DIE ERDE
Journal of the Geographical Society of Berlin

Vol. 149, No. 2-3 · Research article

Implications of hydraulic anisotropy in periglacial cover beds for flood simulation in low mountain ranges (Ore Mountains, Germany)

Christian Reinhardt-Imjela[1], Katja Maerker[2], Achim Schulte[1], Arno Kleber[2]

[1] Department of Earth Sciences, Freie Universität Berlin, Malteserstraße 74-100, 12249 Berlin, Germany, christian.reinhardt-imjela@fu-berlin.de, achim.schulte@fu-berlin.de

[2] Department of Geosciences, Dresden University of Technology, Helmholtzstraße 10, 01069 Dresden, Germany, katja.heller@tu-dresden.de, arno.kleber@tu-dresden.de

Manuscript submitted: 20 July 2017 / Accepted for publication: 18 December 2017 / Published online: 27 September 2018

Abstract

The simulation of floods with conceptual rainfall-runoff models is a frequently used method for various applications in flood risk management. In mountain areas, the identification of the optimum model parameters during the calibration is often difficult because of the complexity and variability of catchment properties and hydrological processes. Central European mountain ranges are typically covered by Pleistocene periglacial slope deposits. The hydraulic conductivity of the cover beds shows a high degree of anisotropy, so it is important to understand the role of this effect in flood models of mesoscale mountain watersheds. Based on previous field work, the study analyses the sensitivity of the NASIM modeling system to a variation of vertical and lateral hydraulic conductivity for the Upper Flöha watershed (Ore Mountains, Germany). Depending on the objective function (Nash-Sutcliffe coefficient, peak discharge), two diametric parameter sets were identified both resulting in a high goodness-of-fit for total discharge of the flood events, but only one reflects the hydrological process knowledge. In a second step, the knowledge of the spatial distribution of the cover beds is used to investigate the potential for a simplification of the model parameterisation. The soil types commonly used for the spatial discretisation of rainfall-runoff models were aggregated to one main class (periglacial cover beds only). With such a simplified model, the total flood discharge and the runoff components were simulated with the same goodness of fit as with the original model. In general, the results point out that the anisotropy in the unsaturated zone, which is intensified by periglacial cover beds, is an important element of flood models. First, a parameter set corresponding to the hydraulic anisotropy in the cover beds is essential for the optimum reproduction of the flood dynamics. Second, a discretisation of soil types is not necessarily required for flood modeling in Central European mountain areas.

Zusammenfassung

Im Hochwasserrisikomanagement werden häufig konzeptionelle Niederschlag-Abflussmodelle eingesetzt, um den Ablauf von Hochwasserereignissen in kleinen Einzugsgebieten zu simulieren. Im Bergland ist die Bestimmung der optimalen Parameter für die Modellkalibrierung oft problematisch, da die Einzugsgebiete durch eine hohe räumliche Variabilität der Gebietseigenschaften gekennzeichnet sind. Ausgangssubstrat für die Bodenbil-

Christian Reinhardt-Imjela, Katja Maerker, Achim Schulte, Arno Kleber 2018: Implications of hydraulic anisotropy in periglacial cover beds for flood simulation in low mountain ranges (Ore Mountains, Germany). – DIE ERDE **149** (2-3): 86-101

DOI:10.12854/erde-2018-374

dung in den zentraleuropäischen Mittelgebirgen sind typischerweise periglaziale Deckschichten, die wiederum durch einen hohen Grad von hydraulischer Anisotropie gekennzeichnet sind und damit die hydrologischen Prozesse im Einzugsgebiet maßgeblich beeinflussen. Um die Rolle der Anisotropie in den Deckschichten bei der Modellierung von Hochwasserereignissen besser zu verstehen, beschäftigt sich die vorliegende Studie am Beispiel des Einzugsgebiets der Oberen Flöha (Erzgebirge/Sachsen) mit der Sensitivität der Reaktion des konzeptionellen Modellsystems NASIM auf eine Variation der Modellparameter für vertikale und laterale hydraulische Leitfähigkeit der Bodenzone. In Abhängigkeit der Zielfunktion (Nash-Sutcliffe Koeffizient, Scheitelabfluss) konnten dabei zwei gegensätzliche Parametersätze identifiziert werden. Beide Sätze lassen zwar eine Simulation mit hoher Modellgüte zu, jedoch nur einer davon spiegelt die Kenntnisse zu den hydrologischen Prozessen in den Deckschichten tatsächlich wider. In einem zweiten Schritt wird das Wissen zur räumlichen Verteilung der periglazialen Deckschichten genutzt, um Möglichkeiten einer Vereinfachung der Modellparametrisierung aufzuzeigen. Die mit dem vereinfachten Modell generierten Simulationsergebnisse zeigen dabei eine im Vergleich mit dem ursprünglichen Ansatz vergleichbare Modellgüte. Insgesamt veranschaulichen die Ergebnisse, dass die hydraulische Anisotropie der periglazialen Deckschichten eine wichtige Rolle bei der Modellierung von Hochwasserereignissen spielt. Um die Dynamik der Abflussbildung bei Hochwasserereignissen abbilden zu können, ist einerseits ein Parametersatz essentiell, der diese Anisotropie angemessen widerspiegelt. Anderseits ist die herkömmliche Diskretisierung der ungesättigten Bodenzone nach Bodentypen für die Modellierung von Hochwasserereignissen in den zentraleuropäischen Mittelgebirgen nicht zwingend erforderlich.

Keywords periglacial cover beds, rainfall-runoff modeling, floods, hydraulic conductivity, anisotropy, parameter sensitivity

1 Introduction

Floods caused by storm events or the interaction of snowmelt with rainfall are a major problem in low mountain areas because of the rapid response of the rivers and the short early-warning times. Many local events (*Büttner* and *Walther* 2007) as well the 2002 and 2013 floods show that such events frequently occur and their flood discharge may even increase in the future as a possible result of global climate changes (cf. *Schädler* et al. 2012). For the management of flood risks, rainfall-runoff models are widely used in science as well as at government offices or engineering consultancy companies, e.g. as a tool for the extrapolation of extreme discharge values, the simulation of design flood events and flood protection measures, or for flood forecasts. However, the complexity of mountain catchments with surface and subsurface flow processes controlled by strongly varying relief, soil properties, vegetation (e.g. different forest types and agriculture), and preferential flow paths presents many challenges for modelers.

Among these challenges are Pleistocene periglacial cover beds (PGCBs) and their influence on subsurface flow processes. PGCBs (also referred to as periglacial slope deposits) are a prevalent element of the geology of low mountain areas in Central Europe and represent the main parent material for soil development. Their existence, distribution, and sedimentary properties are well documented for the mountain areas of Germany and other regions in Central Europe such as Tharandter Wald (*Dietze* and *Kleber* 2010), Pfälzer Wald (Palatinate Forest: *Stolz* and *Grunert* 2010), Rheinisches Schiefergebirge (Rhenish Massif: *Stückrad* et al. 2010; *Sauer* and *Felix-Henningsen 2006*; *Felix-Henningsen* et al. 1991), Sauerland (*Chifflard* et al. 2008), Fichtelgebirge (*Völkel* and *Leopold* 2001), Frankenwald (*Kleber* et al. 1998), Harz (*Becker* and *McDonnell* 1998; *Schröder* and *Fiedler* 1977), Bayerischer Wald (Bavarian Forest: *Völkel* 1995) as well as Pieniny Mountains (Poland: *Kacprzak* and *Derkowski* 2007) and Cracow Uplands (Poland: *Pawelec* 2006).

