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Comparative predictions of discharge from an artificial catchment (Chicken Creek) using sparse data

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Abstract

We used ten conceptually different models to predict discharge from the artificial Chicken Creek catchment in North-East Germany. Soil textural and topography data were given to the modellers, but discharge data were withheld. We compare the predictions with the measurements from the 6 ha catchment and discuss the conceptualization and parameterization of the models. The predictions vary in a wide range, e.g. the predicted actual evapotranspiration ranged from 88 to 579 mm/y and the discharge from 19 to 346 mm/y. All model simulations revealed systematic deviations between observations of major components of the hydrological cycle (not known to the modellers) and the simulation results. Discharge was predicted mainly as subsurface discharge with little direct runoff. In reality, surface runoff was a major flow component despite the fairly coarse soil texture. The actual evapotranspiration (AET) was systematically overestimated by nine of ten models as was the ratio between actual and potential ET. Overall, none of the model simulations came close to the correct water balance during the entire 3-year study period. The comparison indicated that the personal judgement of the modellers was a major source of the differences between the model results. The most important parameters to be guessed were the soil parameters and the initial soil water content while plant parameterization had in this particular case of a sparse vegetation only a minor influence on the results.

1 Rationale and scientific concept

Hydrological catchment modelling is a tool for testing the assumptions and conceptualization of dominant system properties and advancing our process understanding of discharge formation. Often, the discharge record is known to the modeller when setting up the model but in ungauged catchments this is not the case. The PUB research initiative (Predictions in Ungauged Basins) addresses the problem of a priori predicting an unknown system response (Sivapalan et al., 2003). Such endeavours are typical for real world applications when the dominant processes are unknown and the data are too sparse to meet the model requirements. An important question now is how to improve the predictive model performance by acquiring additional information on process understanding and catchment characteristics and/or by reducing the parametric requirements.

In this study, we make use of data obtained in an artificial catchment for a comparative prediction of discharge. Artificial catchments are per se the opposite of ungauged catchments because they are supposed to provide a well documented case (e.g. a clear definition of catchment geometry and boundary conditions). We use conceptually different models to predict the discharge – yet unknown to the modellers – based on minimum information. The purpose of this collective exercise is neither a rating of model suitability nor success, but the question about the crucial elements of discharge modelling for an "a priori prediction" of the catchment response. This prediction exercise is the first of three steps. In a second step more detailed information on the catchment characteristics will be provided to the modellers but runoff data will still be withheld. In a third step, the entire data base including the discharge records will be made available to the modellers, which will lead to the usual calibration of the models. The process of stepwise satisfying the model needs will allow us to relate the gain of predictive performance to the efforts and costs of providing the information needed for the model parameterization. This paper documents the first step of the exercise and focuses on the comparison of the underlying model assumptions, because we think that this is the crucial element in making discharge predictions.

2 Artificial catchments and predictions in ungauged basins

Artificial catchments are an approximation to hydrological systems in their initial phase, because of the short time span since construction. Hydrological processes have been studied in artificial catchments, e.g., in China (Gu and Freer, 1995), Canada (Barbour et al., 2001), Spain (Nicolau, 2002) and in Germany (Gerwin et al., 2009). The main objective of most of these studies was to determine the water and element budgets of catchments under well defined boundary conditions to identify the flow paths through and the storage behaviour of the various catchment compartments by characterizing the processes of runoff formation (Hansen et al., 1997; Kendall et al., 2001). There is a general agreement that a good correspondence of observed and calculated discharge at a catchment outlet is a weak and insufficient criterion for the validity of a hydrological model (Grayson and Blöschl, 2000). Additional knowledge on internal variables is required for model validation (e.g. Beven, 1989). Both, local boundary conditions, e.g. the size of the surface and of the subsurface catchment, as well as internal structures, e.g. discharge points and stratification, can be controlled and more precisely documented in artificially constructed systems, so this is much closer to the "experiments" that are the paradigm of the natural sciences. Also detailed observations of discharge, soil water and groundwater, both in terms of quantity and quality, allow for verifying the hypotheses about the causes of the multi-responses of the system provided the catchment properties do not change too rapidly during the very initial phase of catchment construction. Such data sets reduce the uncertainties by using part of them for an "a posteriori" calibration. In our case we will use the artificial catchment data set only after having predicted the system response based on information that is usually available in catchment at the regional scale.

The "a priori" attempt – when target variables such as discharge are yet unknown – is an important step in any model application if the system, including its boundary conditions, changes or if a calibrated model is used for another ungauged catchment. This can only work if the dominant and system-relevant processes are known and can be adequately described. Here, we use the artificial catchment "Chicken Creek" in Lusatia, Germany (Gerwin et al., 2009) to test the "a priori" attempt of discharge prediction.

Predicting state variables within and fluxes between compartments as well as across catchment boundaries, is often hampered due to the considerable uncertainties which may due to catchment heterogeneity and poorly defined boundary and initial conditions. The PUB initiative has the objective to improve and to develop methods for such cases. Sivapalan et al. (2003) propose several approaches to address this problem either by conceptually simplifying process based models and/or by using more comprehensive data including proxy data. Pretending that the Chicken Creek catchment is a data-poor, ungauged catchment allows us to investigate the dependence of the predictive performance on the amount of data available to the modellers.

3 Experiment and models

3.1 Chicken Creek catchment

The Chicken Creek catchment (Fig. 1) is 6 ha in size and currently the largest artificial catchment worldwide. It was built in 2005 by the mining company Vattenfall Europe Mining in a scientific cooperation with the Brandenburg University of Technology (Gerwin et al., 2009). It is located in an open mining pit area in Lusatia, Germany. The catchment bottom consists of a 2 m thick tertiary clay layer placed on top of the reclaimed mining land. The clay layer forms a longitudinal catchment (450 m×150 m) draining into a depression at the bottom outlet. This depression is now a small lake which collects the outflow from the catchment. The longitudinal slope is 1 to 5% and, in transverse direction, it is 0.5 to 2% (Fig. 2a and b). A 2 to 3 m sand layer has been put onto the clay basement. It mainly consists of quaternary sand with variable fractions of 2 to 25% silt and 2 to 16% of clay. The slope of the surface is roughly given by the slope of the clay base but the thickness of the sand layer tapers off towards the lake. The clay layer hence forms the lake bottom. The catchment boundary is defined by the high edges of the clay layer. The catchment and the depression are separated by a V-shaped clay dam to funnel the deep seepage through a narrow outlet into the depression (Fig. 2b). The climate is temperate and humid. Annual precipitation in the past decades has varied from 335 mm (1976) to 865 mm (1974), and the mean annual temperature is about 9.3°C (1971–2000). The catchment remained unplanted after construction and natural re-vegetation is under way. The re-establishment of the natural vegetation is closely monitored (Gerwin et al., 2009).

3.2 Hydrological models

In this section we describe the conceptual differences of the ten models used by ten different groups for predicting the discharge. The models are listed in Table 1, followed by a brief description and the pertinent model references. We then discuss the underlying assumptions and the basic concepts such as the dimensionality of the various approaches from 1-D to 3-D, the different handling of surface processes, e.g. the links to the channel network. Furthermore we also highlight the similarities, e.g. the description of evapotranspiration.

3.2.1 Catflow

Catflow (Maurer, 1997; Zehe and Flühler, 2001a; Zehe and Bloeschl, 2004; Zehe et al., 2005) is a physically based model. It relies on a detailed process representation: soil water dynamics are represented by the Richards equation (mixed form), evapotranspiration by the Penman-Monteith equation, surface runoff by the convection diffusion equation which is an approximation to the 1-D Saint Venant equation. Surface saturation, infiltration excess runoff, re-infiltration of surface runoff, lateral subsurface flow and return flow can be simulated by Catflow. It has been used as a virtual landscape generator to investigate the role of initial soil moisture and precipitation in runoff processes (Zehe et al., 2005), and for simulating water flow and bromide transport in a loess catchment (Zehe and Flühler, 2001b), for process analysis within a slowly moving landslide terrain (Lindenmaier et al., 2005), among other applications. Here, we used the quasi-3-D hillslope module of the model.

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3.2.2 CMF

The Catchment Modelling Framework (CMF) is a multi-model toolkit. Work on it is still in progress (Kraft et al., 2008). The main objective of the model framework is to connect local scale transport models with lateral transport processes between neighbouring sites. So far, a model similar to DHSVM (Distributed Hydrology Soil Vegetation Model) (Wigmosta et al., 1994) has been implemented in CMF based on previous work by (Vaché and McDonnell, 2006). The model represents subsurface transport and water flow by the 3-D solution of the Richards equation. We used the two layer approach with one unsaturated and one saturated zone per cell, where the depth of the boundary between the two layers changes according to the saturation of the soil column. Infiltration and unsaturated percolation is calculated with the Richards equation, and the lateral saturated flow with Darcy's law. Infiltration excess and ponded water is directly routed to the stream network using a mass balance approach and re-infiltration is neglected.

3.2.3 CoupModel

The CoupModel is a processed-based model for coupled heat and mass transfer in soil-plant-atmosphere systems (Jansson and Moon, 2001). Vertical movement of water in a 1-D soil profile is represented by Richards equation for unsaturated flow, using a water retention function (Brooks and Corey, 1964) and an unsaturated hydraulic conductivity function (Mualem, 1976) for each soil layer. Lateral water flows are considered as a drainage system, with horizontal outflow from saturated soil layers to a hypothetical drainage pipe following the Hooghoudt drainage equation (Hooghoudt, 1940). Semi-2-D and semi-3-D representation is achieved by taking the outflow from one or several 1-D soil column as lateral inputs to a downstream column. The model considers freezing of soils, including effects on thermal and hydraulic conductivity (Stähli et al., 1996). Water and heat exchange between soil and atmosphere are calculated separately for different surface compartments including bare soil, snow, vegetation, and interception, with individual energy balance sub-models.

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3.2.4 Hill-Vi

The distributed conceptual hillslope model, Hill-Vi, was developed by Weiler and McDonnell (2004) to test the benefit of virtual experiments to hillslope hydrology. Subsequently, it has been modified to simulate nutrient flushing (Weiler and McDonnell, 2006) and the effects of preferential flow networks (Weiler and McDonnell, 2007).

Two storages define the saturated and unsaturated zone for each grid cell. The unsaturated zone with time variable water content is defined by the depth from the soil surface to the water table, whereas the saturated zone is defined by the depth of the water table to an impermeable soil-bedrock interface. The water balance of the unsaturated zone is calculated by precipitation input, actual evapotranspiration and vertical recharge into the saturated zone, described by gravity flow and using the equations by van Genuchten (1980). The lateral water exchanges in the saturated zone are controlled by Dupuit-Forcheimer assumption (Freeze and Cherry, 1979), based on an explicit grid cell approach, as presented by Wigmosta and Lettenmaier (1999).

