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Conceptual model building inspired by field-mapped runoff generation mechanisms

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Abstract: Since the beginning of hydrological research hydrologists have developed models that reflect their perception about how the catchments work and make use of the available information in the most efficient way. In this paper we develop hydrologic models based on field-mapped runoff generation mechanisms as identified by a geologist. For four different catchments in Austria, we identify four different lumped model structures and constrain their parameters based on the field-mapped information. In order to understand the usefulness of geologic information, we test their capability to predict river discharge in different cases: (i) without calibration and (ii) using the standard split-sample calibration/validation procedure. All models are compared against each other. Results show that, when no calibration is involved, using the right model structure for the catchment of interest is valuable. A-priori information on model parameters does not always improve the results but allows for more realistic model parameters. When all parameters are calibrated to the discharge data, the different model structures do not matter, i.e., the differences can largely be compensated by the choice of parameters. When parameters are constrained based on field-mapped runoff generation mechanisms, the results are not better but more consistent between different calibration periods. Models selected by runoff generation mechanisms are expected to be more robust and more suitable for extrapolation to conditions outside the calibration range than models that are purely based on parameter calibration to runoff data.

Keywords: Rainfall-runoff; Catchment geology; Hydrologic models; Runoff response times; A-priori information.

INTRODUCTION

Several strategies have been developed in recent years to cope with the diversity of hydrological processes in hydrological modelling. One avenue has been to develop models that include all the relevant processes in as much detail as possible, i.e. using the equations derived in laboratory studies for processes such as infiltration, subsurface flow etc. The epitome of this group of models is the SHE model (Abbott et al., 1986). The rationale is that one universal model should represent all processes based on universal concepts of physics. However, because of their detail, these models tend to be highly complex involving a large number of parameters and model structural elements. It may then be very difficult to identify the parameters and the suitability of the model structure at the catchment scale because of the diversity of the hydrological environment and measurement constraints (e.g. Beven, 2001; Blöschl, 2006; Savenije, 2009).

An alternative has hence been to propose simple models with a structure that is tailor made to the processes occurring in a particular catchment (e.g., Fenicia et al., 2011; Hrachowitz et al., 2014; Van den Bos et al., 2006). These models were developed in a way to strike a balance between model complexity and data availability, by keeping models as simple as possible, but complex enough to explain the dynamics of the data. While the universal models of the first group can be compared to a Swiss multi tool Army knife, the models of the second group can be compared to speciality tools – for each purpose a dedicated tool. The models, typically, consist of a combination of reservoirs and threshold functions. The models can differ in terms of the way they represent dominant catchment scale processes. Bai et al. (2009), for example, tested eight model variants with different hypotheses on the mechanisms of soil moisture accounting at the catchment scale. The complexities of the models and their related hypothesis on the model structure provided an indication of the dominant controls on catchment response at the inter-annual, intra-annual, monthly, and daily time scales. The models can also differ in terms of the way they represent dominant local runoff generation processes. For example, Hellebrand et al. (2011) identified Hortonian overland flow, saturation overland flow, subsurface stormflow and deep percolation by a classification scheme (Müller et al., 2009). They then represented each of these runoff generation processes by a combination of reservoirs.

Several studies compared model performance and model development strategies for different landscape characteristics (e.g., Hogue et al., 2006; Nijzink et al., 2016; Rosero et al., 2010; Samuel et al., 2008). The studies indicated differences in the signatures, the controls, and the need to adapt model structures and parameters to the particular vegetation and hydroclimatic conditions when moving from one catchment to another. Winter (2001), Wolock et al. (2004) and Savenije (2010) highlighted the role of the geomorphological landscape characteristics. Winter (2001) suggested that hydrological landscapes are multiples or variations of fundamental hydrological landscape units and defined fundamental hydrological landscape units on the basis of land-surface form, geology and climate. By describing actual landscapes in terms of land-surface slope, hydraulic properties of soils and geology, and the difference between precipitation and evapotranspiration, the hydrological system of actual landscapes can then be conceptualised in a uniform way. Savenije (2010) argued that plateaus, hillslopes and wetlands are associated with different flow pathways, so the model structures for these units should also differ. This is particularly important in water-limited landscapes (Caylor et al., 2006). Wagener et al. (2007) and Gutknecht et al. (2008)

summarised the storage and transport characteristics of a landscape by the notion of "catchment functions". It is interesting that regionalisation studies (e.g., Blöschl et al., 2013; Merz and Blöschl, 2009) provided similar evidence of contrasting controls on runoff for wet and dry regions and for different geographic regions. Differences were also evident from theoretical studies that explored the sensitivity of the dynamic water balance to its controls at catchment scale (e.g., Milly and Dunne, 2002).