A general overview of the concept of PGCBs in Germany is given by *Kleber* (1992, 1997), *Semmel* and *Terhorst* (2010), and *Kleber* et al. (2013a) who provide a review of the recent literature. The development of the deposits in Central Europe is related to Late Pleistocene periglacial conditions, which occurred in unglaciated mountain areas at that time and was thus characterised by permafrost. Under these conditions the weathered bedrock was reworked by solifluction processes in the active layer (*Kleber* 1997; *Semmel* and *Terhorst* 2010), leading to characteristic fossil sediment structures, which are similar in all mountain areas of Central Europe. Three main units can be identified in these regions: the Basal Layer, the Intermediate Layer, and the Upper Layer. This three-membered classification is generally accepted by most of the authors mentioned above and was introduced into the official classification of the German Soil Mapping Manual (*AG Boden* 1994, 2005). The structural characteristics of the units are listed in *Table 1.*

Table 1 Classification and sedimentary properties of periglacial cover beds in Central European mountain regions. Source: Adopted from AG Boden (1994, 2005), Kleber (1992, 1997), Völkel et al. (2001), Dietze and Kleber (2010), Semmel and Terhorst (2010), Kleber et al. (2013a, b)

Unit	Characteristics
Upper Layer	- constant thickness between 30 and 70 cm - distribution independent of topography or relief position - eolian components (loess) and intercalated, often well-oriented clasts - low bulk density
Intermediate Layer	- varying thickness - presence is related to loess deposits (lower parts of wind-sheltered slopes on lee sides of mountains and surface roughness on luff side of slopes) - often dominated by eolian components (loess) - few clasts with varying orientation
Basal Layer	- large variation of thickness (from a few deci-meters to several meters) - no eolian material - rich in angular rock fragments (weathered bedrock material and periglacial debris) - orientation of clasts parallel to slope - high bulk density

During the Holocene, soils developed from the cover beds under more temperate climatic conditions. Soil horizons are often adapted to the boundaries between the layers of the cover beds as a result of changing sedimentological properties such as texture, bulk density, and composition (*Kleber* 1992). Moreover, since PGCBs represent the parent material for soil development, subsurface flow processes are controlled by their structure and sedimentology. An overview of the hydrology of PGCBs is provided by *Chifflard* et al. (2008) and *Heller* (2012). During rainfall events, water infiltrates into the more permeable Upper Layer and, if present, into the Intermediate Layer. If infiltration reaches the less permeable Basal Layer, temporal saturation occurs in the units above and the vertical water movement turns into interflow in the soil matrix, in macropores, and along the layer boundaries respectively (*Becker* and *McDonnell* 1998; *Chifflard* et al. 2008). The portion of the water that infiltrates into the Basal Layer may cause further saturation resulting in additional lateral flow processes, which are promoted by the horizontal orientation of the rock fragments. This effect is even more distinctive in mountain areas where the Basal Layer is rich in platy clasts (e.g. weathered schists, *Kleber* et al. 1998). Interflow that reaches the river channels includes event water as well as pre-event water, which is pressed out as a result of the infiltration upslope (*Becker* and *McDonnell* 1998; *Schwarze* et al. 2011).

Most of the investigations on the hydrological processes in cover beds of Central Europe focus on smaller rainfall events and little is known about their influence on runoff generation during flood events of higher magnitude. On the basis of infiltration experiments in two small catchments in the Rhenish Massif, *Hümann* et al. (2011) identified the physical soil properties as one of the crucial factors for fast runoff generation and report a remarkable amount of interflow above the compacted Basal Layer during an experimental heavy storm event. The runoff coefficients for the experimental subsurface flow depend on the varying hydraulic conductivity at different sites. In general, PGCBs may be assumed to intensify flow in the unsaturated zone.

All this information raises the question regarding the role of PGCBs in the context of flood modeling in low mountain areas. Can the hydrological characteristics of the cover beds be incorporated in a conceptual distributed rainfall-runoff model by the user and can the knowledge about cover beds be used to simplify the parameterisation of such models? Based on such knowledge, two different modeling approaches will be tested: 1) the adjustment of soil calibration parameters according to the understanding of hydrological processes in cover beds, and 2) a simplified parameterisation by disregarding the different soil types in the model and implementing periglacial cover beds instead. Thus, the aim of this study is to show how basic geomorphological and hydrological investigations may be combined with applied research in order to improve the parameterisation of rainfall-runoff models in low mountain areas.

2. Study area

2.1 Overall setting

For the investigations, the Ore Mountains (Erzgebirge) were selected, a typical low mountain area at the border between the German Free State of Saxony and the Czech Republic. The mountain range is composed of magmatic and metamorphic rocks and characterised by a steep scarp to the Eger Graben in the southeast and a low inclination in northwestern direction. The highest points are Klínovec (1244 m a.s.l., Czech Republic) and Fichtelberg (1214 m a.s.l., Germany). The climate may be classified as moist continental, whereas mean temperature decreases and precipitation increases towards higher elevations. At Fichtelberg, the mean annual temperature reaches 3.5 °C and the annual precipitation is 1130 mm (1981-2010). For the same period in the town of Marienberg (Central Ore Mountains), a mean annual temperature of 6.8 °C and a precipitation of 865 mm were observed at an elevation of 639 m a.s.l. (data provided by German Weather Service, *Climate Data Center* 2016). Between November and March/April the mountain areas are snow covered but in elevations below 750 m a.s.l. the snow cover is not persistent and snow accumulation and snow melt alternate. In the highest regions with a persistent snow cover (e.g. Fichtelberg), snow depth is between 0.5 and 2.5 m but may also reach more than 3 m (data provided by German Weather Service, *Climate Data Center* 2016).

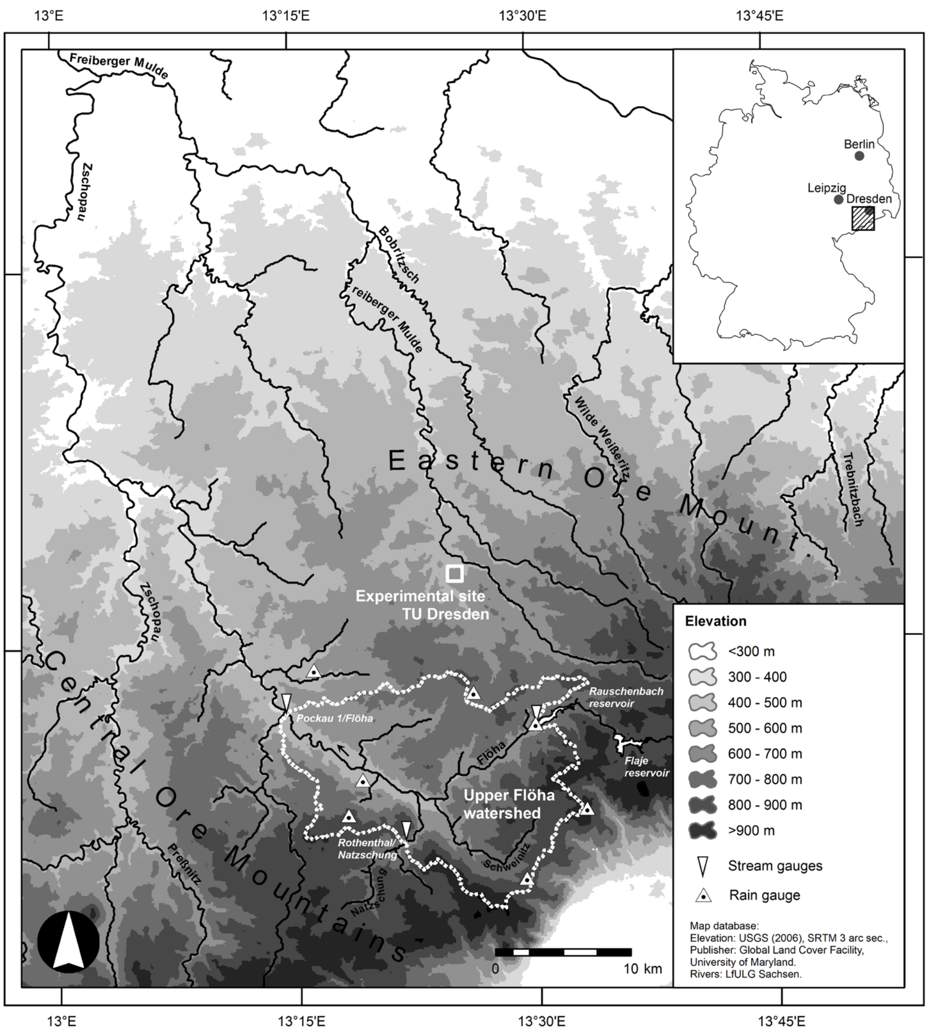

Fig. 1 Map of the Central and Eastern Ore Mountains with the study area and the network of stream and rain gauges. Only stations used in the study are shown. Source: Own elaboration

Petrow et al. (2007) identified two main mechanisms of flood generation in the region: events of smaller magnitude are generated frequently in spring by a combination of rainfalls and snowmelt, whereas extreme summer events with a high magnitude but longer return periods are caused by storm rainfall related to Vb cyclones. The term Vb is based on the van-Bebber classification and refers to a low-pressure system that develops in Western Europe and moves south along a path across the Mediterranean Region and east of the Alps to Central Europe (see *Petrow* et al. 2007 for details).

A subwatershed of the Upper Flöha was selected for the study. The Flöha is a tributary of the Zschopau River, which merges with the Freiberger Mulde River north of the Ore Mountains. This study refers to the part of the basin between the Rauschenbach Reservoir and the gauges of Rothenthal at the Natzschung River, a tributary to the Flöha, and Pockau 1/Flöha (*Fig. 1*) with a total area of 239 km^2 and an elevation ranging from 397 m (gauging station Pockau 1/Flöha) to 921 m a.s.l. In the higher parts of the basin, a plateau-like landscape with wide valleys and gentle slopes is found, turning into steep v-shaped valleys towards the lower reaches of the Flöha tributaries. Bedrock mainly comprises Proterozoic and Paleozoic metamorphic rocks (gneisses, mica-schists, metagranitoides, metarhyoliths). The main soil types in the catchment are different types of Cambisols and Podzols as well as Gleysols on fluvial sediments of the valley floors. More than half of the area is covered by forests, of which 28.8% are coniferous forests, 6.3% deciduous forest, 6.5% mixed forests, and 10.2% are transitional woodland shrub vegetation representing afforested and recovering forest-decline areas. The remaining parts are composed of agricultural areas (30.0%), pastures (13.5%), and settlements (4.8%).

