Development and test of a modular hydrological model concept with different degrees of complexity

H. Holzmann and C. Massmann

Entwicklung und Test eines modularen hydrologischen Konzeptmodells mit unterschiedlicher Komplexität

1 Introduction

Rainfall-runoff models consider many processes which need to be parameterized according to the basin characteristics found at that specific place. Due to the limited amount of information regarding data availability, a unique parameter calibration of the models is difficult and can lead to different parameter combinations yielding similar results. A significant disadvantage of having more than one ideal parameter set producing satisfactory results is that this makes the impact assessment of changes of external forcings (e.g. climate changes, land use changes) difficult.

One way to deal with this is to reduce the complexity of the models so that there are fewer parameters to calibrate. In this context it was decided to avoid using and developing more and more complex models, bu to try simplifying them by focusing only on the most relevant processes. GRAYSON & BLÖSCHL (2000) coined the term Dominant Processes Concept (DPC), comprising the identification of the dominant processes and, as a second step, the development and use of models that focus on these processes. SIVAKUMAR (2004) summarizes that the main ideas behind the formulation of the DPC were: 1) the recognition that "trying to model everything" is a difficult, if not impossible, task 2) the many observations suggesting that only a few processes dominate the response in a specific catchment and 3) the insight (gained through modeling) that simple models with a few dominating parameters, can lead to good results and can capture the characteristics that determine the hydrological response of a specific catchment.

It is important to notice that the dominating processes might be different at varying locations in a catchment and also vary depending on the season, characteristics of rain and other factors. MASSMANN & HOLZMANN (2012a, 2012b) showed a method how to identify dominant processes and their temporal sequences. Also the objective of

Zusammenfassung

In den letzten zwei Dekaden wurde weltweit eine Vielzahl hydrologischer Modelle entwickelt. Die meisten davon verwenden zur Beschreibung der hydrologischen Prozesse eine starre Modellstruktur mit der Annahme der Repräsentativität für alle raumzeitlichen Skalenbereiche. Die Interpretierbarkeit der Modellergebnisse hinsichtlich der realistischen Wiedergabe einzelner Prozesseigenschaften ist jedoch aufgrund der eingeschränkten Verfügbarkeit beobachteter Systemdaten schwierig, da die Modelle zumeist nur anhand von integrierenden Abflusswerten validiert werden. Daher wird angenommen, dass einfachere Modellstrukturen unter Berücksichtigung dominanter Prozesse durchaus gleichwertige Ergebnisse liefern können und zudem die Anzahl der Modellparameter reduzieren. Im Rahmen eines Forschungsprojekts wurde ein modulares Konzeptmodell entwickelt, welches selektiv die Hinzunahme oder die Vernachlässigung einzelner Subprozesse unter Berücksichtigung der Datenverfügbarkeit und der Gebietseigenschaften ermöglicht. Im Beitrag werden die Simulationsergebnisse eines konventionellen Modells mit zwei Realisationen des modularen Modells (einfach und komplex) verglichen. Dabei konnte eine Gleichwertigkeit der Ergebnisse gezeigt werden. Der Vorzug des modularen Modells ist die Möglichkeit zur individuellen Anpassung der Modellstruktur unter Berücksichtigung der Datenverfügbarkeit und der Vereinfachung der Parametererfordernisse.

Schlagworte: Modulares Modell, hydrologische Modellierung, flexibles Modelldesign, dominante hydrologische Modelle.

Summary

Many hydrological models have been developed in the past two decades. Most of them used a fixed design to describe the variable hydrological processes assuming to be representative for the whole range of spatial and temporal scales. This assumption is questionable as reported by McDonell et al. (2007). But it was also evident that model application and the interpretation of results are limited by data availability to identify the particular sub-processes, since most models were calibrated and validated only with discharge data. Therefore it can be hypothesized that simpler model designs, focusing only on the dominant processes, can achieve comparable results with the benefit of fewer parameters. In the context of a research project a modular model concept was developed that allows the integration and neglection of hydrological sub-processes depending on the catchment characteristics and data availability. In this paper a comparison between a conventional HBV-type hydrological model and a modular concept with (1) simple and (2) complex process representation will be discussed. It could be shown that a flexible model design – and even the simple concept – can reach equivalent performance compared to the conventional model type. The main benefit is the individual adaptation of the model structure with respect to data and process availability and the option for parsimonious model design.

Key words: Modular model, hydrological modeling, flexible model design, dominant processes.

the model application determines what kind of processes might be relevant since it is expected, for instance, that the processes involved in the production of discharge during low water periods will differ from the dominating processes during floods.