Geology usually has a marginal role in the identification of model structures, mainly because of the lack of information, although, for example, Rogger et al. (2012b) and He et al. (2015) have demonstrated the value of geologic information for hydrological processes. In a comparative hydrology study, Gaál et al. (2012) have also shown that geology is, together with climate, an even stronger control than catchment area in determining flood timescales through soil characteristics. The aim of this work is to understand how useful geologic information can be for the derivation of model structure for different catchments (from high alpine to lowland). To this purpose a detailed modelling exercise is performed for four different catchments in Austria, where detailed geological information is available. Model structures and parameters are first derived mainly based on this information and then cross validated against each other. We therefore focus on the information that can be obtained from runoff generation mapped in the field (i.e. resulting from a combination of soils maps, geology maps and in-situ surveys performed by a expert geologist). Our hypothesis is that using this information may be an advantage over the usual procedure of using soil type, texture, geological units because it is a procedure more geared towards hydrology.

STUDY SITES AND DATA

The four study sites belong to the set of catchments described in Gaál et al. (2012), who analysed the hydrographs of 396 Austrian catchments as a function of climatic controls such as storm type and catchment controls such as soils, soil moisture, geology and land form. They identified 13 hot spot regions with distinct runoff characteristics. Four catchments of four of these hot spots regions are chosen for this study because of the availability of field-mapped geologic information: one high alpine catchment, the Gail, two alpine/midland catchments, the Dornbirnerach and Wimitzbach, and one lowland catchment, the Perschling. An overview over the location of the catchment is given in Figure 1.

The Dornbirnerach is the westernmost catchment, located in Vorarlberg. It is an alpine catchment with elevations ranging from 485 m to 1804 m characterised by very steep slopes. The catchment is mainly forested with some grassland and a few pastures in the higher elevations. It has a size of about 51 km^2.

The highest catchment in the study is the Gail which is located in Eastern Tyrol at the Southern border of Austria. It has a size of 146 km^2 and elevations ranging from 1094 m to 2622 m.

The catchment is characterised by forest and grassland areas on the hillslopes, while the alluvial soils in the valley bottom are used as pastures. The side valleys are steep in the north and shallower in the south. The third catchment is the Wimitzbach, a midland catchment located in Carinthia with elevations ranging from 529 m to 1309 m. Most of the catchment is forested with a few agricultural areas in the mid and lower parts close to the gauging station. The catchment has a size of about 106 km^2. The only lowland catchment in the study is the Perschling which is located in Lower Austria. The elevation ranges from 230 m to 640 m and a size of 55 km^2. The catchment is dominated by forested areas in the southern parts and agricultural areas in the northern parts. An overview over the most important catchment characteristics is given in Table 1.

To obtain hourly rainfall inputs at the catchment scale, daily precipitation of stations belonging to the network of the Austrian Hydrografische Dienst are interpolated using the classical Thiessen polygon technique. The result is then time-downscaled to hourly values using the timepatterns obtained by averaging the timepattern values at sites equipped with tipping bucket rain gauges (as in Merz et al., 2006). Hourly mean basin air temperature is obtained from linear regression between hourly measurements at climate stations and their elevation (i.e., lapse rate method). In the first step, climate stations with hourly air temperature observations are identified in radius 50 km around the runoff gauge. In the second step, linear regression is estimated between hourly air temperature and elevation of climate stations. Finally, the mean basin air temperature is estimated from linear regressions by using mean elevation of each basin. Hourly mean basin potential evaporation (EP, in mm) is estimated by modified Blaney-Criddle method as in Parajka et al. (2003) and Nester et al. (2012), e.g. as a function of air temperature and the sun shine duration index that was estimated from 1 km digital elevation model at the European scale. Hourly discharge data are provided by the Austrian Hydrografische Dienst Zentralbüro (https://www.bmlfuw.gv.at/wasser/wasser-oesterreich/wasserkreislauf/hydrographie_oesterreich.html).

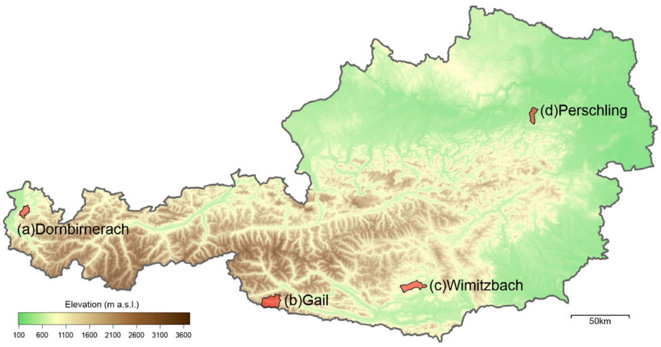


Fig. 1. Location of four study sites in Austria (see Table 1 for an overview of catchment characteristics).