2.2 Hydrological characteristics of periglacial cover beds in the Eastern Ore Mountains

The hydrological processes in periglacial cover beds of the Ore Mountains were previously investigated by *Heller* (2012; see also *Heller* and *Kleber* 2016) in a spring catchment near the small town of Mulda (area: 0.06 km^2, elevation: 521 to 575 m a.s.l., *Fig. 1*). The forested experimental site is located 15 km north of the modeling area and has a similar topography and geological setting (Proterozoic gneiss). The structure of the PGCBs is typical for the gneiss-dominated locations in the Ore Mountains. The Upper Layer has a thickness of 30 to 65 cm and consists of silty-loamy material with a low bulk density and many roots. In the central part of the site the upper sequence is underlain by a silty-loamy Intermediate Layer with a higher bulk density and a thickness of up to 55 cm. The ubiquitously present sandy-loamy Basal Layer is characterised by an even higher bulk density and a large number of coarse clasts oriented parallel to the slope. On the footslope, the Basal Layer may reach a thickness of at least 300 cm. Some soil-physical and sedimentological properties of the layers are specified in *Table 2*.

Field-saturated hydraulic conductivities of the layers are quite different (*Table 3*). A moderate hydraulic conductivity (27 cm d^{-1}) was measured in the Upper Layer. This may be explained by a relatively low bulk density and a high number of roots. By contrast, a lower hydraulic conductivity with only 9 cm d^{-1} was measured in the Intermediate Layer with a higher bulk density. The high values in the Basal Layer (52 cm d^{-1}) are hardly explained by soil-physical properties. The predominant sandy substrate and the coarse clasts oriented parallel to the slope could be the reason for the high saturated hydraulic conductivity (*Sauer* and *Logsdon* 2002). In line with *Kleber* and *Schellenberger* (1998), we assume that these high values only exist in a lateral direction. In a vertical direction, the hydraulic conductivity of the Basal Layer is estimated to be 0-11 cm d^{-1} (*LfULG* 2007).

Results of hydrometrical, hydrochemical and geophysical measurements as well as tracer investigations show that there are three runoff-process types depending on the pre-event soil moisture:

Table 2 Measured properties of cover beds of a profile. Source: Heller and Kleber (2016)

Layer	Horizon	Color (moist)	Texture	Clasts (%)	Bulk density (g·cm^{-3})	Porosity (%)
Upper Layer	A / Bw	10YR/5/8	loamy-sandy silt	36	1.2	55
Intermediate Layer	2Bg	10YR/5/4	loamy-sandy silt	43	1.5	43
Basal Layer	3CBg	10YR/5/3	very loamy sand	56	1.7	36

Table 3 Hydraulic properties of cover beds in experimental site of TU Dresden. Source: Modified from Heller (2012)

Layer	Field-saturated hydraulic conductivity (cm d^{-1})*			Field capacity (Vol.-%)**	Wilting point (Vol.-%)**
	mean	min	max		
Upper Layer	27 (n=49)	5	264	39	15
Intermediate Layer	9 (n=19)	3	45	35	13
Basal Layer	52 (n=20)	4	220	23	6

*field-saturated hydraulic conductivity measured using the Compact Constant Head Permeameter (CCHP) method (*Amoozegar* 1989); **after *AG Boden* (2005)

(1) With low pre-event soil moisture, vertical seepage dominates along preferential flow paths such as root remnants in the Upper, Intermediate, and in the upper part of the Basal Layer close to the spring. Water is predominantly fixed by capillary force. In the spring bog, saturation overland flow causes short rises of discharge. The runoff coefficient amounts to 0.1%.

(2) With medium pre-event soil moisture, the Intermediate Layer becomes saturated because of reduced vertical percolation into the Basal Layer. With time, water drains into the upper part of the Basal Layer, which saturates, too. Owing to high lateral hydraulic conductivity of the Basal Layer and reduced vertical seepage, interflow occurs but is restricted to the upper part of the Basal Layer. A persistently increasing discharge results from this behaviour. The runoff coefficient amounts to 4%.

(3) Under high-saturated soil moisture conditions, precipitation or snow melt water percolates quickly from the Upper Layer through the Intermediate Layer and into the upper part of the Basal Layer. Anisotropic hydraulic properties of the Basal Layer cause interflow in the upper part of this layer. Close to the spring, lateral water flux from the slope reaches the deeper Basal Layer, causing water to rise up into overlying layers, and return flow occurs. The runoff coefficient amounts to 14-35%.

The main result is that runoff generation processes of the investigated small catchment in the Eastern Ore Mountains are significantly affected by the structure of periglacial cover beds. Thereby, the hydraulic anisotropic structure of the Basal Layer is the major control factor. On the one hand, this layer acts as an aquitard for seeping water because of its high bulk density. On the other hand, water within the layer is able to flow laterally because of the sandy texture and the coarse clasts oriented parallel to the slope surface. For detailed results of the study see *Heller* (2012), *Hübner* et al. (2015), as well as *Heller* and *Kleber* (2016).

3. Methods

3.1 Overview NASIM

The simulation is based on rainfall-runoff developed with NASIM version 3.8.1. NASIM is a conceptual and distributed rainfall-runoff model produced by Hydrotec GmbH in Aachen, Germany. The basic units of the modeling process are user-defined subcatchments, which are subdivided into elementary unit areas determined by the intersection of digital land use and soil data. Vegetation is parameterised by interception capacity and rooting depth for each land use class. Soil data are usually implemented according to the soil types in the area under investigation, which are characterised by the number and thickness of soil layers. Physical parameters such as grain size distribution, total pore volume, field capacity, wilting point, and hydraulic conductivity have to be assigned to each soil layer. The soil water balance is calculated using a conceptual approach with a separation of the soil column in the root zone and the layers below. Infiltration and water transfer between the layers are based on the non-linear Bear/Holtan approach (*Holtan* 1970). Depending on the soil moisture, surface runoff is generated either as infiltration or saturation excess, whereas interflow sets in when rainfall intensity exceeds infiltration. The runoff concentration is simulated using a combination of isochrones (based on the time-area functions of the subcatchments) and subsequent single linear storages for surface runoff, interflow, and baseflow. Finally, the transformation of discharge in the channels is calculated using the Kalinin-Miljukov approach and the Manning-Strickler equation.

Calculation of the runoff generation is a crucial part of the hydrological process chain especially in the context of flood modelling and has to be calibrated carefully. In NASIM, the soil water balance is calibrated by an adjustment of wilting point, field capacity, pore volume, maximum infiltration rate, and the hydraulic conductivity of the soil column. In this context, it is important to note that the implemented soil parameters are stored separately from the calibration factors. In contrast to other software packages, a major advantage of NASIM is that it allows a separate control of the vertical and lateral hydraulic conductivity (in NASIM also referred to as horizontal conductivity) during calibration.

3.2 The Upper Flöha Model

The analysis uses a model previously developed with NASIM by *Reinhardt* et al. (2011) for the simulation of flood events and the effectiveness of decentralised water retention measures. The basic data for this model include digital elevation data provided by Saxony's Public Enterprise for Geospatial Information and Surveying and the Czech Office for Land Surveying, land-use data (CORINE Landcover 2000 provided by the European Environment Agency in 2007) as well as soil data from the conceptual 1:25,000 soil map and the 1:50,000 soil map of the Free State of Saxony (including soil profiles). The physical (hydraulic) parameters of the soil layers are based on standard values according to the grain size types in *DVWK* (1999). River and floodplain cross sections were derived from field surveys and Strickler roughness coefficients for channels and floodplains were estimated in the field based on *Chow* (1959). The time series of seven rainfall stations of different operating organizations (German Weather Survey, Czech Hydrometeorological Office, Public Enterprise Sachsenforst, State Reservoir Administration of Saxony, Water Administration of the Ohře Basin and a private station in Olbernhau) distributed over the study area and adjacent regions were incorporated in the model (*Fig. 1*). One of these stations near the town of Olbernhau provided hourly rainfall, temperature and humidity data. For all other stations, daily rainfall data were available that were disaggregated to increase the temporal resolution. For the disaggregation, the temporal distribution function of the hourly time series was transferred to the stations with daily rainfall data (one-station approach). Although the real subdaily rainfall distribution at the disaggregated stations has to be neglected, such an approach reduces the uncertainty in the spatial distribution of rainfall and improves goodness-of-fit for flood events significantly. Discharge time series were provided by the Saxon State Office for Environment, Agriculture and Geology and the State Reservoir Administration of Saxony. The gauges Rothenthal/Natzschung as well as the discharge of the Rauschenbach reservoir were used as upper boundary condition for the model.

