conditions. Therefore, simulated change in subsurface storage was too small and all models did not simulate well the change in catchment storage over time. In addition, most models simulated mainly subsurface flow while the catchment shows a gully network originating obviously from water erosion. Despite most models being based on the Penman-Monteith approach to calculate evapotranspiration, variability in simulated potential as well as actual evapotranspiration was remarkably high (Figure 3).

Process understanding due to field visit

After the *a priori* predictions all modellers met at a workshop to present and discuss their individual modelling results. This revealed that not all modellers exploited the initial data set in the same way. For example, most modellers did not use the information on the subsurface clay wall (Figure 1), banked up during construction in order to stabilize the artificial catchment, which might have an effect on subsurface water flow and storage. Similarly, most of the modellers did not use the shape file of the gully network as information on important runoff generation mechanisms (overland flow, in this case). Afterwards, the modellers visited the catchment together and used their additional process understanding for a revision of the model setup and the parameterisation. Most of the modellers introduced a soil crust in order to be able to generate infiltration excess

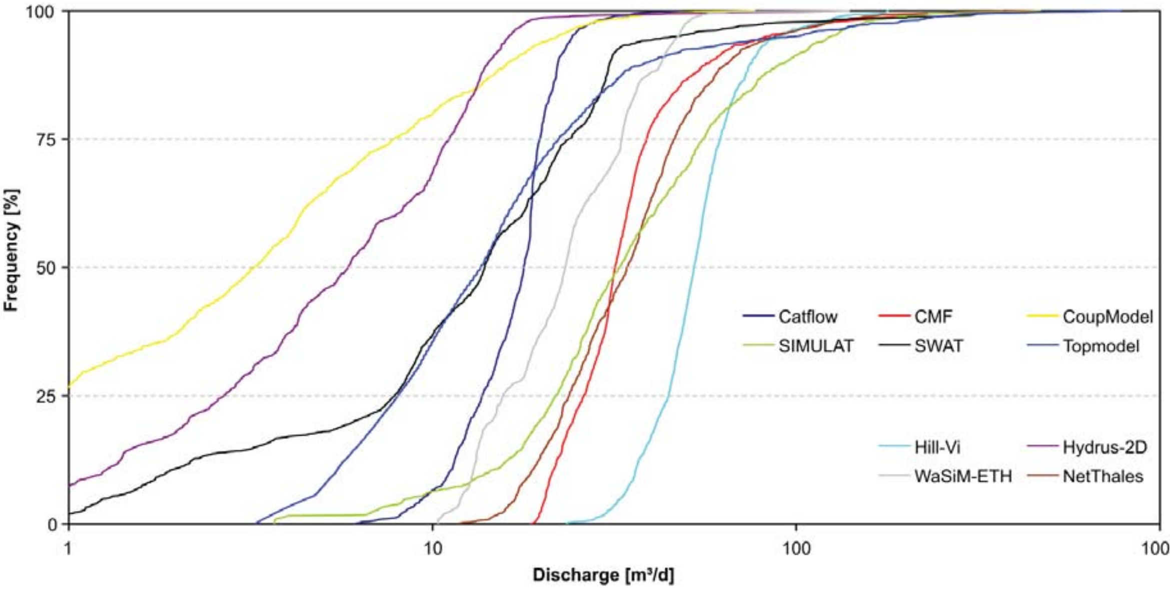

Figure 2: Differences in model specific frequency distribution of a priori simulated discharge (from Holländer et al., 2009)
Abbildung 2: Unterschiede zwischen den Häufigkeitsverteilungen der modellspezifischen Abflüsse bei A-Priori-Parameterschätzung (nach Holländer et al., 2009)

runoff by the models. According to FISCHER et al. (2010), biological soil crusts have developed already as part of initial pedogenesis. Some modellers considered the clay wall by generating subsurface structures in their models. Some modellers adapted the vegetation parameterisation because vegetation development in terms of leaf area index and plant height went faster then expected. Two modelling groups even decided not to use their model for further model predictions. One group revised their model philosophy and selected a different simulation model (usage of Mike-SHE instead of Hill-Vi model). Compared to the first modelling stage, the variability among the model predictions decreased considerably (Figure 3). Following the workshop and the field visit, modellers tended to change the model set-up in the same direction, resulting from a common understanding of process, aiming towards decreasing total runoff generation and increasing surface runoff generation. In general, predictions in discharge decreased while predicted actual evapotranspiration and subsurface storage, particularly for the first year, increased. In agreement with the acquired information about on-site processes, surface runoff generation increased for most of the models while simulation of base flow decreased significantly.