2 Objectives and Methods

Since 2010, the Austrian Academy of Sciences has been financing the project "development and testing of a modular conceptual hydrological model to identify dominating hydrological processes". The applied project aims at the development of a model concept that considers a flexible model design based on variable dominating processes. The process variation can be due to changing processes in time (environmental feedback), to spatial basin characteristics (e.g. hydrogeology) or to varying perspectives and different variables of interest. Similar concepts have been introduced by Van den Bos et al. (2006), Fenicia et al. (2011) and Kavetski & Fenicia (2011). The objective of the ongoing project is to test the dynamic model concept with observation data of experimental basins in different scales. Tests have been carried out with data from lysimeter, irrigation plots, small and medium sized basins. Comparable investigations in different basin scales have been reported in Brocca et al. (2011). This current paper describes preliminary results for the mean sized basin Jalovecky creek in Slovak Republic.

The modular hydrological model BOKU-Modmod considers different flow and storage processes listed in table 1.

Table 1: Processes of the modular model BOKU-Modmod and corresponding IDs
Tabelle 1: Verfügbare Prozesse mit Kennziffer im modularen Modell BOKU-modmod

ID Sub-Process	
1 ... snow/glacier	6 ... plant available water storage
2 ... interception	7 ... mobile soil water storage
3 ... single linear storage	8 ... groundwater storage
4 ... API storage	9 ... linear storage cascade
5 ... split function	10 … delay function

These sub-processes correspond to particular fluxes and state variables which can be monitored in nature for providing observation data of experimental basins to the modeler. In terms of water fluxes these modules take into account water storage and release (snow/glacier accumulation and melt, interception, soil water and groundwater storage), water division into surface and sub-surface flow (split function) and delay processes with respect to routing and flow propagation (storage cascade, delay function). An antecedent precipitation module (API storage) keeps track of the moisture state conditions and affects the proportions into which the runoff is separated by the split function. In the first test phase only a lumped version of the model has been applied so far. This can be justified by the small size of the test domains.

The BOKU-Modmod model was written in Fortran source code. New and updated process modules can easily be integrated in the model concept. If the modeler applies the full range of processes and options, the number of required parameters will reach approximately 25. This means there would not be a big difference to existing models like the conceptual model BOKU-HBV, an HBV-type model developed by HOLZMANN & NACHTNEBEL (2002). But the objective is to focus primarily on the dominant processes and select a reduced sample of modules.

The model can be interlinked with external parameter optimization procedures for instance the PEST software (see Watermark Numerical Computing, 2010), which allows the automatic calibration of any model with input and output files in an ASCII format. Furthermore the Gauss-Marquardt-Levenberg nonlinear estimation technique – which was used in our study –, the global methods CMA-ES and SCE (“shuffled complex evolution”) are also implemented in PEST.

In the following section the comparison between the BOKU-HBV-type model (version 1) and the flexible BOKU-Modmod with a simple (version 2) and a complex (version 3) representation is described. The test basin Jalovecky Creek is located in the High Tatra mountains. The basin area is approx. 22.2 km^2, the elevation ranges from 800 to 2200 m a. s. l. Discharge is observed at the outlet of the basin. The meteorological input (precipitation and air temperature) is observed in different locations in daily and hourly time steps and is interpolated to the gravity point (precipitation) and elevation bands (temperature) respectively. A more detailed description of the basin is given in HOLKO & KOSTKA (2010) and DÓSA et al. (2011).

Figure 1 (a) shows a simple representation of the hydrological behavior of Jalovecky creek basin. Rainfall and snowmelt form the input for the hydrological system. A split function separates water flow into fast and slow components. The division is related to the moisture state condition computed by the API (antecedent precipitation index) module driven by the rainfall input. The API module was integrated to enable an external estimation of moisture state conditions independently from the selected configuration of the model. Figure 1 (b) exhibits the logical structure by means of a hierarchical flow scheme, which is built by the interactive input generation module, where the user has to define the relevant processes.

In addition to the simple model (version 2), version 3 integrates interception – considering both canopy and litter layer –, plant available water storage and mobile soil water storage, generating interflow and saturation excess flow. The scheme of version 3 is shown in figure 2.