The analysis of model results versus soil parameters was performed using two different approaches. The original model (in the following referred to as version 1) was developed using conventional soil data (soil types) and calibrated for two flood events in March/April 2006 and August 2002, both with hourly resolution and identical calibration parameters. The observed peak discharges of these events correspond to return periods of ten years (2006) and 200 years (2002). However, because of the low number of available flood events that could be simulated with a high resolution, there was no differentiation between calibration and validation in this initial calibration step. The initial watershed conditions at the beginning of the flood events (e.g. soil moisture, snow depth etc.) were determined by a separate water balance model with daily resolution for the period from 2002 to 2006.

Subsequently, iterative model runs with varying calibration factors for the hydraulic conductivity were performed in order to assess the sensitivity of the model and to determine the optimum parameter set. The factors range from 0.5 to 2 for the vertical (50-200% of the initially implemented value) and 0.3 to 3 (33-300%) for the horizontal conductivity. All other calibration factors for the soil water balance were adopted from the original model and were not modified. The objective functions for the sensitivity analysis as well as the evaluation of the model performance in general are the Nash-Sutcliffe coefficient of efficiency (NSE) and the difference between simulated and observed peak discharge (ΔHQ). The NSE was developed by *Nash* and *Sutcliffe* (1970) and since that it became one of the most frequently used statistical parameters to evaluate the goodness-of-fit for rainfall-runoff models. It is calculated using the following equation:

$$NSE = 1 - \frac{\sum_{i=1}^{N}(o_i - p_i)^2}{\sum_{i=1}^{N}(o_i - \overline{o})^2},$$

where o_i is the observed discharge at time step i, p_i the simulated discharge at time step i and $\bar{o}$ the mean of the observed discharge time series. Values range from 1 to $-\infty$ where 1 would be a one hundred percent match of observed and simulated time series. Coefficients higher than 0 are regarded as being acceptable (0.75-1: very good; 0.65-0.75: good; 0.5-0.65: satisfactory; *Moriasi* et al. 2007).

In a second step, the model parameterisation was simplified, assuming that PGCBs occur across the slopes of the entire watershed with similar characteristics except in areas with thick younger sediments such as floodplain deposits. Accordingly, all soil types except for floodplain soils and peat bogs were aggregated to the class periglacial cover beds with a three-layer profile including Basal, Intermediate and Upper Layers (model version 2 in the following). For this class, the standard hydraulic parameters according to *DVWK* (1999) were replaced by the local parameters determined by *Heller* (2012) *(Tables 2* and *3*), whereas floodplain and peat bog soil parameters are identical to model version 1. Finally, the soil calibration parameters for the cover beds were slightly adjusted to ensure optimum simulation results.

4. Results

The results of the rainfall-runoff modeling refer to the spring flood event of 2006. The pre-event conditions are characterised by a high amount of snow accumulated during the winter season especially in the higher regions of the Ore Mountains. At the end of March, warm western-air inflow caused a rapid snowmelt and a first rise of the discharge to about 50 m^3s^{-1} at the Pockau 1 gauge. On 30 and 31 March, additional rainfall resulted in a further increase of the discharge to a peak of 115 m^3s^{-1}.

In addition, the 2002 extreme flood event was considered for the validation of the results. The flood developed during a storm event with heavy rainfall (up to 220 mm in 24 hours) caused by a Vb cyclone that passed the Ore Mountains on August 11 and 12. However, the gauging station Pockau 1/Flöha was damaged heavily during the event so that a continuous time series is not available and only the peak discharge value of about 315 m^3s^{-1} could be used as a reference (data provided by the Saxon State Office for Environment, Agriculture and Geology).

The first part of the sensitivity analysis refers to a variation of the horizontal conductivity (hhc), whereas the vertical conductivity (vhc) remains unchanged (constantly 1.0). *Figure 2* provides an insight into the simulation results. The highest Nash-Sutcliffe coefficient occurs in the simulations with a horizontal conductivity between 1 and 1.25. Although the NSE decreases slightly for conductivity values below 1 and above 1.25, the index is generally on a very high level for the entire range of simulations (> 0.85). The simulated peak discharge in *Figure 2* (middle) decreases with an increase of the horizontal conductivity, whereas the observed flood peak of 115 m^3-s is met with a value of 1.25. This means that with an increasing horizontal conductivity an increasing amount of water in the model is transferred from the flood peak towards the falling limb of the hydrograph and thus from surface runoff to interflow.

In the second phase of the sensitivity analysis, the vertical hydraulic conductivity is modified in combination with the horizontal conductivity. This results in the response surfaces of the objective functions shown in *Figure 3*. In addition, *Figure 4* gives an overview of the ensemble of the related hydrographs. The optimum of the NSE with values of 0.95 and higher occurs in simulations with a reduced horizontal conductivity in combination with a high vertical conductivity. However, the efficiency is generally high (NSE > 0.75), except for extremely high conductivity values in the upper right corner of the diagram.

In contrast to the NSE optimum, the best fit of the simulated peak discharge can be achieved with an increased horizontal conductivity (1.25) and a vertical conductivity near 1.0 (*Fig. 3*, bottom). This first optimum in the response surface represents the same conductivity values as for the optimum in the one-dimensional analysis (variation of the horizontal conductivity only) described above. The NSE for this parameter combination reaches 0.935, and the ΔHQ is 0.1 m^3s^{-1}. A second optimum occurs for a vertical conductivity of 0.75 and a horizontal conductivity of 1.75 (NSE: 0.905, ΔHQ: 1.3 m^3s^{-1}).

In general, best model results can be achieved with an anisotropic hydraulic conductivity. However, depending on the objective function, the two observed optima are based on inverse parameter sets, i.e. the NSE optimum occurs with a reduced horizontal/increased vertical conductivity and a flood peak optimum with an increased horizontal/reduced vertical conductivity.

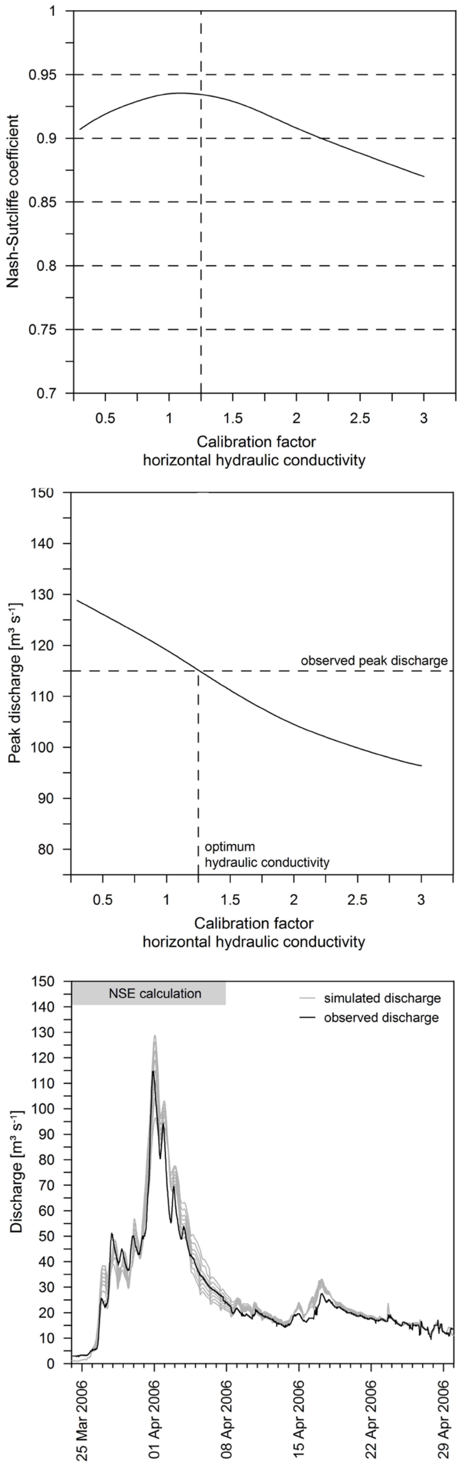

Fig. 2 *Sensitivity of the model to the variation of the horizontal hydraulic conductivity. Top: Nash-Sutcliffe coefficient (NSE); middle: simulated peak discharge; bottom: simulated and observed hydrographs. The grey bar on top of the diagram indicates the time interval for the NSE calculation. The dashed vertical lines mark the determined optimum horizontal conductivity (1.25). Time series for the gauging station Pockau 1/Flöha were provided by the Saxon State Office for the Environment, Geology, and Agriculture. Soure: Own elaboration*