3.2.5 HYDRUS-2D

HYDRUS-2D simulates the movement of water, heat and solutes in 2-D variably saturated porous media. Here, we simulate the water flow through the longitudinal transect of the catchment. The Richards equation is numerically solved for the saturated-unsaturated flow region considering vertical and horizontal flow under variable boundary conditions such as atmospheric conditions, free drainage or seepage faces. A detailed manual describes the relevant technical details (Simunek et al., 1999). Here, we use HYDRUS-2D in a catchment context. Lateral groundwater and unsaturated flow is represented by Richards' equation. All precipitation is infiltrating into the soil except in some scenarios during frozen soils conditions. Evapotranspiration is determinate by Penman-Monteith method.

3.2.6 NetThales

NetThales (Chirico et al., 2003) is a distributed, continuous, terrain-based hydrological model, simulating the hydrological processes distributed on a spatial network of elements, whose properties are defined by terrain analysis, which provides the spatial dimensions of the elements, the flow directions within the elements and the connectivity of the elements.

The water fluxes are calculated at the element scale with a computational time-step of one hour, accounting for the following processes: evapotranspiration, surface and subsurface lateral flow. Lateral surface and subsurface flow are modelled as one-dimensional within each element. The processes controlling the subsurface lateral movement are vertically lumped in a non-linear kinematic subsurface module. The vertical distribution of the water within the soil column is not modelled. No infiltration excess overland flow is simulated. All available water at the surface is assumed to infiltrate unless the soil column is not entirely saturated. Overland flow also occurs by exfiltration as the element soil column is saturated by lateral subsurface flow. The actual evapotranspiration is estimated as a fraction of potential evapotranspiration, depending on the soil water content within the root zone.

3.2.7 SIMULAT

SIMULAT (Diekkrüger and Arning, 1995; Bormann, 2001, 2008) is a physically based and time continuous hydrological SVAT model (Soil Vegetation Atmosphere Transfer), which has been developed to simulate local-scale (vertical 1-D) hydrological processes and nutrient fluxes. It solves the Richards equation to estimate infiltration and soil water fluxes and uses the approach by Feddes et al. (1978) to estimate transpiration and the approach by Ritchie (1972) for evaporation as a function of surface soil moisture. Lateral groundwater flow is represented by concentration time. Surface runoff is estimated by semi-analytical solution of the Richards' equation and the interflow based on Darcy's law. In this study, a quasi 2-D slope version of SIMULAT (Giertz et al., 2006)

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represented by 1-D soil columns is used where the slope is represented by a number of soil columns (e.g. three to four).

3.2.8 SWAT 2005

The Soil and Water Assessment Tool (SWAT), (Arnold et al., 1998) has been developed to simulate the long-term water and nutrient balance in mesoscale catchments. It is a physically based semi-distributed model (Gassmann et al., 2007). The surface of each sub-catchment is divided into Hydrological Response Units (HRU) corresponding to single combinations of a land use classes and a soil types. Each HRU is an idealized hill slope and there are no interactions between them.

Soil types are divided into layers for which several physical properties are required. Below the deepest soil layer stands a double groundwater system which was switched off for this study by using an impervious layer at the bottom of the soil. Surface runoff, lateral flow, and base flow contribute to total discharge out of each HRU and the SCS (Soil Conservation Service) curve number method.

Here, model version SWAT 2005 (http://www.brc.tamus.edu/swat/) has been used.

3.2.9 Topmodel

Topmodel is a semi-distributed hydrological model built around the concept of the topographic index, which is the ratio between the surface area that drains through a given location and the local slope (Beven and Kirkby, 1979; Beven et al., 1995; Beven, 2001). The topographic index represents the tendency of a location in the catchment to develop saturated soil conditions, and thus to generate saturated overland flow. Pixels with a similar topographic index are expected to behave hydrologically in a similar way and are therefore lumped in 16 classes.

Topmodel assigns a combination of stores to each topographic index class. This combination consists of root zone storage, unsaturated zone storage and saturated zone storage. Water enters the root zone, which is affected by evapotranspiration and overflows into the unsaturated zone. A time delay function regulates vertical flow from the unsaturated to the saturated zone. Finally, saturated subsurface flow is calculated by an exponential transmissivity function.

3.2.10 WaSiM-ETH

The Water balance Simulation Model (WaSiM-ETH) is a process-based and spatially distributed hydrological model based on raster cells. It is capable to calculate climate change effects in heterogeneous catchments and represents major processes of the water cycle (Schulla and Jasper, 2007). The model focuses on spatially variable atmospheric boundary conditions. It has been widely used in various contexts (Niehoff et al., 2002; Bronstert et al., 2007; Jasper, 2005). Here we use the version 7.9.11.

Except for the saturated soil zone model, all algorithms of the chosen model configuration are process-based (Table 2–4). Groundwater flow for one aquifer was described by a linear storage approach. The effective parameter for regionalization are generally obtained by calibration, but here we transferred them from another model application (Hölzel and Diekkrüger, 2008).

3.3 The data set

The data set provided to the modeller for the first step of prediction was selected to represent the initial information of an ungauged catchment as usually available or easily accessible in such cases. The following data were supplied for this modelling study:

- positions of instrumentation and of the area-wide 20×20 m observation squares as shown in Fig. 1,
- digital elevation models (DEM) of soil and clay layer surface,
- soil texture (mean value and standard deviation) at all observation squares,
- gully network and aerial photo (summer 2007) (Fig. 1)

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- hourly, daily and monthly record of weather data at Chicken Creek weather station (precipitation, temperature (air and soil at 10 cm depth), wind speed and direction, humidity, global radiation in the period from 29 September 2005 to 9 September 2008),
- yearly vegetation coverage in the observation squares (one per year),
- initial hydraulic head at 15 locations in the catchment observed on 19 September 2005 in the groundwater observation wells installed down to the clay surface.

The hourly data were used in all models except in HYDRUS-2D, where wind-corrected daily precipitation was used. CoupModel used wind-corrected hourly precipitation data.

None of the modelling groups visited the field site before their predictions were presented during the 1st workshop (Cottbus, 1./2. December 2008). During this workshop, the catchment was visited by all participants except by the SIMULAT and the Topmodel modellers.

The data set can be accessed at https://www-fs.tu-cottbus.de/SFB38/PUBLIC. Password request should be addressed to the corresponding author.

3.4 Conceptualization of catchment features

Since the shape of the catchment's soil surface as well as that of the clay base are well defined in the provided data set, all modelling groups assumed zero flow through the clay layer and across the lateral catchment boundary.

The Catflow modeller selected the single hillslope module instead of the full catchment model because the catchment is small, the runoff routing judged to have little effect on the overall response, and most of the gullies oriented in parallel. The two 2-D models, Catflow and HYDRUS-2D, modelled the catchment as a single slope (Fig. 3) and did therefore not include the gully network. The low hydraulic conductivities of the clay dam (Fig. 3) caused a rise of the water table upslope and increased the water content in the unsaturated zone.

Catflow assumes that the hillslope characteristics are uniform along the elevation contour lines and thus defined by a single parameter set. The Catflow modeller assumed that most of the dynamics happens downslope. In the upper slope the horizontal resolution was 10 m, in the middle slope 5 m, and lower slope 1 m. Because the near-surface processes were assumed to be important, the vertical resolution was 4 cm for the top 20 cm and below 20 cm. Since soil texture shows little variability along the slope and with depth, the soil (apart from the clay dam) was assumed to be a homogeneous loamy sand, parameterized after Carsel and Parrish (1988). Vegetation was assumed to be uniform. Grass coverage was estimated to be 5% and the vegetation height as well as LAI varied with the season.

The HYDRUS-2D group compared rainfall intensities and texture-derived estimates of soil hydraulic properties and concluded that surface runoff (not handled by HYDRUS-2D) would hardly ever occur. But HYDRUS-2D was allowed to generate runoff caused by different porosities and hydraulic conductivities upslope of the clay dam (Fig. 3). Soil parameters were estimated according to Schaap et al. (2001) using the routine implemented in the HYDRUS-2D program.

The HYDRUS-2D group computed six scenarios: two of them were carried out with the empirical pore tortuosity/connectivity parameter $L=0.5$ (Mualem, 1976) and four of them using $L=-0.78$ because recent studies reported considerable deviations from this value (Schaap et al., 2001). The precipitation events were split into two categories: (i) precipitation as an immediate input during the day of occurrence and (ii) precipitation on frozen soil being directly routed to discharge. This was done for L-parameter of 0.5 and -0.78. For the other two scenarios with $L=-0.78$-parameter, the hydraulic parameters were lowered for the unsaturated zone to create more discharge.

CMF was set up as fully distributed horizontally and vertically discretized as a two-layer model, dividing each soil column into a saturated and an unsaturated zone with time-variant layer thickness to shorten the computing time. The impact of the gully network on the flow regime was not modelled, because the information about gully shape and depth was lacking. However, the mere existence of gullies was included as an experimental model of infiltration excess into CMF, to produce overland flow during storm events.

The CoupModel group used a semi 3-D application to represent the catchment, mainly because of the high spatial resolution of the soil properties, vegetation coverage, and observed water balance components (to be provided later).The model was set up as 20 by 20 m grid cells centred on the soil sampling grid points (Fig. 1). This representation avoided interpolation between data points and kept the number of grid cells small. The thickness of the soil layer was calculated as the average difference between the elevation of soil surface and clay base averaged over the 20 by 20 m cell, and was not allowed to be smaller than 0.5 m for numerical reasons. Similarly, the information on the initial ground water levels was neglected since it was wrongly assumed that the catchment was older and already "initialized" at the start of the simulation period. However, the information about the gullies was incorporated in the parameterization of the surface runoff process by reducing the surface pool threshold to get a fast surface runoff response. Hydraulic properties of the soil layer were estimated from the numerous soil water retention data of Swedish sandy soils (Lundmark and Jansson, 2009).

The Hill-Vi modeller was set up the model with 10 by 10 m grid cells to assure an accurate representation of the topography. The study area is spatially discretized into approximately 3000 Thiessen polygons as an irregular digital elevation network. Due the lack of bulk density data, the computer program Rosetta (Schaap et al., 2001) was applied to estimate soil hydraulic parameters with hierarchical pedotransfer functions. Hill-Vi recalculates the drainage network for every time step so that the information of the gullies was not incorporated in the model. However, the Hill-Vi group assumed that surface runoff is important because of the distinctive gully network but they had difficulties to account for high hydraulic conductivities on one hand, and large amounts of surface runoff on the other. Preliminary test runs with a snowmelt routine did not yield notable effects. Snow was therefore disregarded in the model.