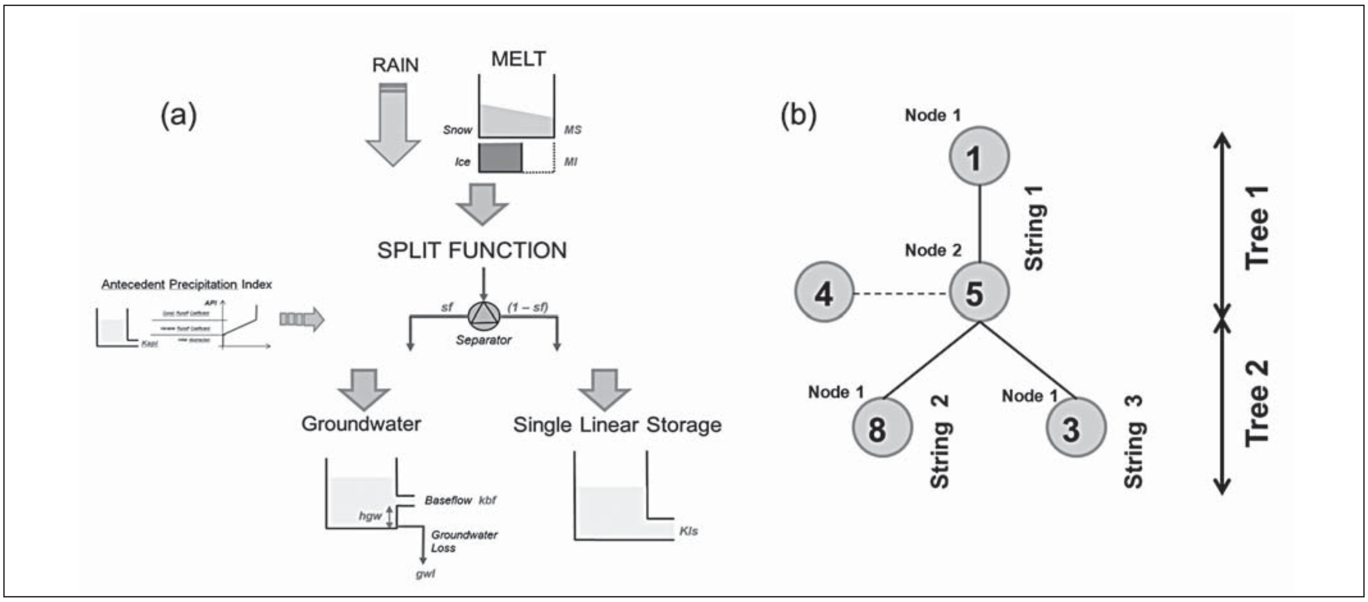

Figure 1: (a) Simple process representation with the BOKU-Modmod model considering antecedent precipitation index, melt and split into slow (groundwater) and quick (linear storage) runoff. (b) Logical design considering tree and string hierarchy

Abbildung 1: (a) Einfache Prozessbeschreibung anhand des BOKU-Modmod-Modells unter Berücksichtigung des Vorregenindex, der Schneeschmelze und einer Trennfunktion zwischen langsamem (Grundwasser) und raschem Abfluss (Linearspeicher). (b) Logischer Modellaufbau mit Baum- und Stranghierarchie

3 Results and Discussion

The described model simulations are carried out in lumped mode, but snowmelt and accumulation are modeled for 100 m elevation bands. The snowmelt module is uniformly applied for all three model versions using a time variable day degree method. The numbers of the parameters used in the model versions are given in Table 2.

Table 2: Number of parameters of the applied models
Tabelle 2: Anzahl der Parameter der angewandten Modelle

Model type	**Number of parameters**
BOKU-HBV	18
BOKU-Modmod (simple)	7
BOKU-Modmod (complex)	16

Data time series are available for the period of 2002 to 2007. Skipping the initial warm-up period, which was considered to last 6 months, the calibration was carried out including the years 2002 to 2005, whereas the remaining years 2006 and 2007 were used for validation. The performance criteria were mean squared error (MSE), determination factor R2 and the Nash-Sutcliffe criteria (NSC). The results can be seen in the following table:

Generally performance of all three models is satisfactory, indicated by determination factors from 0.79 to 0.88 and Nash-Sutcliffe values ranging from 0.63 to 0.78. The calibration phase performs better but also the validation phase is acceptable. The ranking exhibits best values for BOKU-HBV, second for the complex BOKU-Modomod and third for the simple BOKU-Modmod model. The temporal ac-

Table 3: Model performance of BOKU-HBV and BOKU-Modmod simple and complex
Tabelle 3: Modellgüte der angewandten Modelle (BOKU-HBV, BOKU-modmod einfach, BOKU-modmod komplex)

Model type	**calibration**			**validation**		
	MSE	**R2**	**NSC**	**MSE**	**R2**	**NSC**
BOKU-HBV	0.06	0.88	0.78	0.08	0.85	0.68
BOKU-Modmod simple	0.17	0.85	0.72	0.10	0.79	0.63
BOKU-Modmod complex	0.17	0.86	0.74	0.09	0.82	0.65