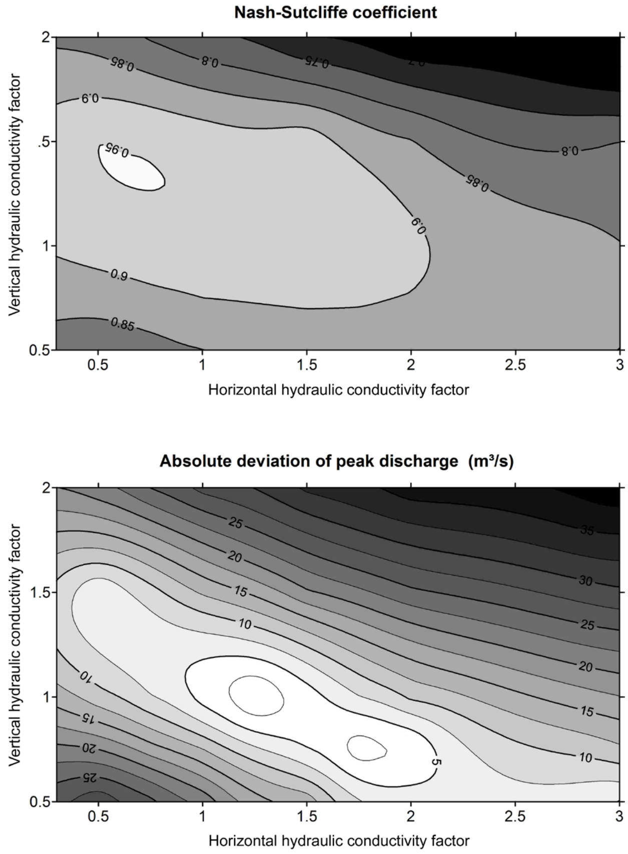

Fig. 3 *Nash-Sutcliff coefficient (top) and absolute deviation of simulated and observed peak discharge (bottom) for the 2006 spring flood as a result of a combined variation of vertical and horizontal hydraulic conductivity (observed discharge: 115 m^3s^{-1}). Contours of the response surfaces indicate lines of identical Nash-Sutcliffe coefficients and peak deviation for varying parameter combinations. Source: Own elaboration*

Such cases of equifinality with two or more inverse parameter sets resulting in high-quality model outputs are typical for conceptual rainfall-runoff models. However, it should be noted that only the latter of the two parameter sets (hhc > vhc) may be brought into agreement with the aforementioned knowledge of subsurface flow processes in the study area.

Since the simulations refer to one event only, a further validation using the August 2002 flood event is required to support the results (*Table 4).* In this case, both parameter sets, again, result in a very good simulation of the observed peak discharge with only minor deviations. For parameter set A (hhc < vhc), the peak discharge in the model exceeds the observed peak by only 2 m^3s^{-1}, whereas for parameter set B (hhc > vhc) the simulated peak is 7 m^3s^{-1} higher than the observed peak. This means that both parameter sets are able to approximate the rain on snow event in 2006 as well as the storm rainfall event in 2002.

Table 4 *Comparison of the observed peak discharges of the flood events in 2002 and 2006 with simulated peaks based on different parameter sets in model version 1. Source: Own elaboration*

	conductivity		2006		2002	
	horizontal	vertical	peak discharge	ΔHQ	peak discharge	ΔHQ
	[-]	[-]	[m^3s^{-1}]	[m^3s^{-1}]	[m^3/s^{-1}]	[m^3/s]
Observation (Pockau 1/Flöha)	–	–	115	–	315	–
Simulation parameter set A (hhc < vhc)	0.75	1.5	106	-9 (-7.8%)	317	2 (0.6%)
Simulation parameter set B (hhc > vhc)	1.25	1	115	0 (0%)	322	7 (2.2%)

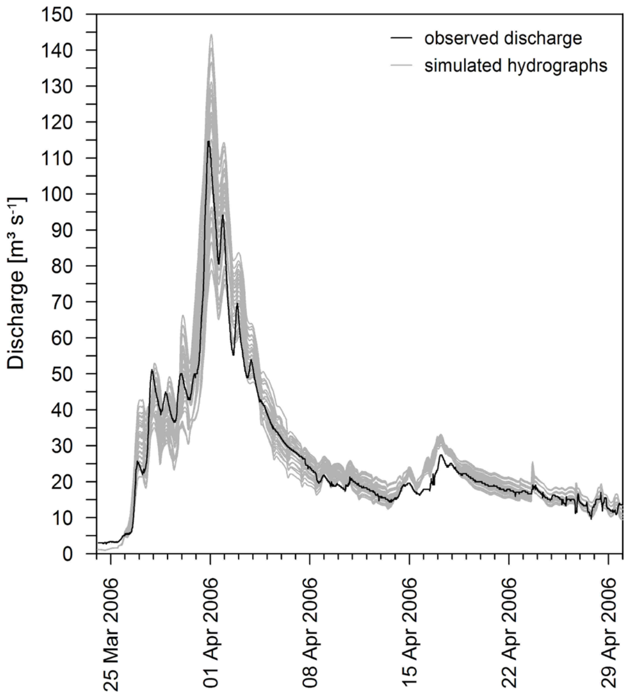

Fig. 4 *Range of hydrographs for the variation of both horizontal and vertical hydraulic conductivity (N=32). Source: Own elaboration*

The results of the sensitivity analysis and the ubiquitous distribution of PGCBs in low mountain areas raise the question whether the conventional spatial discretisation of rainfall-runoff models in soil types may be replaced by PGCBs distributed over the entire watershed (model version 2). The results of the simulation with this modified model version in comparison with the hydrographs from the original model with soil types are shown in *Figure 5*.

For the total discharge, the difference between the observed discharge and both simulated hydrographs is higher than the difference between the two model versions (*Fig. 5a*). Except for some minor differences at the beginning and the end of the event, the simulated hydrographs are identical, indicating an almost identical model performance. During the first phase of the event between 25 and 31 March, both models underestimate the total discharge, whereas the underestimation is slightly higher in model version 2 with the PGCBs (*Fig. 5*). The reason for this difference may be found in an underestimation of the surface runoff shown in *Figure 5b*, which is probably related to a lower pre-event soil moisture in model version 2. During the peak phase of the event (after 31 March, 2006), the hydrographs of both models are identical in total discharge and surface runoff, i.e. the difference at the beginning appears to be of minor relevance.

Besides the surface runoff, a comparison of the subsurface flow processes (*Fig. 5c* and *5d*) is more interesting with reference to the role of the PGCBs. The most remarkable differences occur at the crest (after 31 March) and the recession limb of the interflow hydrograph (*Fig. 5*). The absolute difference between both models with regard to the subsurface-flow processes is shown in *Figure 6*. During the peak phase, model version 2 generates a slightly higher interflow but the difference is balanced by a lower baseflow, i.e. the total discharge at the gauge is identical. Hence, in model version 2 using PGCBs, the components of the quick subsurface flow processes are slightly higher and the slow processes decreased. However, the absolute difference is less than 5 m^3s^{-1}, which is in the range of the general model uncertainty. Thus, the performance of both models has to be regarded as almost identical.