Table 1. Catchment overview. Temporal means are lumped basin averages from 1976–2008.

	Dornbirnerach	Gail	Wimitzbach	Perschling
Hot Spot Region (Gaál et al., 2012)	Bregenzwald (BreWa)	Gail (Gail)	Gurktal (Gurk)	Flysch (Flysch)
catch. size (km^2)	51.1	146.1	106.5	55.3
min-(mean)-max elevation (m a.s.l.)	485-(1118)-1804	1094-(1793)-2622	529-(900)-1309	230-(379)-640
mean annual prec. (mm/y)	2099	1260	892	782
mean annual temp (ºC)	6.2	2.8	6.9	9.2
mean potential evaporation (mm/y)	603	477	621	703
mean annual runoff (mm/y)	1743	924	287	256

Data for the years 2000 to 2010 are used in all sites with the exception of Wimitzbach, where overlapping hourly timeseries are available for the period 2004–2009 only.

GEOLOGICAL FIELD-MAPPING OF RUNOFF-GENERATION MECHANISMS

For the four study sites hydrogeologic runoff process maps are derived by Herbert Pirkl, an Austrian geologist, based on the method described in Pirkl (2009, 2012). The maps are obtained by a detailed assessment of geologic maps, hydrogeologic maps, orthophotos and digital terrain models. Based on this information different hydrogeologic response units are defined that discriminate areas dominated by interflow, deep groundwater flow or surface runoff processes. These maps give an idea about the runoff processes in the catchment from a hydrogeologic point of view and highlight areas with high storage potential during flood events. Such maps have successfully been implemented in hydrological studies by Rogger et al. (2012a,b) and proved to be very valuable in understanding the storage properties of a catchment. The geologic conditions and hydrogeologic runoff process maps of the four study sites are described in detail below.

Dornbirnerach

The catchment is part of the Helvetic zone including limestone, sandstone and marl with a small part of flysch in the northern area. A few areas consist of carbonates that have a tendency to karstify, but no fast runoff reaction related to these processes has been observed. The hillslopes are very steep resulting in a high relief energy. The hydrogeologic runoff process map of the catchment is shown in Figure 2a. Large parts of the catchment are characterised by shallow interflow processes. These areas, especially in the upper part of the hillslopes, may get saturated and form surface runoff. The scree areas in the lower parts of the hillslopes have rather large depth and are dominated by deeper interflow processes which may buffer some of the fast surface runoff generated in the upper parts.

Gail

The catchment is part of the Karnic Alps, the Gail crystalline and the Lienzer dolomites. The Karnic Alps are characterised by phyllitic schists, quarzites and metamorphic tuffites, the Gail crystalline by gneiss and mica schist and the Lienzer dolomites by dolomites. The main valley is east-west orientated with rather steep valleys discharging into the Gail from north and shallower valleys from south. The hydrogeologic runoff process map is shown in Figure 2b.

Large areas of the catchment are characterised by surface runoff. There is, however, a potential for runoff retention during strong precipitation events on areas dominated by deep groundwater flow and interflow of different origins. Both in the Karnic Alps as well as in the Gail crystalline deep creeping areas occur (dark green areas) that are characterised by deep groundwater flow (Figure 3a). Scree areas in the lower parts of the hillslopes and valley deposits in the shallower valleys of the Karnic Alps are dominated by deeper interflow. The dolomites in the Lienzer dolomites are strongly weathered forming additional scree areas with deep interflow in the valley bottoms. Runoff retention of the tributaries from the southern and northern valleys may also occur on the large alluvial cone in the valley bottom. During very wet conditions, the alluvial cone may however get saturated so that tributaries can bypass it.

Wimitzbach

The catchment is located in the crystalline series of the Gurktaler Alps characterised by mica schist, phyllites, amphibolites and marble. The hillslopes have a similar structure all over the catchment and are rather plane in the upper parts and steep in the lower parts. The Wimitzbach was not glaciated during the last ice age resulting in a strong weathering of the upper parts and tops of the hillslopes. The hydrogeologic runoff process map is shwon in Figure 2c. Due to the strong weathering processes the upper parts an crests of the hillslopes are dominated by deep interflow. The steeper lower parts of the hillslopes on the other hand are characterised by shallow interflow or surface runoff on rocks. The valley bottoms are filled with fine sediments and not very permeable.