Topmodel does not account for several processes that do occur in the catchment, such as snowmelt, gully erosion. Its semidistributed nature does not allow to explicitly describing the clay dam. Although Topmodel could be customised to include such processes, the modeller decided not do so at this stage of the modelling process, in order to provide a reference performance. A 2 m resolution digital elevation map (DEM) was generated from the available elevation measurements and used to calculate the topographic index map. The index values were sorted into 16 classes.

Transmissivity, maximum root zone storage deficit, and flow velocity were estimated from the available catchment data. Only one parameter the shape of the recession curve was estimated from literature values.

The NetThales modellers performed a preliminary analysis for assessing the dominant runoff generation mechanisms. The aerial photo of summer 2007 showed evidence of surface runoff across the entire catchment. However, the modellers argued, by performing simulations with a 1-D Richard-based infiltration model, that no-infiltration excess runoff could be generated, given that the soil hydraulic conductivity (estimated with pedotransfer functions from soil texture) was very high compared with the maximum hourly rainfall intensity. Saturation excess runoff was therefore considered the only dominant runoff generation mechanism. A critical point of was assessing the parameters, which control evapotranspiration, and the "root-zone depth". Initially, it was assumed to be only 5 cm. This led to an annual runoff-rainfall ratio of 70%. Based on the modeller's knowledge of relatively dry Austrian and German catchments, the NetThales modellers considered this ratio being too high as one would expect an annual runoff ratio of no more than 30% in Brandenburg. As the catchment was still unvegetated a larger runoff ratio was expected, but certainly not 70%. Also the baseflow contribution of the initial simulations was considered too high in this climate. Thus the root-zone soil depth was increased to 30 cm, which reduced the runoff-rainfall ratio to about 50% at the annual scale.

The SIMULAT user used a 1-D model to represent the hydrological dynamics because it was assumed that overland flow as well as interflow and therefore neighbourhood relations do not play a major role in the catchment. The catchment was represented by the 20 by 20 m grid based on the available data (Fig. 1) and neglected the information on existing gullies. The clay dam was considered as a locally shallow soil layer but this did not affect the concentration time of subsurface flow. Lateral transport processes were considered by a concentration time based approach neglecting neighbourhood relations. The thickness of the soil layer was directly taken from soil data set. The SIMULAT modeller treats the soil to be compacted because it was dumped and shaped with large machines and used he highest bulk density class according to Adhoc AG Boden (2005). Based on the soil and the soil layer information it was concluded that subsurface runoff exceeds surface runoff with a minor contribution of interflow making baseflow the dominant runoff component.

The SWAT model describes a shallow and a deep groundwater compartment but the latter was switched off due to the presence of the clay layer.

WaSiM-ETH reduced the calculation effort by an aggregating the DEM to a 5 m×5 m raster. The aggregated DEM does not resolve the gully structures nor the clay dam and are not considered in the model. Main principle for soil parameterisation was "as simple as possible". Therefore, the data from each soil depths were aggregated to a single average value was conducted with catalogue values from the AdHoc-AG Boden (1999) because of data about soil compactness was available. WaSiM-ETH did not consider macropores because the soil material has been recently dumped and repacked and also because of the initial state of the vegetation. In WaSiM-ETH the effective parameters are upscaled measurement-derived parameters, which are gathered "normally" during the calibration by measured outputs. Therefore, they were taken from another headwater catchment in Germany (Hölzel and Diekkrüger, 2008). The sparse vegetation was neglected and therefore, only evaporation losses are included.

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3.5 Process concepts and implementation

3.5.1 Infiltration, saturated and unsaturated flow

The saturated and unsaturated flow was simulated either as 1-D linear storage approach (CoupModel, Topmodel, WaSiM-ETH), 1-D Richards equation (SIMULAT), 2-D horizontal or complete 3-D. For calculating 2-D and 3-D saturated flow Richards equation was used (Catflow, HYDRUS-2D) or the Dupuit-Forchheimer assumption (Hill-Vi), or Darcy‘s law (CMF) (Table 2). Unsaturated flow was mostly calculated by the Richards equations. Topmodel used an exponential transmissivity function. Detailed information is provided in Table 2.

In the all models except SWAT, Topmodel, and WaSiM-ETH, infiltration was handled as unsaturated flow and represented by using Richards equation, the latter represented the infiltration excess mechanism. SWAT used the SCS curve number method and Topmodel and WaSiM-ETH used the Green-Ampt model.

In some scenarios HYDRUS-2D routed 10% of the precipitation directly to the bottom layer above the clay base representing preferential flow, e.g., due to hydrophobic conditions in summer. This was achieved by introducing a flux boundary condition at the bottom. In a similar way, precipitation was direct routed to surface runoff due to frozen top soil in frost periods and was not accumulated as snow.

3.5.2 Stream flow routing

The catchment is relatively small and has a maximal length of 450 m. Therefore, some modelling groups assumed that stream flow is of minor importance (CoupModel, Hill-Vi, and HYDRUS-2D). Catflow and WaSiM-ETH approximate the stream flow as a kinematic wave using either the 1-D Saint-Venant or the Manning-Strickler equation. Simple mass balance approaches were used by CMF and NetThales. SIMULAT assumed a concentration time based approach and Topmodel a simple time delay function so that they both neglected the gully network. SWAT used the gully network map to define the stream-network. They neglected the lake to allow ArcView to define a stream network routing water to the lake's outlet.

3.5.3 Snow accumulation, snowmelt and interception

The snow accumulation and melt had a strong influence in the winter 2005/06 with a period of 42 days below 0°C with 15.6 mm precipitation but was not important for the other winter periods. Snow accumulation and snowmelt were considered by CoupModel, SIMULAT, SWAT and WaSiM-ETH. These models are using the energy balance and temperature index or degree day methods to accumulate and melt the snow (Table 3). The other models do not include snow nor soil frost. The HYDRUS-2D scenarios did not account for snow accumulation and snow melt. Some scenarios included the frozen soil condition by routing the precipitation directly to surface runoff.

Interception was mostly neglected because vegetation was very sparse in the initial phase after catchment construction. However, the vegetation is rapidly increasing and its impact will get a larger importance for further predictions. Catflow, CMF, CoupModel, SIMULAT and WaSiM-ETH explicitly describe the interception losses from plant surfaces. CMF used a constant 20% loss of all precipitation events whereas the other four models were using a leaf-area-index (LAI) dependent approach (Table 3).

3.5.4 Evapotranspiration

Potential evapotranspiration (PET) was calculated by most models using the Penman–Monteith equation. Hill-Vi used the Turc equation and SWAT relied on the Hargreaves equation. Additionally, the CoupModel calculated soil and snow evaporation based on a surface energy balance. For all models the actual evapotranspiration (AET) was determined on the basis of PET in relation to the available soil water status. The CoupModel also includes the root zone soil temperature as a parameter in this calculation (Table 4).

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3.5.5 Clay dam

All 3-D models except CoupModel, Topmodel, and WaSiM-ETH incorporated the subsurface clay dam using the two DEMs for the soil and the clay base, which reduced the depth of the sandy soil layer above the clay dam to a few centimetres. The clay dam had no influence on the calculation of lateral flow components (concentration times) in SIMULAT. In WaSiM-ETH, the clay dam was neglected by using a constant thickness for the soil layer of 181 cm. Topmodel implemented the subsurface dam by calculating the topographic index based on the subsurface topography rather than the surface topography but the topographic index distribution function did not show large differences. The soil thickness was constant for the whole catchment (300 cm). CoupModel was not recognising the dam itself, due to limited understanding of the construction. In the model, the wall was smoothed out to a large extent, since the sand layer thickness was calculated from the average difference between the sand surface elevation and the base layer elevation over the 20 by 20 m calculation cells. Further more, the sand layer thickness was not allowed to be smaller than 0.5 m, for numerical reasons. Thus, the clay wall was only weakly represented as a shallower sand layer. The 2-D models (Catflow and HYDRUS-2D) used a constant thickness and a reduced hydraulic conductivity to represent the clay dam (Fig. 3).

The 2-D models had to mimic certain features of the flow domain such as the presence of the clay dam, which is supposed to funnel the subsurface flow towards a narrow outlet into the lower part of the catchment. Catflow and HYDRUS-2D assigned a low hydraulic conductivity to the V-shaped subsurface dam (Fig. 3). HYDRUS-2D simulations were run with a low porosity soil material being placed uphill of the dam to mimic the funnelling effect of the subsurface dam. Its porosity was about one fifth of the remainder of the soil and the saturated hydraulic conductivity reduced by the same factor. This forced the streamlines towards the soil surface above the clay layer producing a seepage face, which allows runoff generation (Fig. 3).

3.6 Parameterization of physical soil properties

All modelling groups received only information on soil texture for describing the physical properties of the saturated and the unsaturated zone. This was the basis for estimating the porosity and the saturated and unsaturated hydraulic conductivity. Catflow, CMF, HYDRUS-2D, and NetThales considered hydraulic conductivity being a constant for the whole catchment. CoupModel, Hill-Vi, SIMULAT, SWAT, Topmodel, and WaSiM-ETH used hydraulic conductivities with a spatial variation based on the soil particle distribution.

In case of NetThales, SIMULAT, and SWAT, the parameters were estimated on the basis of the transfer functions of Rawls and Brakensiek (1985) (Table 5). They obtained similar mean saturated hydraulic conductivities K_{sat} (NetThales: 50 mm/h; SIMULAT: 61 mm/h; SWAT: 75 mm/h). Also, the modellers of HYDRUS-2D (54 mm/h) and Topmodel (58 mm/h) obtained a value in that range using the approach of Saxton et al., 1986). Slightly larger K_{sat} were used in the CoupModel and Hill-Vi (90 mm/h, calculated after Schaap et al., 2001) and CoupModel (84 mm/h, in analogy to Swedish sands – Lundmark and Jansson, 2009). WaSiM-ETH used a German soil definition (Adhoc AG Boden, 2005) and obtained 118 mm/h. Catflow used the approach of Carsel and Parrish (1988) and estimated a value of 146 mm/h for the aquifer. The largest hydraulic conductivity was used by CMF. CMF derived the hydraulic properties using the German soil mapping manual (AG Boden, 1994). Since in situ saturated conductivity is in most cases underestimated a higher value of 417 mm/h was estimated.

The porosity n (m^3/m^3) was in all cases estimated to be in the range of 0.40 to 0.45. The models which used a smaller porosity were CMF (0.35) and SIMULAT (0.34) both using the German soil definition (Adhoc AG Boden, 2005), which was also used by WaSiM-ETH. The German soil definition, the estimators of Carsel and Parrish (1988) and Saxton et al. (1986), and analogy to Swedish sands do require bulk density nor organic matter content, information which was not available in this case. The water content at the wilting point (m^3/m^3) was estimated within in small range between 0.045

and 0.090 and the field capacity between 0.125 and 0.280 (m^3/m^3).