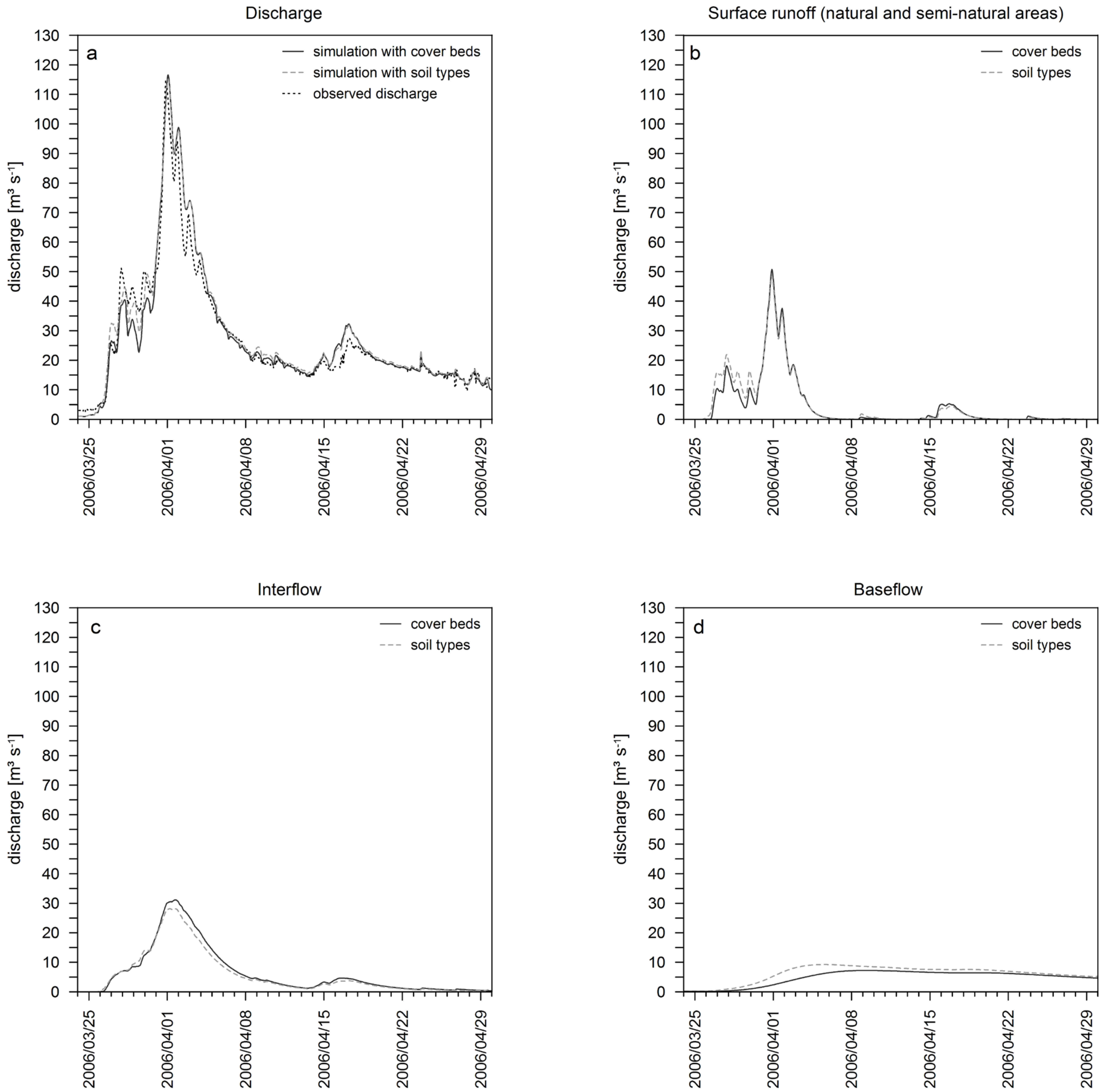

Fig. 5 Comparison of the results of the original model with results of the modified model version 2, which is based on a simplified spatial discretization with PGCBs instead of soil types. The graphs show the total river discharge of both models for the flood event of 2006 compared with the observed hydrograph at the Pockau 1/Flöha gauge (5a) as well as the simulated runoff components (5b: total surface runoff; 5c: interflow; 5d: baseflow). Not shown: surface runoff of urban areas. Source: Own elaboration

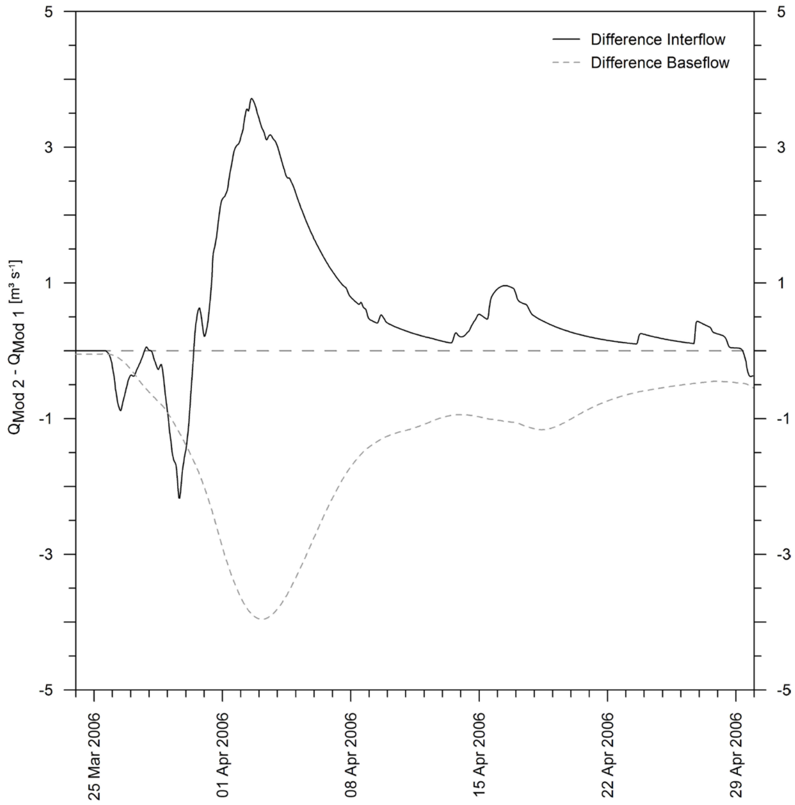

Fig. 6 Difference of the total subsurface runoff components between model versions 1 and 2. The slightly higher interflow in model version 2 is compensated by a lower base flow. Source: Own elaboration

5. Discussion

In the past, anisotropic hydraulic properties of soils were observed in general as results of the soil-forming processes (e.g. sedimentation, stratification, compaction, particle orientation, and others; *Assouline* and *Or* 2006). Depending on the factors which control soil development in different regions, however, the resulting structures of the soils differ strongly. For the study area, field investigations indicate that the periglacial cover beds with their anisotropic hydraulic conductivity have to be considered as one important factor controlling subsurface flow processes and hence are an important element of flood runoff generation. These results are similar to or in line with previous studies on flood generation and subsurface-flow processes in areas with PGCBs (*Wenninger* et al. 2004; *Chifflard* et al. 2008; *Hümann* et al. 2011). In addition, quick lateral flow processes usually occur along horizontal macropores (e.g. the root system). Although this is not directly related to the soil system, it also contributes to the total lateral flow on the catchment or subcatchment scale. However, the existence and distribution of such horizontal macropores depend mainly on the vegetation type, i.e. a high connectivity of the macropore system from upslope regions down to the river channels in a catchment has to be questioned if there are varying land use types (forest, grassland, arable land). Even if a watershed is completely covered by forests, the full connectivity of macropores is uncertain. By contrast, because of the well-known area-wide distribution of PGCBs, especially in the Basal Layer, there is a high lateral connectivity for subsurface flow processes. Thus, it may be concluded that, in addition to preferential flow, the hydrologic effect of the cover beds is relevant for the generation of floods with medium to high magnitudes.

The discussion of the simulation results is based on this knowledge, taking into account that conceptual rainfall-runoff models were designed for a simulation of processes at the catchment scale. In such models, simplified and abstracted approaches are used for the description of subsurface flow using parameters which are part of the calibration process. Thus, the potential for a detailed parameterisation of anisotropy in the PGCBs is limited. However, it is generally accepted that the complexity and variability of hydrological processes on the slope scale are averaged at larger scales (cf. *Soulsby* et al. 2006). Therefore we consider the abstractions in conceptual catchment models to be appropriate.

The most important limitation of the model system NASIM is that it cannot distinguish between vertical and horizontal conductivity in the original parametrisation, although a hydraulic-conductivity value is assigned to each soil layer. Such a differentiation is available for the separately stored calibration parameters but with only one correction factor for the entire soil column, not for individual layers. However, in many other commercial and non-commercial modeling systems, anisotropic hydraulic conductivities are not considered at all. *Eckhardt* et al. (2002) already reported this deficit for the widely distributed Soil and Water Assessment Tool (SWAT; *Arnold* et al. 1998) and introduced an anisotropy factor for the third soil layer in their modified version SWAT-G.

Another important point is that the number of flood events available for the analysis is limited to two events in 2002 and 2006. For earlier flood events, there is a lack of input data in the required temporal resolution (e.g. time series of rainfall). However, the modelled events reflect the two main flood-generating processes in the study area (storm rainfall and the combination of rain and snowmelt, cf. *Petrow* et al. 2007) and, hence, are used exemplarily. In 2006, the beginning snowmelt resulted in high water content in the soil column and rising interflow already before additional rainfall triggered higher surface runoff on 30 March 2006 (*Fig. 5*). In the model, the peaks of surface runoff and interflow occur almost at the same time. According to the field results of *Heller* and *Kleber* (2016), we assume that under such conditions interflow in the PGCBs, including the Basal Layer, plays a dominant role. Also, during the extreme summer event of 2002, a substantial reaction of the interflow was observed in the model. However, since there are no field data on soil moisture for this event, particular subsurface flow pathways remain undetermined.