Perschling

The catchment is located in the flysch/molasse zone of Austria. The northern parts lay in the molasse zone and are characterised by fine sands and clay marl, while the southern parts are part of the flysch zone and consist of clay marl, marl and sand stone. The hydrogeologic runoff process map is shown in Figure 2d.

The whole catchment is characterised by interflow processes in the weathering zone that has a depth from 2 to 5 m. The valley bottom is filled with sandy gravel and influenced by groundwater. A cross section of the runoff processes on a typical hillslope in the flysch zone is shown in Figure 3b. On the upper parts of the hillslopes water infiltrates into the shallow subsurface while at the slope toes some saturation and surface runoff may occur.

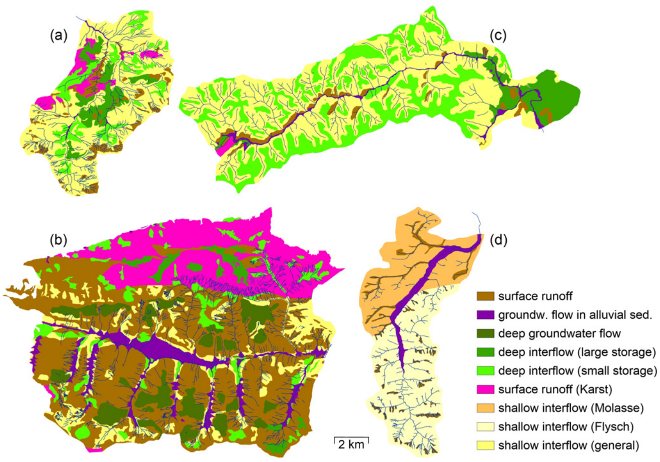


Fig. 2. Hydrogeologic runoff process map of the four austrian catchments: (a) Dornbirnerach; (b) Gail; (c) Wimitzbach; and (d) Perschling.

MODEL STRUCTURES FROM RUNOFF GENERATION MECHANISMS

The model structure of the four study sites is derived based on the information on hydrogeological processes as explained in the previous section. Simple lumped modelling approaches are chosen with the aim to only represent the dominating runoff processes of the catchments (similarly to Hrachowitz et al., 2014). All models are characterised by a snow-accumulation and snow-melt module. A very simple degree day factor is used with four parameters (ddf, the degree day factor; t_s, the threshold temperature below which precipitation is snow; t_m, thresh-

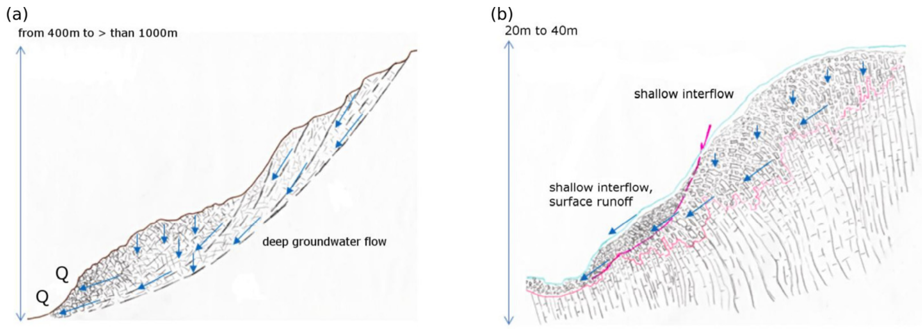


Fig. 3. Examples of cross sections of runoff processes hand-drawed by Herbert Pirkl: (a) deep creeping areas in the Gail catchment; (b) Typical hillslope in Perschling catchment.

old temperature above which melt starts; and SCF, a snow correction factor, see Table 2). All models have a routing module consisting in a simple linear reservoir with response time k_r. For all other model parts, the runoff generation mechanisms identified using the geological information is used and a detailed description of the derivation of the four model structures is given below.

Dornbirnerach

The hydrogeologic runoff process map of the Dornbirnerach looks rather complex (see Figure 2a), but most of the different hydrogeologic runoff response units are directly connected to the river network so that processes occur in parallel rather than in series. For this reason, the different storages representing these processes are arranged in parallel in the model structure (Figure 4a).

Large parts of the Dornbirnerach are characterised by shallow interflow processes. On the upper hillslopes of the catchment very fast interflow occurs (and potentially also surface runoff) which is represented in the model by the fast storage S_s . The remaining interflow areas in the lower parts of the catchment produce a slower interflow component and are modelled by the slower interflow storage S_i. The scree areas that are dominated by deep interflow in the lower parts of the hillslopes produce a slow deep interflow component or baseflow and are represented in the model by a slow storage S_d.