The hydraulic parameterization of the unsaturated zone was mostly done using the method of Mualem (1976) and van Genuchten (1980) (Catflow, Hill-Vi, HYDRUS-2D) and that of Brooks and Corey (1964) (CoupModel, NetThales, SIMULAT). The relative saturation S_e is defined by

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{1}$$

with θ being the water content (m^3/m^3), θ_r the residual (m^3/m^3) and θ_s the saturated water content (m^3/m^3). The model of Brooks and Corey (1964) describes the hydraulic conductivity by

$$K(S_e) = K_{\text{sat}} S_e^{3+\frac{2}{\lambda}} = K_{\text{sat}} \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^{3+\frac{2}{\lambda}} \tag{2}$$

$$S_e = \left(\frac{h_b}{h} \right)^{\lambda} \tag{3}$$

and van Genuchten (1980) by

$$S_e = \frac{1}{(1 + (\alpha h)^{n_{vG}})^m} \tag{4}$$

$$K(S_e) = K_{\text{sat}} S_e^L \left\{ 1 - \left[1 - \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^{n_{vG}} \right]^m \right\}^2 \tag{5}$$

$$m \approx 1 - \frac{1}{n_{vG}} \tag{6}$$

with h being the matric potential (m), h_b the air entry pressure (m), $K(\theta)$ and equivalently $K(S_e)$ the unsaturated hydraulic conductivity (mm/h), K_{sat} the saturated hydraulic

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conductivity (mm/h). L is an empirical pore tortuosity/connectivity parameter usually assumed to be 0.5 (Mualem, 1976), but was varied in some HYDRUS-2D simulations because more recent studies revealed considerable deviations from this value (Schaap et al., 2001). The λ parameter is the pore-size index, which is related to the m, n_{vG} parameters. If $\alpha \cdot h_b \gg 1$ then

$$[1 + (\alpha h)^{n_{vG}}]^{-m} \approx (\alpha h)^{-mn_{vG}} \quad (7)$$

and

$$S_e \approx \frac{(\alpha h)^{-mn_{vG}}}{(\alpha h_b)^{-mn_{vG}}} = \left(\frac{h}{h_b}\right)^{-mn_{vG}} = \left(\frac{h_b}{h}\right)^{\lambda} \rightarrow \lambda = mn_{vG} \quad (8)$$

$$\lambda = \left(1 - \frac{1}{n_{vG}}\right) n_{vG} = n_{vG} - 1 = \frac{m}{1-m}\,. \quad (9)$$

The Brooks-Corey λ parameter (used by some models) is represented in terms of n_{vG}. WaSiM-ETH used the smallest n_{vG} (1.13). Also CoupModel used a constant n_{vG}=1.42. HYDRUS-2D used an n_{vG} between 1.15 and 1.88. Catflow used soil specific n_{vG} (loamy sand: 2.28 and sandy clay loam: 1.48). The models CMF, Hill-Vi, and SIMULAT assumed a spatial variation of n_{vG} from 1.15 to 1.37, 1.37 to 3.57, and 1.56 to 2.33, respectively. NetThales, SWAT, and Topmodel did not account for unsaturated flow nor did they use Richards equation for representing the unsaturated flow. In Topmodel the flow between the unsaturated and saturated storage is controlled by one parameter representing the time delay per unit storage deficit (Gallart et al., 2007; Choi and Beven, 2007). The parameter set used by the modelling groups is listed in the Annex.

3.7 Initial conditions

All models require defined initial conditions, in particular for guessing the initial volumetric soil water content $\theta(t_0)$ (m^3/m^3) but this information was not available. SIMULAT

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estimated the soil to be dry. Other models were run to initialize this variable and its spatial variation: Hill-Vi trice (0.20±0.25) and CMF (0.22±0.06), SWAT ($\theta(t_0)$=0.11±0.04) and WaSiM-ETH ($\theta(t_0)$=0.27±0.05) in each case once. CMF used the existing 3 year period of rainfall data for the initialization run, with a wet year in 2008. Catflow was run twice to find stable initial conditions, in this case not for soil water content but for suction head. Pre-runs of the models were used to find a quasi-steady-state condition, which can be used as initial condition. WaSiM-ETH archived system-stable initial conditions of the whole model period using model intern default values.

CoupModel initialized it at field capacity. Hydrus-2D was run with different $\theta(t_0)$. The wet scenarios assumed a constant matric potential of −0.3 m, whereas the dry runs started with a matric potential of −1.0 m. When model runs were started assuming dry soil, the discharge was too little to fill the lake at the outlet of the catchment within a period of about one year. Since the presence of the lake was known to the modellers, such model runs were rejected. SIMULAT assumed a matric potential of −3 m at the bottom of the sand layer and decreasing values towards the soil surface assuming hydrostatic equilibrium. Topmodel is initialised with an initial subsurface flow parameter of 0.017 mm/h per unit area which was estimated from the mean annual rainfall of 496 mm and the assumed runoff coefficient of 0.3.

The groundwater levels were part of the initial data set but none of the models expect SIMULAT made use of it because the case of an "empty", newly constructed catchment without initial groundwater is mostly not considered for the models and would lead to numerical problems. Therefore, Catflow, Hill-Vi, and WaSiM-ETH used also a warm-up run for the formation of a groundwater table. HYDRUS-2D defined the groundwater table at 40 to 60 cm within a soil cover of constant thickness (1.90 m) (Fig. 3).

4 Results and discussion

The Chicken Creek catchment drains into a lake (Fig. 1). The gauge for measuring the catchment discharge is located at the outflow of the lake. The inflow into the lake is not monitored. Since several models did not consider the lake as a buffer compartment, the catchment outflow into the lake was determined by subtracting the lake storage changes and the precipitation into the lake from the measured lake outflow and adding the evaporative losses from the lake The back calculated inflow into the lake is the standard against which the modelled discharge is compared.

We first compare the predictions and observations in terms of the water budget, discharge, and groundwater levels. The predictions are presented for the three hydrological years from November through October (2005/2006, 2006/2007, and 2007/2008 only until 8 September 2008). These periods are referred to as the 1st, 2nd, and 3rd year.

4.1 Water budget

Below, the annual values of the 1st, 2nd, and 3rd year are reported as triplets (1st, 2nd, and 3rd year). Precipitation was given as an input as 372.5, 565.5, and 511.4 mm (Tables 6a–c). All models used these values. In CoupModel and HYDRUS-2D a wind correction for the rainfall was used, which resulted in higher precipitation. In CMF a 20% interception loss of the total precipitation (Table 3) was assumed. This value neglects the sparse vegetation and overestimates the interception losses.

The offered choice between three sets of precipitation data (hourly, daily, and monthly values) did not result in different input conditions because eight models used the hourly data set. Only Hydrus-2D and SWAT used daily data. This indicates that input data with a high temporal resolution are preferred by process based models for predictions in ungauged basins. Different input data resulted from including a wind dependent correction, which somewhat increased precipitation (CoupModel and Hydrus-2D) whereas subtracting the interception losses decreased them (CMF).

For reference, the potential evapotranspiration (PET) of the Chicken Creek catchment was calculated using grass-referenced Penman-Monteith using standard parameterization (Allen et al., 1994) resulting in 779, 782, and 511 mm/y. Using the grass-referenced PET most likely overestimates the role of the sparse vegetation in the

Chicken Creek, so PET is likely smaller. PET predicted by the ten model ranges from 146 to 807 mm/y (1st year). The values for the 2nd and 3rd year vary in the same range.

Although most models predicted a PET in the order of 600 to 800 mm/y, few values were surprisingly much smaller, e.g. the 139 mm/y (CMF) and the 421 mm/y (NetThales, 2nd year, Table 6b), despite the fact that most groups used the Penman-Monteith method and that the information about vegetation coverage was available. Therefore, the differences originate from the parameterization of the models, in case of CMF due to the constant PET-independent interception loss and the time-invariant sparse vegetation for all three years (LAI=0.1, plant height 10 cm).

HYDRUS-2D and Topmodel did not account for any vegetation and got both about 600 mm/y for the 1st and 2nd year. The 3rd year cannot be used for this comparison because HYDRUS-2D used a shorter time period than the other models. SIMULAT and WaSiM-ETH also estimated similar PET (680 and 700 mm/y, respectively) using a sparse vegetation (plant height from 5 to 15 cm and LAI between 0 and 1) although they used different stomatal resistances (50 and 150 s/m, respectively). Catflow and CoupModel did not output PET.

SWAT calculated the highest PET using the Hargreaves equation and Hill-Vi the second highest (Turc equation.) In SWAT a relatively well established plant cover (maximum LAI=2.68, plant height 50 cm) and the lowest stomatal resistance were assumed. The second highest PET was calculated by Hill-Vi. The Turc equation, which yields a grass-referenced PET, excluding additional information about the vegetation, overestimates the role of the vegetation and therefore PET.

The reference actual evapotranspiration (AET) of the Chicken Creek was estimated using a modified Black approach (Black et al., 1969; DVWK, 1996), which yielded 163, 165, and 137 mm/y. Comparing the ratio between PET and AET only Hill-Vi predicted a similar behaviour. All other models overestimated systematically the actual evapotranspiration as the ratio between actual and potential ET.

The measured discharge of the Chicken Creek was 113, 105, and 113 mm/y.

The predicted discharge range is between 12 and 306, 27 and 346, and 76 and 329 mm/y. CMF predicted the significantly lowest PET and the lowest AET, whereas Hill-Vi predicted high PET but a low AET. Catflow produced AET values of 161, 170 and 163 mm/y with a vegetation cover of 5%, a LAI ranging between 1 and 2, vegetation height ranging from 13–40 cm (both depending on the season) and a stomatal resistance of 200.

AET is in all models a function of PET and of the soil water status. Since the range of PET is similar for most models, the differences must originate from the actual soil water content. The main inputs and parameters beside precipitation were the available field capacity, the hydraulic conductivity K_{sat}, and the α-parameter of the $\theta(h)$ and the $K(\theta)$ functions. The groups used different pedotransfer functions (Table 4) to estimate the hydraulic soil parameters from soil texture given at each observation square (Fig. 1).