The sensitivity analysis in model version 1 reveals that, in terms of the objective functions NSE and ΔHQ, both the horizontal and the vertical hydraulic conductivities are sensitive parameters for the simulation. The observation that the NSE is generally on a high level – although its high sensitivity to deviations in extreme values is known (e.g. *Harmel* and *Smith* 2007) – may be explained by the fact that in all model runs the temporal offset between simulated and observed hydrographs is very low. In addition, one must consider that the Natzschung watershed was excluded from the model and the time series of the Rothenthal/Natzschung gauge was used as an input.

However, depending on the objective function, two inverse parameter sets were identified, both with anisotropic conditions and resulting in a high model performance. The validation with the extreme flood in 2002 does not solve this problem but indicates that both parameter sets are also valid for an extreme summer event. But if the previous knowledge about flow processes in PGCBs is considered, parameter set A with a vertical conductivity higher than the horizontal one may be excluded. The slightly higher ΔHQ for parameter set B (hhc > vhc) for the 2002 event does not necessarily contradict this interpretation. This event has to be treated with caution because an exact time series is not available and the observed peak discharge is more uncertain and may be slightly underestimated.

The results of the sensitivity analysis are in line with previous studies on model calibration in mountain areas with periglacial cover beds. An analysis of the sensitivity of calibration parameters in NASIM was presented by *Buchholz* and *Wolf-Schumann* (2008) for the river Schwarze Pockau bordering on the study area in the west. In this study, an optimal horizontal conductivity factor between 1.5 and 2.0 was observed for two flood events, though this finding was not discussed in the context of PGCBs. By contrast, *Eckhardt* et al. (2002) previously recognised the role of PGCBs in the context of hydrological modeling. In their investigations in the Dietzhölze catchment in Western Germany, which are based on SWAT-G, the best reproduction of flood events was achieved with an anisotropy factor of 8, which is much higher than in our study (1.25). The difference may be explained by the fact that *Eckhardt* et al. (2002) applied this factor to the third soil layer (Basal Layer) only, whereas in NASIM the anisotropy is averaged over the entire soil column. Unlike NASIM, however, SWAT-G operates with daily time steps (*Lenhart* et al. 2002), so it cannot be used for high resolution flood event modeling.

Moreover, *Eckardt* et al. (2001) provided evidence that in hydrologic models different soil types do not differ significantly with respect to runoff generation. As a consequence, they questioned the use of soil maps as spatial input and suggested an aggregation of soil types to larger units. The combination of this idea with the knowledge of the distribution of periglacial cover beds results in the high degree of aggregation in the study presented here. The results indicate that in fact such a strong aggregation is applicable and that the performance of a model with aggregated soils can be as high as that of a model with differentiated soil types. In this case, it is also acceptable that the natural lateral variability of thickness and hydraulic parameters of the PGCBs and the absence of the Intermediate Layer in some areas were neglected by the use of a standard three-layer profile. On the other hand, a more detailed implementation of cover beds may be disregarded for two main reasons: (1) Taking into account that the natural variability of hydrological processes at the slope scale is generally averaged at the catchment scale, a more detailed implementation of PGCBs would contradict the idea of aggregation and simplification and (2) although the general trends of the distribution of PGCBs are well known (*Kleber* et al. 2013a), detailed maps of their characteristics (including the occurrence of the Intermediate Layer) as required for a rainfall-runoff model are not available.

Finally, the question of transferability to other regions arises. The available information about the characteristics of PGCBs shows a very similar structure in all Central European mountain areas with magmatic or metamorphic bedrock. Although the calibration factors in different studies such as *Buchholz* and *Wolf-Schumann* (2008) and *Eckhardt* et al. (2002) are not identical (which is to be expected for conceptual rainfall-runoff models), the principle of cover bed related anisotropy is identical and hence transferable to flood models in other Central European regions with a similar geological setting. This also applies to the idea of a simplification of the model parameterisation based on PGCBs. Furthermore, *Kleber* (1997), *Kleber* et al. (2013b), and *Völkel* et al. (2011) show that similar deposits also occur in other regions such as the European Alps, the Russian Plain, and the USA, but for a transfer of the results to these regions further hydrological investigations are required.

6. Conclusions

The following conclusions may be drawn from the combination of field data and subsequent rainfall-runoff modeling: hydraulic anisotropy is a factor that has to be considered in flood models with a high temporal resolution (1 hour or higher). Hence, options for an implementation of anisotropy in the soil column in conceptual rainfall-runoff models are essential if they are used for flood simulations in mountain areas with periglacial cover beds. However, further field experiments are necessary to fully understand the interaction of anisotropic flow in the cover beds with preferential flow pathways and their implications for flood modelling.

An abstracted approach with a differentiation between vertical and horizontal hydraulic conductivities averaged over the whole soil column during the calibration process provides reasonable results, although a separate implementation for each soil layer would allow a much more detailed process description. In areas with periglacial cover beds, a high goodness-of-fit can be achieved at the mesoscale without a detailed differentiation in soil types, allowing a reduction of the number of model parameters without quality loss. Hence, in practice (e.g. in the context of flood risk management) the suggested degree of aggregation in the flood model may reduce data demand, time, and effort for the model development.

References

AG Boden (ed.) 1994: Soil Mapping Manual. Third Edition. – Stuttgart/Germany (in German)

AG Boden (ed.) 2005: Soil Mapping Manual. Fourth Edition. – Stuttgart/Germany (in German)

Amoozegar, A. 1989: A Compact Constant-Head Permeameter for measuring saturated hydraulic conductivity of the vadose zone. – Soil Science Society of America Journal **53**: 1356-1361

Arnold, J.G., R. Srinivasan, R.S. Muttiah and *J.R. Williams* 1998: Large area hydrologic modeling and assessment, Part I: model development. – Journal of the American Water Resources Association **34**: 73-89

Assouline, S. and *D. Or* 2006: Anisotropy factor of saturated and unsaturated soils. – Water Resources Research **42**: 1-11, doi:10.1029/2006WR005001

Becker, A. and *J.J. McDonnell* 1998: Topographical and ecological controls of runoff generation and lateral flows in mountain catchments. Hydrology, Water Resources and Ecology in Headwaters. – International Association of Hydrological Sciences Publication **248**: 199-206

Buchholz, O. and *U. Wolf-Schumann* 2008: The application of automated calibration strategies for the investigation of the extrapolation potentials of rainfall-runoff models using the example of NASIM. Veröffentlichter Posterbeitrag auf CD-Beilage. – CD-Beilage in: Haberlandt, U., B. Riemeier, M. Billib, H.-R. Verworn and H.-B. Kleeberg (eds.): Hochwasser, Wassermangel, Gewässerverschmutzung – Problemlösungen mit modernen hydrologischen Methoden. – Forum für Hydrologie und Wasserbewirtschaftung **23.08.** – Hennef/Germany

Büttner, U. and *P. Walther* 2007: Flooding in Saxony during the past 10 years. – In: *Horlacher, H.-B.* and *K.-U. Graw* (eds.): Five years after the flood: flood protection concepts – planning, computation, implementation. –

Dresdner Wasserbauliche Mitteilungen **35**. – Dresden/Germany: 13-23

Chifflard, P., J. Didszun and *H. Zepp* 2008: Analysis of runoff generation at different scales in areas characterized by periglacial cover beds (Sauerland, Germany). – Grundwasser – Zeitschrift der Fachsektion Hydrogeologie **13**: 27-41, doi:10.1007/s00767-007-0058-1 (in German)

Chow, V.-T. 1959: Open-Channel Hydraulics. – Tokyo/Japan

Climate Data Center (CDC) 2016: Vieljährige Stationsmittelwerte für die Klimareferenzperiode 1981-2010, für aktuellen Standort und Bezugsstandort, Version 2016. – Offenbach/Germany

Dietze, M. and *Kleber, A.* 2010: Characterisation and prediction of thickness and material properties of periglacial cover beds, Tharandter Wald, Germany. – Geoderma **156**: 346-356, doi:10.10167j.geoderma.2010.03.004

DVWK (Deutscher Verband für Wasserwirtschaft und Kulturbau) 1999: Bodenkundliche Untersuchungen im Felde zur Ermittlung von Kennwerten zur Standortcharakterisierung, Teil II: Ableitungen zu Wasser- und Lufthaushalt von Böden. DVWK-Regel 136/1999. – Bonn/Germany

Eckhardt, K., C. Friedrich and *H.-G. Frede* 2001: Distinctive characteristics of soils in hydrologic modeling. – Mitteilungen der Deutschen Bodenkundlichen Gesellschaft **96**: 595-596 (in German)

Eckhardt, K., S. Haverkamp, N. Fohrer and *H.-G. Frede* 2002: SWAT-G, a version of SWAT99.2 modified for application to low mountain range catchments. – Physics and Chemistry of the Earth **27**: 641-644