The parameters p_s, p_i and p_d indicate the proportion of input water (rain + snowmelt) that enters the fast storage, the interflow storage and the deep interflow storage respectively. These storages respond linearly with response times k_s, k_i and k_d. The fast storage is characterised by a maximum level S_{smax} above which fast surface runoff occurs. Evaporation happens at potential rate (if the buckets are not empty) and is reparted among the three buckets as specified by parameters e_s, e_i and e_d. These parameters controlling evapotranspiration have not been related to the surface cover or land use since the interest here is in runoff generation by the geological units. Only the fast surface runoff is routed through the linear reservoir with response time k_r. The total runoff is given by the routed runoff plus near surface, interflow and deep interflow runoff. See Table 2 for the description of the parameters and the model equations. Reasonable ranges for the parameters are reported in Table 2.

Gail

Similarly to the case of Dornbirnerach, in the model for the Gail the input rain + snowmelt is partitioned into three components (Figure 4b). One part contributes to the slow storage S_d that represents the deep creeping areas and produces a very slow baseflow component. The storage is arranged in parallel to the other storages since these areas are directly connected to the river. Outflow of this storage is not expected to contribute significantly to flood events.

Another part of the input contributes to the fast storage S_s that generates a fast near surface runoff component. This runoff component originates from the areas classified as surface runoff areas in the hydrogeologic process that cover large parts of the catchment. It should be noted that even if these areas appear as bare rock on the geologic map, they are actually covered by forest or grassland which means they are more likely to produce near surface than surface runoff component.

In the southern valleys the fast runoff reaction is dampened by the scree areas and alluvial soils in the valley bottoms of the tributaries. Similarly discharges from some of northern tributaries are dampened by the large alluvial cone in the main valley. This is the reason way part of the near surface runoff from the fast storage feeds into an interflow storage S_i that causes a runoff retention. The interflow storage S_i is partially also directly fed by rainfall plus snowmelt representing direct precipitation on these areas.

The same parameters as in the Dornbirnerach model appear here, with the additional o_s parameter, which controls the paritioning of the near surface runoff into the one recharging the interflow storage and the one contributing directly to runoff (see Table 2). The fast surface and (part of) near surface runoff are routed with the linear reservoir. The total runoff is given by the routed runoff plus interflow and groundwater runoff.

Wimitzbach

Due to the homogeneity of the hillslopes all over the catchment, a very simple model structure was chosen for the Wimitzbach (Figure 4c). The upper parts of the hillslopes are deeply weathered and represented by the slow storage S_d, that is fed by water infiltrating from the unsaturated zone. This storage forms a very slow runoff component that mainly contributes to the baseflow in the river. The lower parts of the hillslopes are characterised by the faster storage S_i that form a faster runoff component. Part of the deep interflow from S_d enters S_i as specified by (1 minus) the parameter o_d (see Table 2). The fast surface runoff is routed with the linear reservoir. The total runoff is given by the routed runoff plus the interflows.

Perschling

The whole catchment is dominated by shallow interflow processes, but due to the differences in geologic conditions and land use, the molasse zone and flysch zone are represented in the model by two separate storages (Figure 4d). The molasse