The mean saturated hydraulic conductivity was predicted within a small range from 54 to 146 mm/h. Only CMF used a much larger K_{sat} (417 mm/h). The van Genuchten parameter n_{vG} varied from 1.13 to 2.28. The lowest value is used by WaSiM-ETH and introduces a small reduction of $K(S_e)$ on small changes in S_e. This leads to a larger water holding capacity in the top layer of the soil. Therefore, AET in WaSiM-ETH is considerably larger than in Catflow, which uses the largest n_{vG}-parameter. The low AET of Hill-Vi is a consequence also of the parameterization and of the model structure. Due to the assumed saturated hydraulic conductivity and low L, only small amounts of water are stored in the unsaturated zone, which reduces the water content dependent AET. The influence of the assumed K_{sat} can be also seen from the AET predicted by CMF. Infiltration sensitively changes the water table in Hill-Vi leaving only a shallow unsaturated zone, which results in a reduced AET. CoupModel used the second lowest n_{vG} and calculated the second highest AET. HYDRUS-2D predicted the largest AET using a low to intermediate n_{vG}. The changes in L from the standard value 0.5 to -0.78 resulted in a lower AET. NetThales calculated an AET just below the mean of all models using the smallest K_{sat}. In comparison to other models NetThales neglects the vertical redistribution of water within the vertical soil column so that there is no unsaturated

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flow. The water holding capacity in NetThales belongs to the available field capacity of the sand (0.11). SIMULAT and SWAT predicted an AET just above the mean. Their K_{sat} are very similar. SIMULAT uses an n_{vG} in the upper range.

The measured discharges were 164.6, 171.1, and 113.6 mm/y. Expressed as percentage of the measured discharge, the predicted discharge ranges from 10 to 221%, 19 to 329%, and 30 to 290% (Fig. 4a–c). The hydraulic soil properties affect discharge as well. The models predicting a low AET predicted generally a larger discharge due to the faster vertical water movement through the unsaturated zone. The hydraulic conductivities lead to no or little surface runoff and rapid infiltration, which in turn leads to mainly interflow and baseflow.

The catchment was built by dumping relatively dry soil on the clay base so that the groundwater gradually filled up after construction. The groundwater storage was 35.2, 68.9, and 161.9 mm at the end of the three years, determined by the water-table fluctuation method (Meinzer, 1923; Healy and Cook, 2002) using the mean groundwater table rise and the mean porosity. These data neglect the storage in the unsaturated zone. The lack of instrumentation in the unsaturated zone did not allow the estimation of changes in soil moisture. The predicted storage changes (sum of ground and soil water) varied between −63.0 and 25.4, −8.8 and 75.8, and −38.9 and 44.2 mm. The initial water content in the first year prior to the warm-up runs was too high, resulting in a constant outflow of the catchment.

The modellers neglected the initial dry state of the artificial catchment (see Sect. 3.7) and the initial groundwater table was neglected (Fig. 5a and b) and all models used too large soil water contents. Most models assumed field capacity or estimated the soil water contents from pre-runs. Therefore, the predictions cannot be compared with the observed data but can be put in relation to each other. Most models except SIMULAT predicted a loss of soil- and groundwater for the first year. That is not very surprising because the precipitation was below the mean precipitation.

The errors in the internal model mass balance ΔM_{error} (mm/y) are

$$\Delta M_{error} = P - AET - Q - \Delta S \quad (10)$$

with precipitation P (mm/y), simulated actual evapotranspiration AET (mm/y), simulated discharge Q (mm/y) and simulated soil- and groundwater storage changes ΔS, the latter being sometimes in the range of 25% of the precipitation (Table 6a–c). CoupModel, Hill-Vi, HYDRUS-2D, NetThales, Topmodel and WaSiM-ETH produce a ΔM_{error} of less than 5% of P. Catflow 7% and CMF, SIMULAT and SWAT more than 10%. CMF had the highest ΔM_{error} (up to 25%), probably because it is a recently developed code under construction.

The errors of up to 10% for the model SWAT are due to the fact that SWAT was not designed model for small catchments. Therefore, the representation of detailed processes within an artificial, newly constructed small catchment caused relatively large errors.

The errors in the measured mass balance were even larger. In the second year the error was 40% of the total precipitation. The errors are due to the fact that AET was not measured but estimated according to Black et al. (1969; DVWK, 1996). This approach was developed for bare soils and neglects the effect of vegetation. This approach was developed for bare soils and neglects the effect of vegetation. Additionally, the changes in soil storage are neglected. The error in the first year was mainly due to the neglected soil water storage changes, whereas, the error in the last year was mainly due to a denser and taller vegetation and therefore due to the AET estimation.

4.2 Discharge dynamics

The predicted discharge is given in Fig. 4a–c for the three years. NetThales, SIMULAT and Hill-Vi produced a high base flow compared to the other models, 35, 25, and 50 m^3/d, respectively. Hill-Vi used the Dupuit-Forchheimer assumption (Freeze and Cherry, 1979; Wigmosta and Lettenmaier, 1999) for saturated flow and a large K_{sat} of 90 mm/h. NetThales and SIMULAT, both not using a deterministic groundwater flow method, used a K_{sat} of 50 and 75 mm/h, respectively. Catflow predicted a baseflow of 20 to 25 m^3/d based on Richards equation and very large hydraulic conductivity of 146 mm/h. SWAT and HYDRUS-2D showed a seasonally differing baseflow. SWAT predicted a winter base flow of 5 m^3/d, which increased up to 15 m^3/d in spring. HYDRUS-2D predicted consistently a minimum baseflow of nearly zero in autumn and winter and a maximum in spring (10 to 20 m^3/d). SWAT uses the Hooghoudt (1940) approach and a K_{sat} of 75 mm/h, whereas HYDRUS-2D Richards equation and K_{sat} of 54 mm/h. The other models (CoupModel, Topmodel, and WaSiM-ETH) predicted less than 10 m^3/d baseflow. These three models use all different flow equations (Hooghoudt (1940), time delay function, and linear storage approach, respectively) and K_{sat} of 84, 58, and 118 mm/h. CMF predicted nearly no base flow using Darcy's law and largest K_{sat} of 420 mm/h.

All models except CoupModel infiltrated nearly all precipitation directly into the soil. The infiltration methods (Table 2) are based on K_{sat} as limiting parameter. The large K_{sat} allows only marginal direct runoff (Table 7a–c). The processes causing substantial baseflow occur in the saturated zone. Models with a larger water holding capacity – due to a small van Genuchten parameter – predicted large AET and therefore lower baseflow because the water was lost through evapotranspiration (e.g. CoupModel and HYDRUS-2D) and vice-versa (e.g. Hill-Vi and SIMULAT) (Sect. 4.1). Catflow defined the discharge from the 0–100 cm as interflow assuming the gullies to be approximately 100 cm deep in the lower part of the slope in which the water enters. The outflow from the slope at depth 100–200 cm is defined as baseflow. Catflow used large hydraulic conductivity, a van Genuchten parameter in the middle of the whole range of all modellers and predicted a large baseflow. The models with high subsurface flow routed more than 60% of the total discharge via baseflow (SIMULAT, Hill-Vi, and Catflow). SIMULAT could not calculate interflow because the model structure is not able to determine it within a single layer system (only water which releases by damming soil layer except the base layer is described as interflow). NetThales does not make any distinction between base flow and interflow.

The partitioning between baseflow and surface runoff in Topmodel is mainly controlled by two parameters: the shape of the recession curve and the maximum root zone storage deficit. Contrary to maximum root zone storage deficit, the shape of the recession curve is often a very sensitive parameter in the model. Errors in the estimation of m have therefore a large impact on the partitioning. Since the shape of the recession curve has little physical meaning, it was estimated from literature values (Beven, 2001). The shape of the recession curve depends on porosity and storage capacity so that overestimating the porosity and storage capacity would obviously result in underestimating surface runoff and vice-versa. In this study, the lack of a physical interpretation of the shape of the recession curve may be seen as a problem for applying Topmodel in this artificial catchment because there is no analogue for this kind of a catchment in the literature.

NetThales and Topmodel predicted the most immediate and strongest response to precipitation. During intense spring or summer storms their discharge often exceeded 400 m^3/d, in a few cases even 800 m^3/d (Fig. 4a–c).

A strong response to precipitations events is also predicted by SWAT and CMF but they only simulated runoff for very large events. A pronounced response of up to 300 m^3/d was also predicted by SWAT and CMF, but only for very large events. SIMULAT predicted also high discharges during some strong events with a slow recession of up to one month. Table 7a–c show that almost all of this discharge was simulated as baseflow. The discharge simulated by Hill-Vi during precipitation events was relatively low compared to those of the other models and reached a maximum of 170 m^3/d. HYDRUS-2D predicted some peak discharges in the 1st year but it nearly not responded to the intensive events in the summer of the 2nd and 3rd year. Changing the L-factor increased the response somewhat, but in comparison to the much larger discharge of the other predictions, this can be neglected. Catflow and CoupModel predicted the smallest response to the very strong summer events (Fig. 4a–c). CoupModel

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showed the lowest discharge of all models whereas Catflow predicted mainly baseflow.

The calculated direct runoff played a minor role in total simulated discharge (Table 7a–c). Especially in the 1st year no direct runoff was predicted at all. CoupModel produced the largest surface runoff in relative terms, about 80% of the total discharge because it simulated the second lowest total discharge with a maximum direct runoff of 62 mm/y in the 3rd year. Topmodel simulated larger direct runoff (95 mm/y) in this period which was only about 40% of the total discharge.

The soil properties also drive the discharge and the discharge components. Predicted discharge of the other models is mainly interflow and baseflow. WaSiM-ETH and Hill-Vi are the only models which separate the discharge into all three components. Hill-Vi identified about 97% of the discharge as subsurface flow using a K_{sat} of 90 mm/h. WaSiM-ETH gave a similar result but with about 80% interflow, about 20% baseflow, and a very small amount of surface runoff. Although the hydraulic conductivity was larger than in Hill-Vi, most of the water did not reach groundwater table before it laterally discharged. Catflow predicted only interflow (40%) and baseflow (60%) using a higher hydraulic conductivity of 146 mm/h. Interflow was assumed to be released from the upper 1 m of the soil so that it can enter the gullies. The clay dam developed a build-up of the groundwater table which resulted in groundwater discharge. SIMULAT quantifies interflow and baseflow, but interflow was not simulated at any time step. The clay dam had no influence on these predictions because the concentration time method does not consider any barrier. Figure 4a–c indicates that the predicted subsurface flow of SIMULAT is baseflow given the long and slow recession of the discharge. CMF and NetThales did not provide information about the different discharge components.

The models predicting low AET predicted generally higher discharge due to the faster vertical water movement through the unsaturated zone (Sect. 4.1). The chosen hydraulic conductivities of all models except CoupModel resulted in either no or little surface runoff and high infiltration which leads to mainly interflow and baseflow. But CoupModel predicted the second lowest discharge due to the second highest AET. The water was stored a long time in the upper soil and resulted in a high AET and often also in surface runoff due to the saturation. Therefore, CoupModel predicted the highest amount of surface runoff and the second lowest total discharge.