Model improvement due to additional data

After the second modelling step, additional data was provided to the modellers. They were asked to select the data they needed to further improve their model, while considering the costs of the data collection. Most modellers asked for soil hydraulic and soil physical data in addition to soil moisture and infiltration rates. Only a few modellers used the extended vegetation data set, the new digital elevation model and the new aerial photo. Predominantly, the modellers used the data for reassessing model parameterisation and adjustment of initial and boundary conditions. Few groups included available soil moisture data from four soil pits for a calibration of the simulated soil moisture dynamics.

Compared to the first two modelling stages, the use of additional data only resulted in smaller changes in simulated water flows. Changes in all simulated water balance components (discharge, evapotranspiration, storage) were small. While changes in simulated discharge and storage (slight decrease) were uniform over the years of simulation, changes in simulated evapotranspiration were not (increase in the first two, but decrease in the third year of simulation). While the variability among the models increased for discharge and evapotranspiration, it decreased for change in catchment storage (Figure 3).

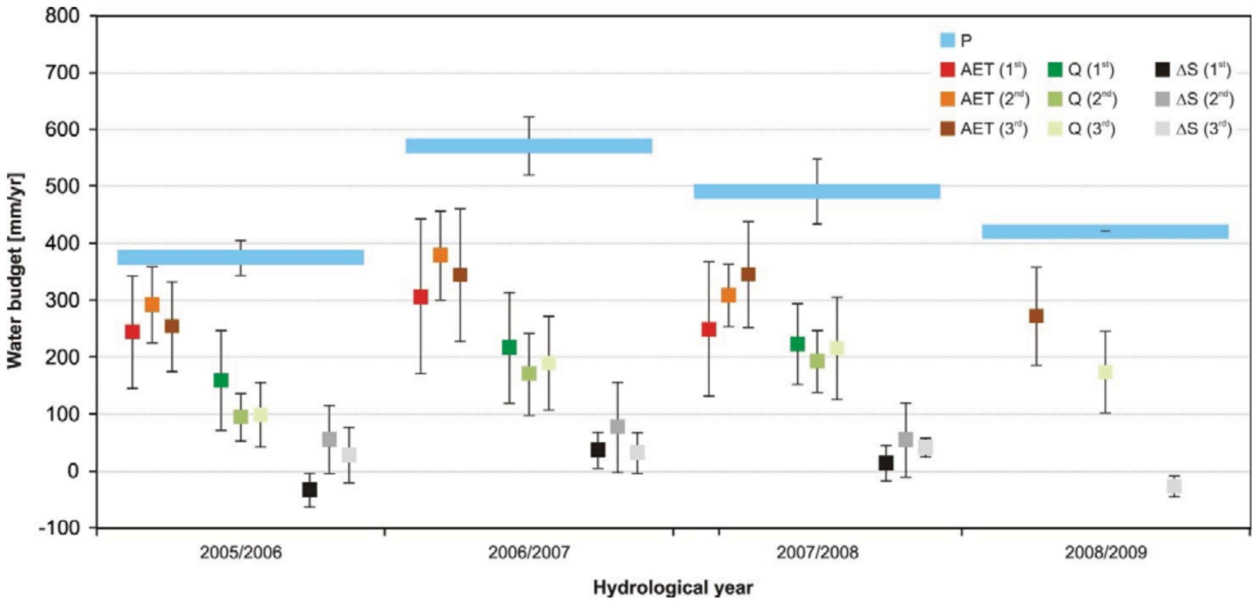

Figure 3: Change in annual water balance components (mean and standard deviation) during the three modelling stages. The variability in precipitation is caused by precipitation correction by a few models (P: precipitation; AET: actual evapotranspiration; Q: discharge; △s: change in storage)