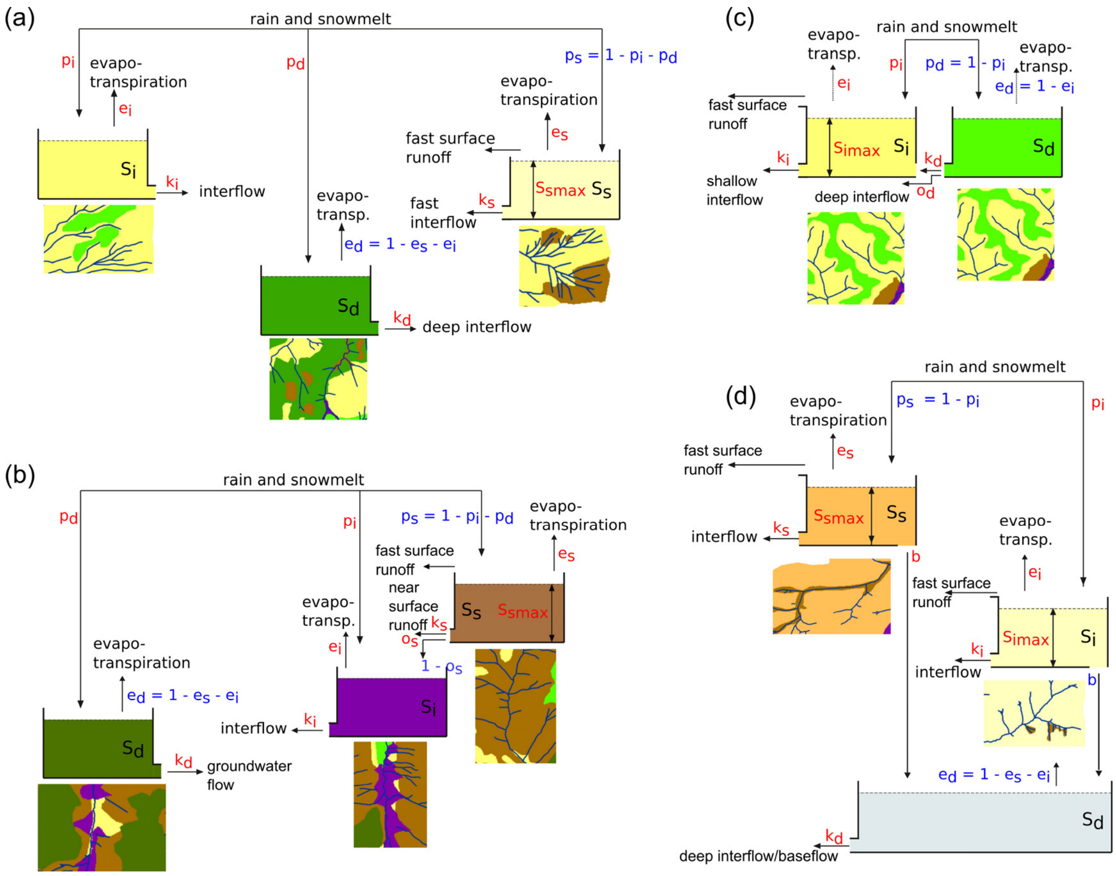


Fig. 4. Model structures for the four austrian catchments based on the hydrogeologic runoff process map of Figure 2. The four catchments are: (a) Dornbirnerach; (b) Gail; (c) Wimitzbach; and (d) Perschling. Outgoing vertical arrows indicate evapotranspiration components. Outgoing horizontal arrows indicate flow components that compose the overall outflow of the models. Model parameters that are set as 'free' in calibration are shown in red. Non-free parameters are shown in blue. See Table 2 for the description of the parameters.

Table 2. Model parameters and model equations where they do appear. Other variables are: E_* evaporation from S_* (s = surface, i = interflow, d = deep interflow) (mm h^{-1}); EP potential evaporation (mm h^{-1}); M melt (mm h^{-1}); P precipitation (mm h^{-1}); Q_* runoff from S_* (mm h^{-1}); Q_{*f} fast surface runoff from S_* (mm h^{-1}); R rainfall (mm h^{-1}); S_* storages (s = surface, i = interflow, d = deep interflow) (mm); Sp snow pack (mm); Sr routing storage (mm); t time (h); T temperature (°C). The last column shows ranges for the parameters used as calibration ranges when no-apriori is set.

Symbol	Dimension	Description	Equation	Range
ddf	(mm K^{-1} h^{-1})	degree day factor	$M = ddf \cdot (T - t_m)$ if $T > t_m$ and $S_p > 0$	0.1
t_s	(°C)	threshold temperature below which precipitation is snow	if $T > t_s$, $R = P$, else $dS_p/dt = P \cdot SCF$	0
t_m	(°C)	threshold temperature above which melt starts	if $T > t_m$, $M = ddf(T - t_m)$	1
SCF	(–)	snow correction factor	$dS_p/dt = P \cdot SCF$ if $T < t_s$	1
p_s	(–)	percentage of rain+melt that enters S_s	$dS_s/dt = p_s \cdot (R + M) - E_s - Q_s - Q_{sf}$	$0 \div 1$
p_i	(–)	percentage of rain+melt that enters S_i	$dS_i/dt = p_i \cdot (R + M) - E_i - Q_i - Q_{if}$	$0 \div (1 - p_s)$
p_d	(–)	percentage of rain+melt that enters S_d	$dS_d/dt = p_d \cdot (R + M) - E_d - Q_d$	$1 - p_s - p_i$
e_s	(–)	percentage of evaporation from S_s	$E_s = e_s \cdot EP$ if $S_s > 0$	$0 \div 1$
e_i	(–)	percentage of evaporation from S_i	$E_i = e_i \cdot EP$ if $S_i > 0$	$0 \div (1 - e_s)$
e_d	(–)	percentage of evaporation from S_d	$E_d = e_d \cdot EP$ if $S_d > 0$	$1 - e_s - e_i$
k_s	(h)	response time of the S_s storage	$Q_s = S_s/k_s$	$0 \div 1000$
k_i	(h)	response time of the S_i storage	$Q_i = S_i/k_i$	$k_s + (0 \div 5000)$
k_d	(h)	response time of the S_d storage	$Q_d = S_d/k_d$	$k_i + (0 \div 10000)$
S_{smax}	(mm)	max storage level for the S_s storage	$Q_{sf} = S_s - S_{smax}$ if $S_s > S_{smax}$	$0 \div 1000$
S_{imax}	(mm)	max storage level for the S_i storage	$Q_{if} = S_i - S_{imax}$ if $S_i > S_{imax}$	$0 \div 1000$
o_s	(–)	percentage of near surface runoff Q_s that doesn't enter the interflow storage S_i	$dS_i/dt = p_i \cdot (R + M) + Q_s \cdot (1 - o_s) - E_i - Q_i$	$0 \div 1$
o_d	(–)	percentage of deep interflow runoff from Q_d that doesn't enter the shallow interflow storage S_i	$dS_i/dt = p_i \cdot (R + M) + Q_d \cdot (1 - o_d) - E_i - Q_i - Q_{if}$	$0 \div 1$
b	(–)	percentage of percolation from Molasse and Flysch storages	$dS_d/dt = b \cdot (S_s + S_i) - E_d - Q_d$	$0 \div 1$
k_r	(h)	response time for the linear routing	$Q_r = S_r/k_r$ where $dS_r/dt = Q_{sf} + \cdots + o_s \cdot Q_s - Q_r$	$0 \div 120$