This can be also seen in Fig. 5 showing the ratio of the measured discharge to maximum and minimum discharge predicted by the ten models. It is obvious that maxima predicted (about 300 times) as well as minima of predicted baseflow (about 80 times) are much larger than the observed baseflow. However, the maximum predicted discharge during the strong spring and summer events reported about 400 times more discharge than measured. The models which predicted low discharge at that times underestimate the observed discharge. Only the models predicting the maximum discharge show similar rain results than the observed during events with small intensities but they predicted not more than their baseflow. The minimum discharges underestimate the observed ones by a factor of about 100. This also indicates that the predicted surface runoff is underestimated and baseflow overestimated.

Snow melt and frozen soil conditions were evident in the first winter 2006 (9 January–7 February 2006). No model was able to predict the discharge during the melt periods. The frozen soil period lasted 30 days and 18.7 mm precipitation occurred during that time. The maximum observed discharge was detected to be 55 m^3/d. The following winter periods were warmer with minor soil frost being observed.

4.3 Groundwater levels

The observed groundwater dynamics are typical for central Europe with a groundwater table rise after the winter period and a drawdown during the vegetation period despite the sparse vegetation cover of the catchment (Fig. 6). Both observation wells were influenced by the clay dam. The water-table fluctuation of the neighbouring observation wells appear to be closely linked.

Figure 6 illustrates the groundwater fluctuations at the observation wells F4 und L4 and the corresponding predictions of Catflow, CMF, Hill-Vi, HYDRUS-2D and WaSiM-ETH. Observation wells F4 and L4 were chosen because they are located in the central part of the catchment (Fig. 6) and are also represented by the 2-D models (Catflow and

HYDRUS-2D). The measured fluctuations exhibit an increasing trend over the three years. This is also evident from the positive storage term in the water budget (Table 6a–c). Since there was no information on the initial soil water conditions, it was handled differently by the various modellers (see Sect. 4.7). The same applies to the groundwater situation. Surprisingly, none of the groups used the information that as present no groundwater at the onset.

All models predicted similar fluctuations at the two observation wells which indicate that the K_{sat} at the two positions is similar (see Annex). The predicted groundwater tables showed no influence of the clay dam. The groundwater fluctuations F4 and L4 predicted by CMF, Hill-Vi and WaSiM-ETH were fairly similar and showed small variations and no seasonal trend. CMF used the Dupuit-Forchheimer assumption and predicted a groundwater table drawdown of about 50 cm in the 1st year, a rise of 50 cm in the 2nd year and a nearly constant water table depth in the 3rd year. Using Richards equation for groundwater flow, Hill-Vi predicted a non-seasonal fluctuation of about 30 cm. WaSiM-ETH calculated the groundwater by linear storage approach and gave only a single average groundwater table depth for the whole catchment. The simulated groundwater table in the first year dropped by 50 cm and remained constant afterwards. A constant groundwater table within a catchment throughout the year is the result of a balance between recharge and discharge at all times. All three models used the K_{sat}. Hill-Vi predicted the highest discharge but used the lowest K_{sat} of the three models. Hill-Vi reported that discharge was almost entirely subsurface flow but did not provide direct information on groundwater flow. The estimated initial groundwater table was near the surface. WaSiM-ETH predicted the lowest baseflow of 22 to 30 mm/y and used the lowest hydraulic conductivity of the three models. The total porosity of all three models was 0.38.

Catflow and HYDRUS-2D were the only models which showed a seasonal fluctuation of the groundwater table. Catflow showed a maximum amplitude of 80 cm with rapid changes. They are a consequence of the model structure because a grid cell is either completely saturated (=groundwater) or not. The use of a cell thickness of

20 cm produced groundwater table jumps of 20 cm. The amplitude of the groundwater table height by HYDRUS-2D are calculated for six scenarios. The fluctuations of HYDRUS-2D are the largest of all models and exceeded the measured fluctuations. They are about 1 m and constant throughout the simulated period. The two scenarios by HYDRUS-2D shown in Fig. 6 were calculated with two different L-factors, the lower groundwater table being predicted using an L-factor of 0.5 and the higher for $L = -0.78$. Both scenarios have been started with the same initial groundwater table and developed differently during the 1st year. The groundwater tables of HYDRUS-2D fluctuated nearly in parallel during the 2nd and the 3rd year. Catflow and HYDRUS-2D simulate the same pattern of the fluctuation. The difference in the amplitude is due to the different K_{sat}. Catflow assumed a hydraulic conductivity which is thrice as large (146 mm/h) than the one which is used with HYDRUS-2D (54 mm/h). Neither Catflow nor HYDRUS-2D predicted the sharp groundwater table rise toward the end of each winter period or the long and very slow drawdown during spring, summer and fall months.

Neglecting the given initial groundwater data and estimating too large initial soil water content, resulted in the situation that none of the models predicted the observed soil- and groundwater storage.

5 Conclusions

Ten modelling groups used ten different catchment models to predict the major hydrological variables of the small artificial catchment Chicken Creek based on the same small data set. The observed discharge was not known to the modellers. This constellation of a minimal set of easily accessible data mimics the modeller's situation when confronted with predicting the response of ungauged catchments.

The initial soil water content was not available. Most of the models estimated it by pre-runs or by assuming field capacity at a certain value. Also, the initial groundwater situation was determined by pre-runs, despite the fact that it was part of the provided data. This influenced the predictions because the soil and groundwater compartment had not to be filled up within the simulation period as observed in the catchment. Therefore, the steadily increasing groundwater table was not reproduced by any model.

Catflow, HYDRUS-2D, WaSiM-ETH and up to the certain degree also SIMULAT and Hill-Vi are based on calculations using Richards equation. However, the predictions vary in a broad range. The largest differences were predicted in case of the discharge with a maximal difference in peak flow from 15 to 840 m^3/d. This was mainly an effect of the estimated soil properties. The models which predicted low actual evapotranspiration predicted a higher runoff. These models mainly used a low van Genuchten parameter n_{vG}. A second result was the low surface runoff as predicted by most models. The observations – not known to the modellers – show that surface runoff is the main flow component.

The differences are mainly due to parameter estimation, process understanding, and conceptualization. The influence of the subsurface clay dam on the flow quantities and pathways in the lower catchment area are not described by any of the models resulting in larger groundwater discharge than measured. Neglecting the information of the gully network and of the aerial photo was leading to too low direct runoff. Only CoupModel integrated the information from this data source and predicted the highest direct runoff. The estimation of the additional parameters and the initial conditions was hampered due to the large uncertainties. For instance, the saturated hydraulic conductivity was estimated primarily in the range of 50 to 146 mm/h with one estimate of 420 mm/h. This parameter had a major impact on the predictions, e.g. in the few cases of infiltration excess which resulted in the low runoff. Introducing threshold values to allow runoff is necessary for a better prediction, which is based on surface sealing occupying the topmost part of the soil pore space. This would enhance surface runoff and lower AET as well.

The plant parameterization was of minor importance for the investigation because the catchment was newly built and left for a natural slow invasion of plants. So most of the models assumed no or a small vegetation and were using the Penman-Monteith method to calculate the potential evapotranspiration. The two models which did not use the Penman-Monteith method calculated the highest potential evapotranspiration. The main impact on the actual evapotranspiration had the choice of the pore size index (van Genuchten parameter n_{vG}) for the parameterization of the hydraulic properties of the unsaturated zone because most models used the Richards equation. Assumptions using higher van Genuchten parameters reported generally a higher actual evapotranspiration.

6 Supplementary material

The supplementary material can be found at:
http://www.hydrol-earth-syst-sci-discuss.net/6/3199/2009/hessd-6-3199-2009-supplement.pdf

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Table 1. Catchment models.

Model	Full name of acronym	Modeller	Institution
Catflow		T. Blume	University of Potsdam
CMF	Catchment Modelling Framework	P. Kraft	University of Giessen
CoupModel	Coupled Heat and Mass Transfer Model for Soil-Plant-Atmosphere System	D. Gustafsson	Royal Institute of Technology KTH Stockholm
Hill-Vi		S. Stoll	University of Freiburg
HYDRUS-2D[a]		C. Stamm	Eawag
NetThales		G. B. Chirico	University of Naples
SIMULAT[a]		H. Bormann	University of Oldenburg
SWAT	Soil and Water Assessment Tool	J.-F. Exbrayat	University of Giessen
Topmodel	Topography-based model	W. Buytaert	University of Bristol
WaSiM-ETH	Water Balance Simulation Model-ETH	H. Hölzel	University of Bonn

[a] Although HYDRUS-2D and SIMULAT are not catchment models in its proper sense, they are adapted to be used as such.

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Table 2. Methods for calculating infiltration, saturated and unsaturated flow.

Model	Infiltration	Saturated flow	Unsaturated flow
Catflow	Richards equation (mixed form)	Richards equation (mixed form)	Richards equation (mixed form)
CMF	Richards' equation with an assumed transition zone of 5 cm thickness	Darcy's law	Richards equation using Brooks–Corey retention curve
CoupModel	Modified Darcy's law infiltration (Jansson and Halldin, 1979); Infiltration capacity depend on saturated hydraulic conductivity in both matrix and macro pores, with correction for frozen soil conditions (Stähli et al., 1996)	Drainage equation by Hooghoudt (1940)	Richards equation, matrix and macro pore flow
Hill-Vi	Infiltration capacity = saturated hydraulic conductivity; Mualem–van Genuchten equation	Dupuit-Forchheimer assumption (Freeze and Cherry, 1979; Wigmosta and Lettenmaier, 1999)	Simplified Richards equation (gravity flow)
HYDRUS-2D	Richards' equation	Richards' equation	Richards equation (matrix flow; macropore flow mimicked as described under 3.3.5)
NetThales	No infiltration excess is simulated Rainfall is assumed to infiltrate totally into the soil. Exfiltration occurs when the soil column saturates.	Lateral non-linear kinematic flow	No unsaturated flow is simulated. The timing of the vertical redistribution of the water into the soil column is neglected Lateral flow occurs when average soil moisture is above the field capacity
SIMULAT	semi-analytical solution of the Richards' equation for separation of surface runoff and infiltration (Smith and Parlange, 1978); interflow (based on Darcy's law), groundwater recharge (flow across the lower boundary of a soil column)	Concentration time	Richards equation
SWAT	SCS (Soil Conservation Service) curve number method	Soil properties and water content	Soil properties
Topmodel	Green-Ampt infiltration	Time delay function	Exponential transmissivity function
WaSiM-ETH	Green-Ampt approach modified by Peschke (1987)	linear storage approach	Richards equation parameterized based on van Genuchten (1980)

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Table 3. Methods for calculating snow melt and interception.