Abbildung 3: Änderungen der jährlichen Wasserbilanzgrößen (Mittelwert und Standardabweichung) während der drei Simulationsstufen. Die Niederschlagsvariabilität ist durch Korrekturansätze verschiedener Modelle bedingt (P: Niederschlag; AET: reale Verdunstung; Q: Abfluss; △s: Speicheränderung)

Discussion

This study confirms the findings of previous studies (e.g., DIEKKRÜGER et al., 1995) about the importance of the modeller in the model application process, especially in terms of an *a priori* prediction. Modellers' decisions on which data to use (and how) resulted in large differences in the model predictions despite the strong similarities in the underlying process descriptions among most of the models (Table 1). With respect to the impact on the simulated water balance, improving an understanding of on-site processes by visiting the catchment and subsequent discussions with colleagues seemed to be more important than using additional data which might be expensive to collect. Similarly, according to SILBERSTEIN (2006), learning about catchment behaviour requires observation. During this study several modellers 'complained about the lack of information from field investigations. Catchment inspection in the field enables identification of dominant processes rather than gleaning a few numbers from additional measurements. In agreement with SEIBERT and MCDONNELL (2002), even semi-qualitative data can contribute to a significant improvement in the simulation results by enhancing the understanding of processes involved. We doubt that additional standard data on system characteristics would significantly alter predictions until discharge time series are provided. However, the fourth stage in this model intercomparison will finally reveal which impact the calibration data of a subcatchment and the entire catchment have on the model predictions. Nevertheless, after the third modelling stage modellers were especially interested in additional information on spatial variability in key properties (e.g., saturated hydraulic conductivity) which is not available so far. According to GERWIN et al. (2009) the catchment is less homogenous than expected. Most modellers assumed that providing such information would improve the simulation of the runoff generation processes. The availability of soil moisture data, in particular, assisted in improving the subsurface storage behaviour which is exceptionally important in case of a catchment in its initial development phase. When a catchment has reached an 'equilibrium' state in terms of subsurface water storage the benefit of such data might be smaller. Finally, the specific characteristic of artificial catchments might cause model parameterisation using transfer functions (e.g., pedotransfer functions) or based on literature values to fail due to the specific conditions in artificial catchments (e.g., soil compaction during catchment preparation). The validity of such transfer functions should be further investigated.

Conclusion

The results of this study indicate that the choice of method (model, parameterisation approach) has an important impact on the simulation results. But this study has also shown that the modeller has an important part in the whole modelling process. His/her prior experience in the field and with the chosen model seems to be at least as important as the model's code. The modeller decides how to use the available information for model conceptualisation and parameterisation. A second important result is the importance to consider all information available for a catchment to determine either important or dominant hydrological processes. This information can be obtained by inspection of catchment photos to identify evidence of erosion and canopy features that might be indicative of surface runoff and root water uptake. Better results can be obtained from field visits undertaken with colleagues and improves an understanding of on-site processes. Modeller decisions whether to consider this information or not, confirms the subjectivity of the modeller in the modelling process, particularly for ungauged catchments. Additional quantitative data can be very valuable for an adjustment of model conceptualisation and parameterisation. In this study such data mainly confirmed the assumptions made during the field visit and helped to improve the choice of initial and boundary conditions. However a fundamental change in predictions is not expected until the models are calibrated against observed discharges during the last modelling stage.

Acknowledgement

The funding for travelling expenses and organisation of three workshops within this study was provided by the Deutsche Forschungsgemeinschaft (DFG), financed through project TRR-SFB 38 "Structures and processes of the initial ecosystem development phase in an artificial water catchment".

References

DIEKKRÜGER, B., SÖNDGERATH, D., KERSEBAUM, K.C., MCVOY, C.W. (1995): Validity of agroecosystem models – a comparison of results of different models applied to the same data set. Ecol. Model. 81 (1–3), 3–29.

FISCHER, T., VESTE, M., SCHAAF, W., DÜMIG, A., KÖGEL-KNABNER, I., WIEHE, W., BENS, O., HÜTTL, R.F. (2010): Initial pedogenesis in a topsoil crust 3 years after construction of an artificial catchment in Brandenburg, NE Germany. Biogeochemistry; 101, 165–176.