Felix-Henningsen, P., E.-D. Spies and *H. Zakosek* 1991: Genesis and stratigraphy of periglacial layer sequences in the flat upland area of the eastern Hunsrück (Rhenish Massif). – Eiszeitalter und Gegenwart **41**: 56-69 (in German)

Harmel, R.D. and *P.K. Smith* 2007: Consideration of measurement uncertainty in the evaluation of goodness-of-fit in hydrologic and water quality modeling. – Journal of Hydrology **337**: 326-336, doi:10.1016/j.jhydrol.2007.01.043

Heller, K. 2012: The influence of periglacial cover beds on the near-surface flow paths at slopes – an experimental process study in the Eastern Ore Mountains. Dissertation at Technical University Dresden. – Dresden/Germany (in German)

Heller, K. and *A. Kleber 2016:* Hillslope runoff generation influenced by layered subsurface in a headwater catchment in Ore Mountains, Germany. – Environmental Earth Science **75**: 1-15. doi:10.1007/s12665-016-5750-y

Holtan, H.N. 1970: Representative and experimental basins as dispersed systems. Symposium of Wellington, New Zealand. IASH 1972-73. – Wellington/New Zealand: 112-126

Hübner, R., Heller, K., Günther T. and *A. Kleber* 2015: Monitoring hillslope moisture dynamics with surface ERT for enhancing spatial significance of hydrometric point measurements. – Hydrological Earth System Science **19**: 225-240, doi:10.5194/hess-19-225-2015

Hümann, M., G. Schüler, C. Müller, R. Schneider, M. Johst and *T. Caspari* 2011: Identification of runoff processes. The impact of different forest types and soil properties on runoff formation and floods. – Journal of Hydrology **409**: 637-649, doi:10.1016/j.jhydrol.2011.08.067

Kacprzak, A. and *Derkowski, A.* 2007: Cambisols developed from cover-beds in the Pieniny Mts. (southern Poland) and their mineral composition. – Catena **71**: 292-297, doi:10.1016/j.catena.2007.01.004

Kleber, A. 1992: Periglacial slope deposits and their pedogenetic implications in Germany. – Palaeogeography, Palaeoclimatology, Palaeoecology **99**: 361-371

Kleber, A. 1997: Cover-beds as soil parent materials in midlatitude regions. – Catena **30**: 197-213

Kleber, A., J. Lindemann, A. Schellenberger, C. Beierkuhnlein, M. Kaupenjohann and *S. Peiffer* 1998: Slope deposits and water paths in a spring catchment, Frankenwald, Bavaria, Germany. – Nutrient Cycling in Agroecosystems **50**: 119-126

Kleber, A. and *A. Schellenberger* 1998: Slope hydrology triggered by cover-beds. With an example from the Frankenwald Mountains, northeastern Bavaria. – Zeitschrift für Geomorphologie N.F. **42**: 469-482

Kleber, A., B. Terhorst, H. Bullmann, D. Hülle, M. Leopold, S. Müller, T. Raab, D. Sauer, T. Scholten, M. Dietze, P. Felix-Henningsen, J. Heinrich, E.-D. Spies and *H. Thiemeyer* 2013a: Subdued mountains of Central Europe. – In: *Kleber, A.* and *B. Terhorst* (eds.): Mid-Latitude Slope Deposits (Cover Beds). – Developments in Sedimentology **66**: 9-81

Kleber, A., M. Leopold, C. Vonlanthen and *J. Völkel* 2013b: Transferring the concept of cover beds. – In: *Kleber, A.* and *B. Terhorst* (eds.): Mid-Latitude Slope Deposits (Cover Beds). – Developments in Sedimentology **66**: 171-228

Lenhart, T., K. Eckhardt, N. Fohrer and *H.-G. Frede* 2002: Comparison of two different approaches of sensitivity analysis. – Physics and Chemistry of the Earth **27**: 645-654

LfULG (Saxon State Office for Environment, Agriculture and Geology) 2007: Soil atlas of the Free State of Saxony. – Dresden/Germany

Moriasi, D.N., J. G. Arnold, M. W. van Liew, R. L. Bingner, R. D. Harmel and T. L. Weith 2007: Model evaluation guidelines for systematic quantification of accuracy in watershed simulation. – Transactions of the American Society of Agricultural and Biological Engineers **50**: 885-900

Nash, J.E. and *J.V. Sutcliffe* 1970: River flow forecasting through conceptual models. Part I: Discussion of principles. – Journal of Hydrology **10**: 282-290

Pawelec, H. 2006: Origin and palaeoclimatic significance of the Pleistocene slope covers in the Cracow Upland, southern Poland. – Geomorphology **74**: 50-69, doi:10.1016/j.

geomorph.2005.07.010

Petrow, T., B. Merz, K.-E. Lindenschmidt and *A.H. Thieken* 2007: Aspects of seasonality and flood generating circulation patterns in a mountainous catchment in south-eastern Germany. – Hydrology and Earth System Science **11**: 1455-1468

Reinhardt, C., J. Bölscher, A. Schulte and *R. Wenzel* 2011*:* Decentralised water retention along the river channels in a mesoscale catchment in Southeastern Germany. – Physics and Chemistry of the Earth **36**: 309-318, doi:10.1016/j.pce.2011.01.012

Sauer, D. and *P. Felix-Henningsen* 2006: Saprolite, soils, and sediments in the Rhenish Massif as records of climate and landscape history. – Quaternary International **156-157**: 4-12, doi:10.1016/j.quaint.2006.05.001

Sauer, T.J. and *S.D. Logsdon* 2002: Hydraulic and physical properties of stony soils in a small watershed. – Soil Science Society of America Journal **66**: 1947-1956

Schädler, G., P. Berg, P. Düthmann, H. Feldmann, J. Ihringer, H. Kunstmann, J. Liebert, B. Merz, I. Ott and *S. Wagner* 2012: Flood Hazards in a Changing Climate, Project Report. Center for Disaster Management and Risk Reduction Technology. – Karlsruhe/Germany

Schröder, H. and *H.J. Fiedler* 1977: Contribution to the knowledge on periglacial cover beds of the Eastern Harz, Part 1: classification, lithology and distribution of periglacial cover beds. – Zeitschrift für geologische Wissenschaften **5**: 51-81 (in German)

Schwarze, R., B. Beudert, and *S. Theiss* 2011: Investigations on the near-surface runoff during floods. – In: *Blöschl, G.* and *R. Merz* (eds.): Hydrologie & Wasserwirtschaft - von der Theorie zur Praxis. – Forum für Hydrologie und Wasserbewirtschaftung **30.11**: 57-64 (in German)

Semmel, A. and *B. Terhorst* 2010: The concept of the Pleistocene periglacial cover beds in central Europe: A review. – Quaternary International **222**: 120-128, doi:10.1016/j.quaint.2010.03.010

Soulsby, C., D. Tetzlaff, P. Rodgers, S. Dunn and *S. Waldron* 2006: Runoff processes, stream water residence times and controlling landscape characteristics in a mesoscale catchment: An initial evaluation. – Journal of Hydrology **325**: 197-221, doi:10.1016/j.jhydrol.2005.10.024

Stolz, Ch. and *J. Grunert* 2010: Late Pleistocene and Holocene landscape history of the central Palatinate forest (Pfälzerwald, south-western Germany). – Quaternary International **222**: 129-142, doi:10.1016/j.quaint.2009.08.022

Stückrad, S., K.-J. Sabel and *W. Wilcke* 2010: Contributions of different parent materials in soils developed from periglacial cover-beds. – European Journal of Soil Science **61**: 844-853, doi:10.1111/j.1365-2389.2010.01288.x

Völkel, J. 1995: Periglacial covers and soils of the Bavarian Forest and adjacent areas (Germany). – Zeitschrift für Geomorphologie N.F. Supplement **96**: 1-309 (in German)

Völkel, J. and *M. Leopold* 2001: Age determination of the youngest phase of periglacial morphodynamics on slopes in Central European Highlands. – Zeitschrift für Geomorphologie N.F. **45**: 273-294 (in German)

Völkel, J., M. Leopold, M. and *M.C. Roberts* 2001: The radar signatures and age of periglacial slope deposits, central highlands of Germany. – Permafrost Periglacial Processes **12**: 379-387, doi:10.1111/j.1365-2389.2010.01288.x

Völkel, J., J. Huber and *M. Leopold* 2011: Significance of slope sediments layering on physical characteristics and interflow within the Critical Zone – Examples from the Colorado Front Range, USA. – Applied Geochemistry **26**: 143-145, doi:10.1016/j.apgeochem.2011.03.052

Wenninger, J., S. Uhlenbrook, N. Tilch and *C. Leibundgut* 2004: Experimental evidence of fast groundwater responses in a hillslope/floodplain area in the Black Forest Mountains, Germany. – Hydrological Processes **18**: 3305-3322