Model	Snow melt	Interception
Catflow	not represented	LAI dependent bucket approach method (seasonal cycle)
CMF	no snow accumulation modelled	20% of total rainfall
CoupModel	snow melt/refreeze based on energy balance, including surface heat exchange, radiation, and near surface soil heat flux Precipitation is assumed to be snow below $T<0^{\circ}C$, and a mixture of rain and snow in a temperature range $0<T<+2^{\circ}C$	LAI dependent bucket model with specific interception capacities for snow and rain (higher for snow) (Stähli and Gustafsson, 2006) sky-view fraction and direct throughfall exponential function of LAI LAI was assumed a seasonal cycle (0 to maximum), and an inter-annual increase (see supporting material)
Hill-Vi	no snow routine implemented	no interception
HYDRUS-2D	cumulative precipitation during periods of snowfall periods is directly converted into discharge upon soil thawing	no vegetation cover assumed
NetThales	no snow fall and snow accumulation is simulated snow has been considered negligible after a preliminary analysis	no interception is simulated
SIMULAT	degree day approach	LAI dependent bucket approach
SWAT	snowfall at $T<1^{\circ}C$ snowmelt above $0.5^{\circ}C$ based on degree-day approach	LAI function daily updated as function of a maximum value
Topmodel	no snow routine implemented	no interception
WaSiM-ETH	temperature-index method	LAI depended bucket approach method

Table 4. Methods for calculating the potential and actual evapotranspiration (PET and AET, respectively).

Model	PET	AET
Catflow	Penman–Monteith equation but not returned as output	(Kolle, 1997)
CMF	Penman–Monteith equation (Allen et al., 1998)	Piecewise linear function of the soil water content within the "root-zone"
CoupModel	Potential transpiration and potential interception evaporation using Penman–Monteith equation (Monteith, 1965), with radiative and vapour pressure deficit regulation of stomatal resistance (Lohammar et al., 1980) Soil (and snow) evaporation by surface energy balance, i.e. bulk transfer equations (Alvenäs and Jansson, 1997; Gustafsson et al., 2001)	Soil moisture and temperature regulation of actual root water (Jansson and Halldin, 1979) Soil surface vapor pressure function of surface temperature and water content of upper soil layer; snow surface vapor pressure correspond to saturation over ice (dry snow) or water (melting snow
Hill-Vi	(Turc, 1961)	linear function of soil water content in the unsaturated zone
HYDRUS-2D	Penman–Monteith	
NetThales	Penman–Monteith equation (Allen et al., 1998; Kroes et al., 2008)	linear function of the soil water content within the "root-zone"
SIMULAT	Penman–Monteith equation	reduction of PET depends on actual soil matric potential, root distribution (Feddes et al., 1978) for transpiration and a soil factor as well as the number of days after the last rainfall in case of evaporation (Ritchie, 1972)
SWAT	Hargreaves empirical method (Hargreaves et al., 1985)	evaporates canopy storage until PET is reached if PET> canopy storage, remaining evaporative demand is partitioned between vegetation and snow/soil
Topmodel	Penman–Monteith equation (Allen et al., 1998)	Function of root zone storage deficit
WaSiM-ETH	Penman–Monteith (Monteith and Unsworth, 1990)	suction depended reduction approach

Table 5. Parameterization of hydraulic conductivity, porosity, and of the unsaturated zone.

Model	Hydraulic conductivity[a]	Unsaturated zone[a]	Porosity[a]
Catflow	(Carsel and Parrish, 1988)	after Carsel and Parrish (1988) Mualem-van Genuchten (Mualem, 1976; van Genuchten, 1980)	after Carsel and Parrish (1988)
CoupModel	Swedish sand (Lundmark and Jansson, 2009, in review)	Hydraulic conductivity function of (Mualem, 1976) and water retention function of (Brooks and Corey, 1964)	Input parameter (estimated by analogy)
CMF	Estimated	(AG Boden, 1994)	(AG Boden, 1994)
Hill-Vi	(Schaap et al., 2001)	Mualem–van Genuchten (parameterized according to – Schaap et al., 2001)	(Schaap et al., 2001)
HYDRUS-2D		Mualem–van Genuchten (Schaap et al., 2001), for the *L* factor we used also the data base implemented in HYDRUS yielding different values	
NetThales	(Rawls and Brakensiek, 1985)	(Rawls and Brakensiek, 1985) PTFs have been used to estimate the saturated and residual water content. according (Romano and Santini, 2002)	FWC has been quantified by analyzing a drainage process (Romano and Santini, 2002), simulated with the SWAP model (van Dam et al., 1997). The FWC value is assumed equal to the average water content in the top 30 cm when the drainage flux at 30 cm depth is equal to 0.10 mm/d.
SIMULAT	(Rawls and Brakensiek, 1985)	(Brooks and Corey, 1964)	(Adhoc AG Boden, 2005)
SWAT	(Rawls and Brakensiek, 1985)		computed by SWAT as a function of bulk density
Topmodel	(Saxton et al., 1986)	Unsaturated zone time delay per unit storage deficit from literature values (Gallart et al., 2007; Choi and Beven, 2007)	Not used explicitly
WaSiM-ETH	(Adhoc AG Boden, 2005)	(Adhoc AG Boden, 2005)	(Adhoc AG Boden, 2005)

[a] The parameter sets are included in the annex.

Table 6a. Predicted and observed water budget of the Chicken Creek catchment for the 1st year.

	P (mm/y)	PET (mm/y)	AET (mm/y)	Discharge (mm/y)	Storage (mm/y)	Balance (mm/y)
Catflow	373	NA	161	249	−59	22
CMF[b]	298	146	88	208	−44	46
CoupModel	401	NA	437	12	−48	0
Hill-Vi	373	717	153	306	−63	−23
HYDRUS-2D	431	611	409–545	34–48	−158–−38	−5–22
NetThales	373	392	226	189	−38	−4
SIMULAT	373	680	239	189	25	−80
SWAT	373	807	350	76	−4	−49
Topmodel	373	570	271	94	0	8
WaSiM-ETH	373	700	283	107	0	−17
Chicken Creek	373	779	163	113[d]	35	62

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Table 6b. Predicted and observed water budget of the Chicken Creek catchment for the 2nd year.

	P (mm/y)	PET (mm/y)	AET (mm/y)	Discharge (mm/y)	Storage (mm/y)	Balance (mm/y)
Catflow	565	NA	170	262	80	53
CMF[b]	452	139	104	238	13	97
CoupModel	666	NA	563	27	76	0
Hill-Vi	565	718	156	346	58	5.3
HYDRUS-2D	635	602	520–579	19–67	27–33	1–17
NetThales	565	421	284	259	23	−1
SIMULAT	565	713	318	339	−9	−83
SWAT	565	815	409	145	18	−7
Topmodel	565	573	384	171	0	10
WaSiM-ETH	565	689	371	162	0	32
Chicken Creek	565	782	165	105	69	226

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Table 6c. Predicted and observed water budget of the Chicken Creek catchment for the 3rd year[a].

	P (mm/y)	PET (mm/y)	AET (mm/y)	Discharge (mm/y)	Storage (mm/y)	Balance (mm/y)
Catflow	511	NA	163	258	55	35
CMF[b]	409	116	78	250	−39	120
CoupModel	563	NA	498	76	−11	0
Hill-Vi	511	588	128	329	44	10
HYDRUS-2D[c]	357	331	277–313	34–64	−9–7	2–26
NetThales	511	307	199	275	39	−2
SIMULAT	511	628	278	283	17	−67
SWAT	511	706	331	164	−4	20
Topmodel	511	486	294	198	NA	19
WaSiM-ETH	511	573	272	178	NA	61
Chicken Creek	511	674	137	113	162	99

[a] until 8 September 2008
[b] 20% interception losses
[c] until 3 July 2008
[d] 69 mm were needed to fill up the lake.

Table 7a. Discharge components predicted for the 1st year[a].

	Runoff (mm/y)	Interflow (mm/y)	Baseflow (mm/y)	Total discharge (mm/y)
Catflow		90	159	249
CMF				208
CoupModel	8		4	12
Hill-Vi	>1	305		306
HYDRUS				34–48
NetThales				189
SIMULAT	>1	0	189	189
SWAT	27	51		76
Topmodel	31		63	94
WaSiM-ETH	0	83	24	107
Chicken Creek				113

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Table 7b. Discharge components predicted for the 2nd year[a].

	Runoff (mm/y)	Interflow (mm/y)	Baseflow (mm/y)	Total discharge (mm/y)
Catflow		101	161	262
CMF				238
CoupModel	20		7	27
Hill-Vi	>1	346		346
HYDRUS				19–67
NetThales				259
SIMULAT	>1	0	339	339
SWAT	61	84		145
Topmodel	75		96	171
WaSiM-ETH	2	138	22	162
Chicken Creek				105

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Table 7c. Discharge components predicted for the 3rd year[a].

	Runoff (mm/y)	Interflow (mm/y)	Baseflow (mm/y)	Total discharge (mm/y)
Catflow		112	146	258
CMF				250
CoupModel	62		14	76
Hill-Vi	>1	329		329
HYDRUS				34–64
NetThales				275
SIMULAT	>1	0	283	283
SWAT	57	112		164
Topmodel	94		104	198
WaSiM-ETH		148	30	178
Chicken Creek				113

[a] no value is equal to no information.

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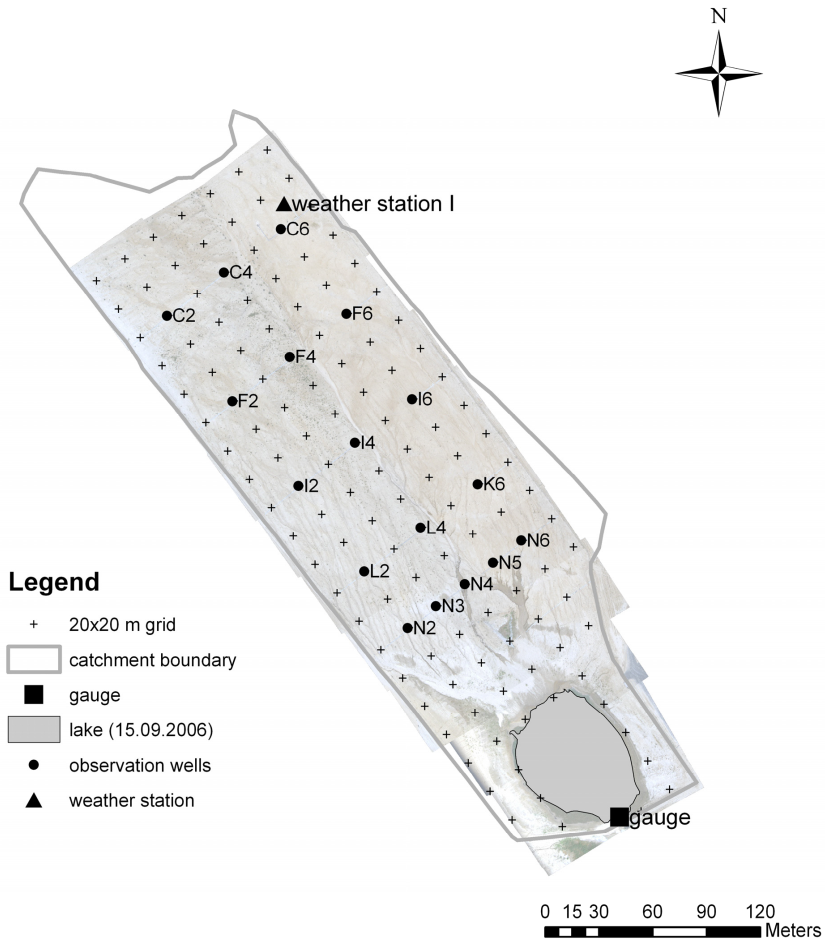

Fig. 1. GIS framework of Chicken Creek catchment.