zone is agriculturally used and represented by the molasse storage S_s that is expected to react somewhat faster than the flysch zone S_i which is mainly forested. Both molasse and flysch storages have a maximum level (S_{smax}, S_{imax}) above which fast surface runoff occurs. There is percolation from S_s and S_i to a groundwater storage S_d controlled by the parameter b, the percolation happening instantaneously and proportionally to the storage (see Table 2). Fast surface runoff and interflows from both Molasse and Flysch reservoirs are routed through the linear reservoir with response time kr. The total runoff is given by the routed runoff plus the baseflow.

MODEL PARAMETERS FROM RUNOFF GENERATION MECHANISMS

The information on runoff generation mechanisms is used further to constrain the parameters of the four models described in the previous section.

Two types of information is used: (1) the geographic repartition of the different geological formations is used to specify (a priori) the partition parameters ps, pi and pd for the rain+snowmelt input and the partition parameters e_s, e_i and e_d for the evaporation; (2) an interview with the geologist is conducted to specify the ratios between response times (k_s, k_i and k_d) of the different response units in normal flow situations.

In Table 3 the area percentages of the geological classes obtained from Figure 2 are listed and summarized for all the catchments. These values are used in the model for the partitioning of rain and snowmelt in the different storages as well as for the partitioning of evaporation (parameters p_s, p_i, p_d, e_s, e_i and e_d in Table 2).

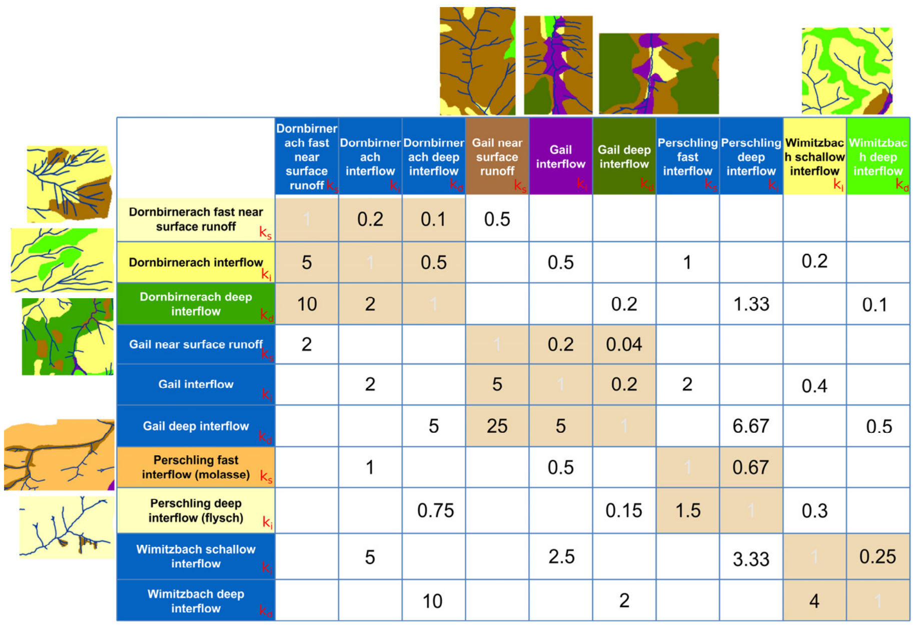
Information on the ratios between response times (k_s, k_i and k_d) between response units in normal flow situations is obtained from an interview with the geologist who produced the runoff generation maps. An iterative framework is used. A squared matrix is produced with all response units for all catchments as row and column names. To each element of the matrix a value is assigned that represents the ratio between the response time of the row unit and the response time of the column unit. At the start, the value 1 could be assigned to every element of the matrix, representing zero knowledge about the response times of the different response units. For the ten response units of the four catchments of this paper, we start with ratios which were reasonable from the point of view of the modeller.