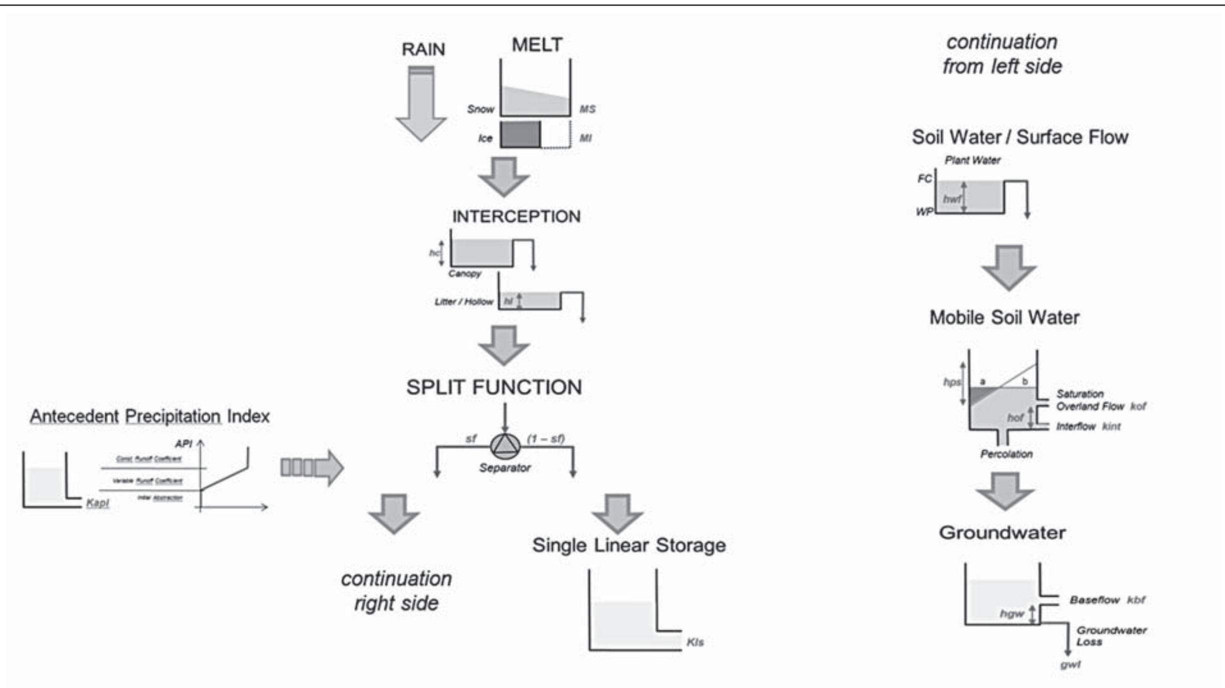

Figure 2: Complex process representation of Jalovecky creek basin with the BOKU-Modmod-BOKU model considering antecedent precipitation index, melt, interception, split into slow (plant available soil water, mobile soil water, groundwater) and quick (linear storage) runoff

Abbildung 2: Komplexe Prozessbeschreibung des Jalovecky-Einzugsgebiets unter Berücksichtigung des Vorregenindex, der Schneeschmelze, der Interzeption, einer Trennfunktion zwischen langsamem (pflanzenverfügbares Wasser, mobiles Bodenwasser, Grundwasser) und raschem Abfluss (Linearspeicher)