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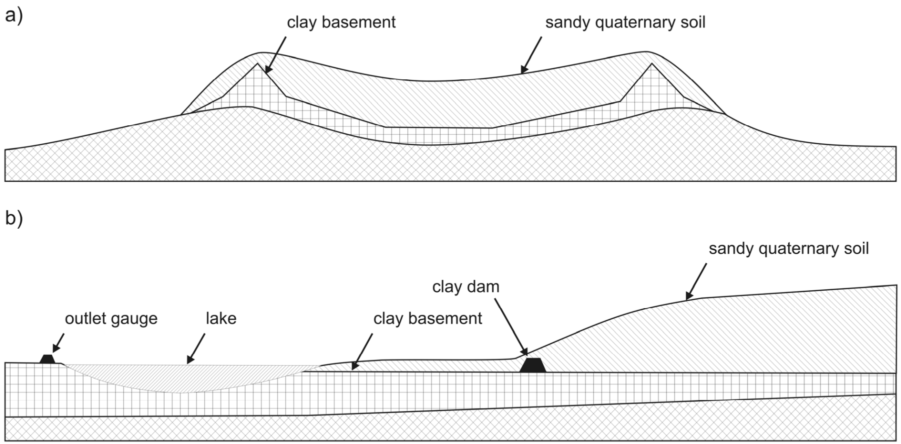

Fig. 2. Schematic of the transverse **(a)** and longitudinal **(b)** transect of the Chicken Creek catchment (not to scale).

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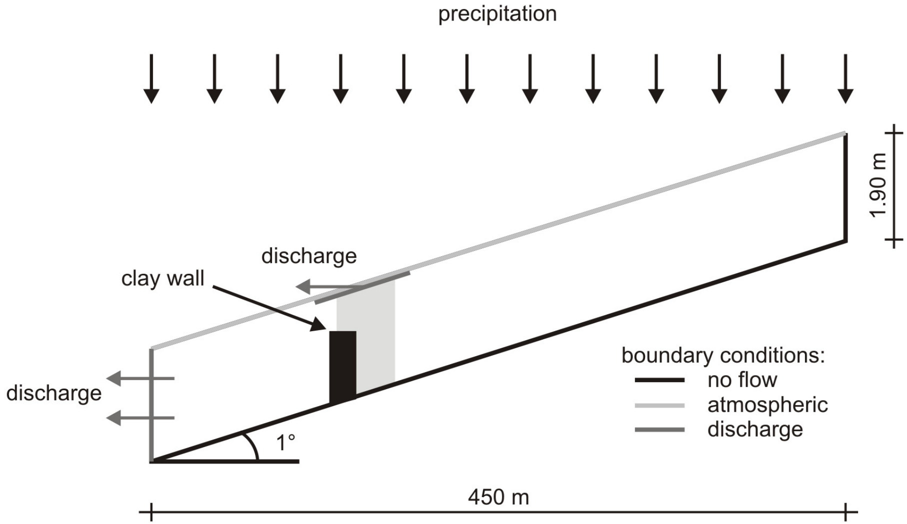

Fig. 3. Geometric representation and spatial arrangement of the boundary conditions used for the HYDRUS-2D simulations; Catflow used the same arrangement but a soil layer thickness of 2.00 m.

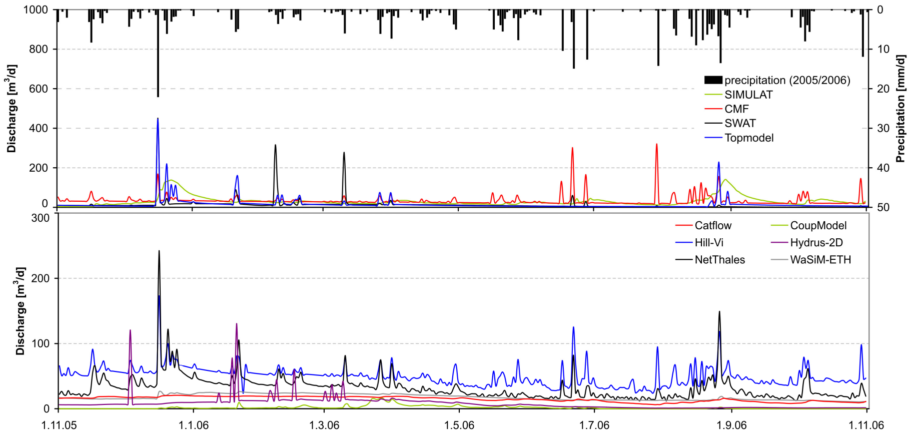

Fig. 4a. Predicted discharge for the hydrological year 2005/2006.

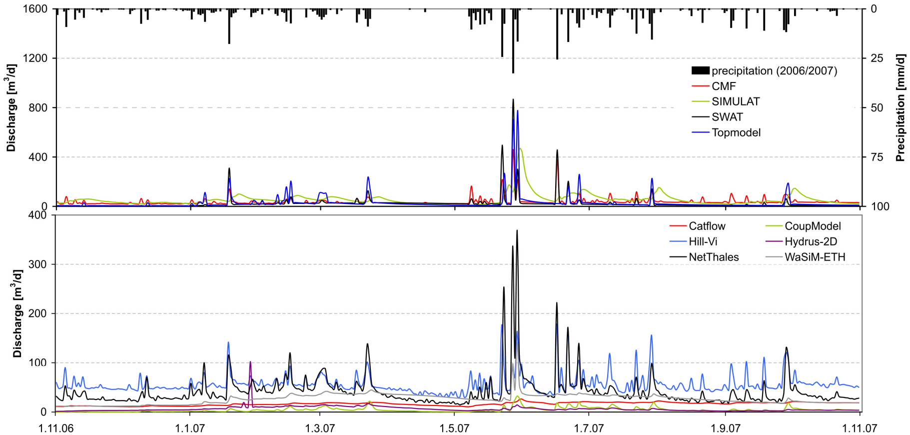

Fig. 4b. Predicted discharge for the hydrological year 2006/2007.

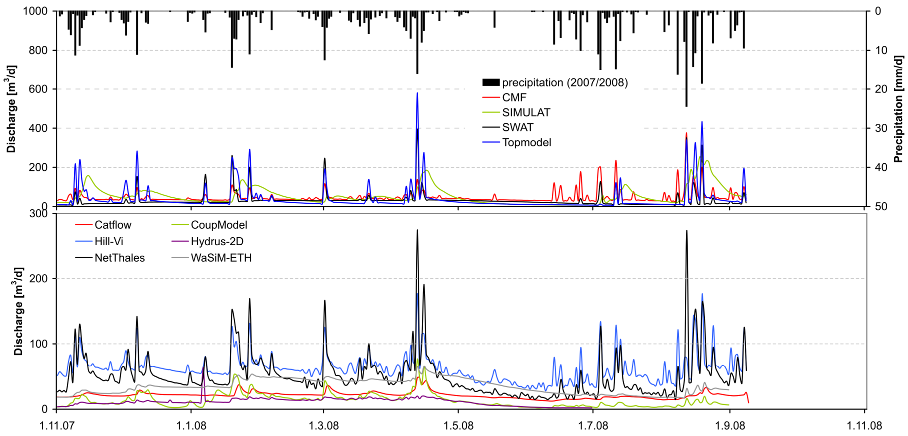

Fig. 4c. Predicted discharge for the hydrological year 2007/2008.

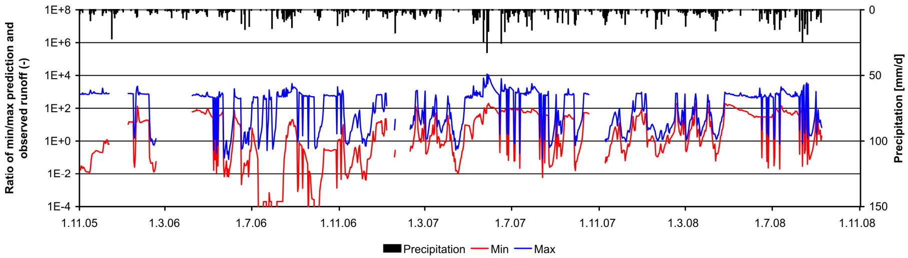

Fig. 5. Comparison of measured discharge to the maximum and minimum predicted discharge.

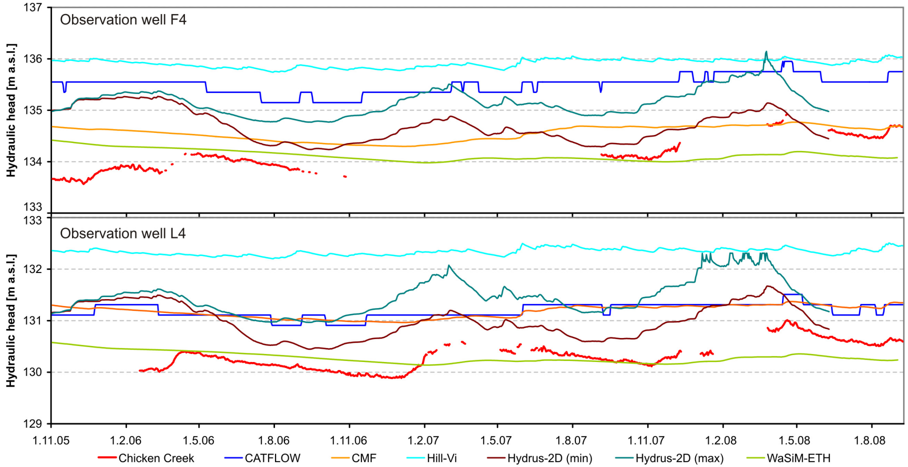

Fig. 6. Predicted and measured hydraulic heads at the observation wells F4 and L4.