HOLLÄNDER, H.M., BLUME, T., BORMANN, H., BUYTAERT, W., CHIRICO, G.B., EXBRAYAT, J.-F., GUSTAFSSON, D., HÖLZEL, H., KRAFT, P., STAMM, C., STOLL, S., BLÖSCHL, G., FLÜHLER, H. (2009): Comparative predictions of discharge from an artificial catchment (Chicken Creek) using sparse data. Hydrol. Earth Syst. Sci., 13, 2069–2094.

HUISMAN, J.A., BREUER, L., BORMANN, H., BRONSTERT, A., CROKE, B.F.W., FREDE, H-G., GRÄFF, T., HUBRECHTS, L., JAKEMAN, A.J., KITE, G., LEAVESLEY, G., LANINI, J., LETTENMAIER, D.P., LINDSTRÖM, G., SEIBERT, J., SIVAPALAN, M.G., VINEY, N.R., WILLEMS, P. (2009): Assessing the impact of land use change on hydrology by ensemble modelling (LUCHEM) III: scenario analysis. Adv. Water Resour., 32, 159–170.

GERWIN, W., SCHAAF, W., BIEMELT, D., FISCHER, A., WINTER, S., HÜTTL, R.F. (2009): The artificial catchment “Chicken Creek” (Lusatia, Germany) – A landscape laboratory for interdisciplinary studies of initial ecosystem development. Ecol. Eng., 35, 1786–1796.

SEIBERT, J., MCDONNELL, J.J. (2002): On the dialog between experimentalist and modeler in catchment hydrology: Use of soft data for multi-criteria model calibration. Water Res. Res., 38(11), 1241.

SILBERSTEIN, R.P. (2006): Hydrological models are so good, do we still need data? Environ. Modell. Softw., 21, 1340–1352.

SIVAPALAN, M., TAKEUCHI, K., FRANKS, S.W., GUPTA, V.K., KARAMBIRI, H., LAKSHMI, V., LING, X., MCDONNELL, J.J., MENDIONDO, E.M., O’CONNELL, P.E., OKI, T., POMEROY, J.W., SCHERTZER, D., UHLENBROOK, S., ZEHE, E. (2003): IAHS Decade on Predictions in Ungauged Basins (PUB), 2003–2012: Shaping an exciting future for the hydrological sciences. Hydrolog. Sci. J., 48(6), 857–880.

Address of authors

H. Bormann, University of Siegen, Department of Civil Engineering, Germany
H. M. Holländer, State Authority of Mining, Energy and Geology (LBEG), Geozentrum Hannover, Germany
T. Blume, Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Potsdam, Germany
W. Buytaert, Imperical College London, Department of Civil and Environmental Engineering, London, UK
G.B. Chirico, Universita di Napoli Federico II, Dipartimento di ingegneria agraria e agronomia del territorio, Naples, Italy
J.-F. Exbrayat, University of Giessen, Institute for Landscape Ecology and Resources Management, Germany
D. Gustafsson, Royal Institute of Technology KTH, Department of Land and Water Resources Engineering, Stockholm, Sweden
H. Hölzel, BTU Cottbus, Chair of Hydrology and Water Resources Management, Cottbus, Germany
P. Kraft, University of Giessen, Institute for Landscape Ecology and Resources Management, Germany
T. Krauße, University of Technology Dresden, Institute of Hydrology and Meteorology, Dresden, Germany
A. Nazemi, University of Saskatchewan, Department of Civil and Geological Engineering, Saskatchewan SK, Canada
C. Stamm, Eawag, Department Environmental Chemistry, Dübendorf, Switzerland
S. Stoll, ETH Zurich, Institute of Environmental Engineering, Zurich, Switzerland
G. Blöschl, TU Vienna, Institute of Hydraulic Engineering and Water Resources Management, Vienna, Austria
H. Flühler, ETH Zurich, Department of Environmental Sciences, Zurich, Switzerland

Corresponding Author
Helge Bormann
email: helge.bormann@uni-siegen.de