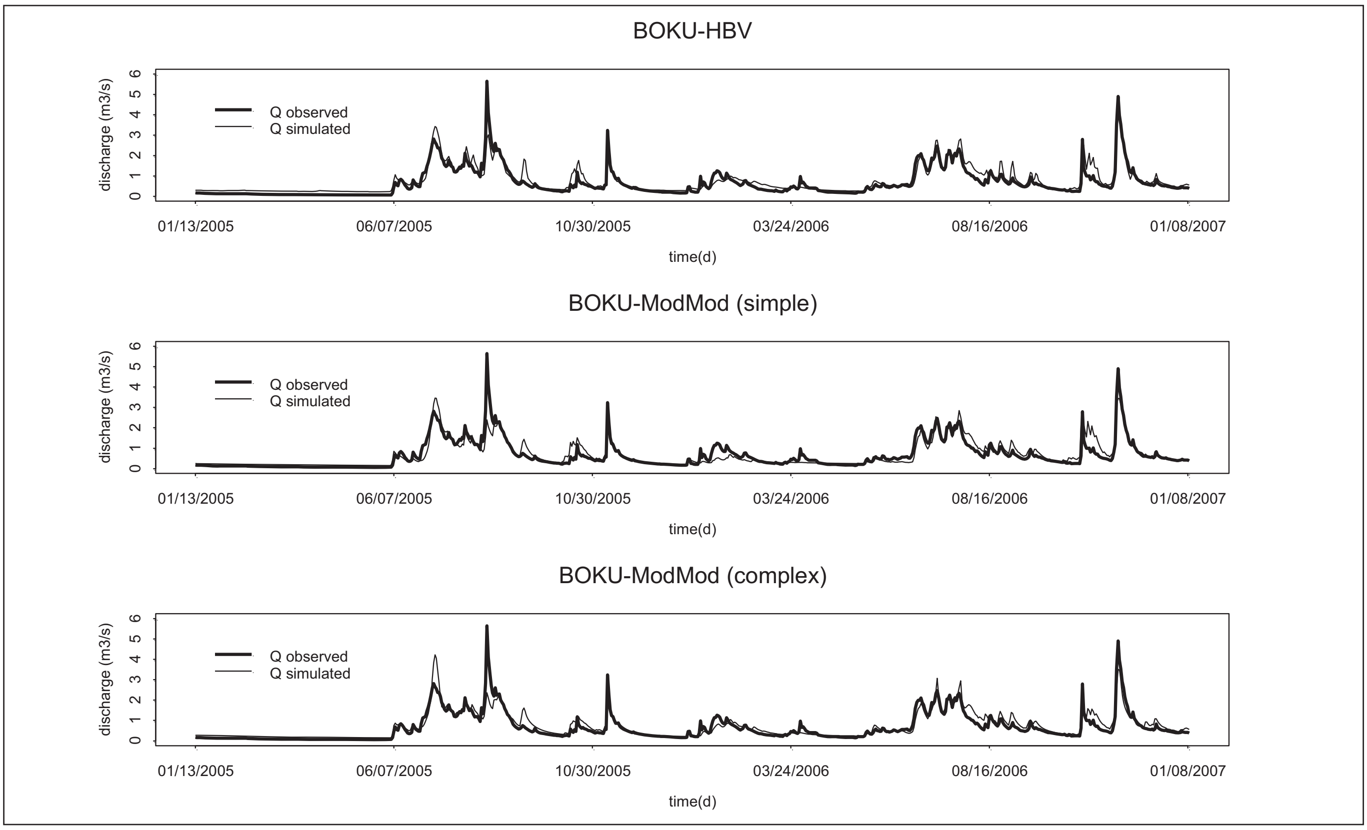

Figure 3: Hydrographs for the observed and simulated discharge using three models: the BOKU-HBV model, the BOKU-Modmod model with a simple structure and the BOKU-Modmod model with a complex structure

Abbildung 3: Ganglinien des beobachteten und simulierten Abflusses der drei Modellversionen (BOKU-HBV, BOKU-modmod einfach, BOKU-modmod komplex)

cordance for the validation phase can be seen in Figure 3. Some little difference in the temporal behaviour of the model simulations is the better performance of BOKU-HBV for peak flow events.

The presented results are based on a pure automatic calibration procedure which minimizes the square error using the PEST software. In next steps some further analysis and plausibility tests of the balance components and state conditions by means of expert knowledge can potentially result in some further improvement of the model performances.

4 Conclusions and perspective

The presented results show that modular model concepts can have a performance equivalent to the conventional HBV-type model. There are some initiatives to establish this kind of flexible models in the hydrological community. The real advantage and expected benefit of such concepts are (1) the potential to validate model results with respect to sub-process state conditions like soil moisture content, piezometric head, surface and sub-surface hillflow components, (2) to integrate expert knowledge of experimental hydrologists for a-priori parameter estimation, (3) to validate sub-modules by means of integrative observation data like remote sensing or geophysical observations providing state conditions of representative domains (not only point data), and (4) to keep parameter variability small and to evolve towards parsimonious model structures.

For further investigations, the following questions will be of primary importance: How to define a proper and satisfying model structure which fulfills the requirement to be "as simple as possible and as complex as necessary". In this context the combination of mathematical methods to identify dominant processes and the expertise of experimental hydrologists will be important. A second point is how to enable a flexible model design also for the temporal evolution. As dominant processes vary in time, the model structure should consider this aspect. Observation data of experimental basins will therefore form an important base for identification and interpretation of state conditions and processes in the hydrological cycle.

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Address of authors

Assoc. Univ.-Prof. Dr. Hubert Holzmann, Dept. for Water, Atmosphere and Environment, University of Natural Resources and Life Sciences, Vienna. Muthgasse 18, 1190 Vienna, Austria; hubert.holzmann@boku.ac.at