Table 3. Area percentages of the geological classes for the four catchments in Figure 2. The partition parameters p_s, p_i, p_d, e_s, e_i and e_d (Table 2) to be used as a-priori information are derived from these area percentages.

	Dornbirnerach	Gail	Wimitzbach	Perschling
surface runoff	9.5%	7.7%	4.0%	
groundwater flow in alluvial sediments	0.5%	8.0%	2.5%	6.0%
deep groundwater flow		12%		
deep interflow (large storage)	11%	0.8%	8.6%	
deep interflow (small storage)	13%	6.4%	29%	
surface runoff (Karst)	6.5%	51%	0.5%	
shallow interflow (Molasse)				41%
shallow interflow (Flysch)				52%
shallow interflow (general)	60%	14%	55%	

With this initial matrix, the interview with the expert starts. The expert (in this case the geologist Herbert Pirkl) is asked whether she/he would suggest changes of the values for particular combinations of response units. She/he will have a perception on the ratio between response times that is different from the proposed values. The elements in the matrix are of course not independent, and changes in one of them will imply changes in the others, which may or may not satisfy the expert. In the second case, the matrix is updated further, based on her/his suggestions. The procedure goes on till the expert is satisfied by the final matrix. The result of our interview with the geologist is shown in Figure 5 where some of the elements are kept empty because they would not add information to the matrix.

In Figure 5, the ratios between response times of response units in the same catchment are shown in the brown square boxes including the diagonal (whose values are 1 for definition). For instance, the response time of the interflow component in the Dornbirnerach and Gail catchments is in the order of 5 times the response time of the respective fast near surface runoff components. Relatively to near surface and interflow



	Dornbirnerach fast near surface runoff k_s	Dornbirnerach interflow k_i	Dornbirnerach deep interflow k_d	Gail near surface runoff k_s	Gail interflow k_i	Gail deep interflow k_d	Perschling fast interflow k_s	Perschling deep interflow k_i	Wimitzbach schallow interflow k_i	Wimitzbach deep interflow k_d
Dornbirnerach fast near surface runoff k_s	1	0.2	0.1	0.5						
Dornbirnerach interflow k_i	5	1	0.5		0.5		1		0.2	
Dornbirnerach deep interflow k_d	10	2	1			0.2		1.33		0.1
Gail near surface runoff k_s	2			1	0.2	0.04				
Gail interflow k_i		2		5	1	0.2	2		0.4	
Gail deep interflow k_d			5	25	5	1		6.67		0.5
Perschling fast interflow (molasse) k_s		1			0.5		1	0.67		
Perschling deep interflow (flysch) k_i			0.75			0.15	1.5	1	0.3	
Wimitzbach schallow interflow k_i		5			2.5			3.33	1	0.25
Wimitzbach deep interflow k_d			10			2			4	1

Fig. 5. Relative response times between response units in normal flow situation based on discussions with the geologist. The matrix reads as follows: the response time of the row unit (e.g., Gail interflow) is VALUE times (e.g., 5 times) the response time of the column unit (e.g., Gail near surface runoff).

components, the Gail catchment has a slower deep interflow component than the Dornbirnerach. In the Perschling catchment, the response times of molasse and flysch components are not so different (the flysch response time being expected to be about 3/2 of the molasse one). A larger difference is expected between the shallow and deep interflow components of the Wimitzbach catchment (with a response time ratio of about 4).

We could perform the interview for each catchment separately but, in the spirit of comparative hydrology (Blöschl et al., 2013; Falkenmark and Chapman, 1989), we consider all catchments together and therefore obtain guesses for the response time ratios between response units belonging to different catchments (white boxes in Figure 5). This is also useful in providing arguments for checking the consistency of the table. For example near surface runoff and interflow in the Gail catchment are expected to have longer response times than the analogous components in the Dornbirnerach catchment (with a ratio of 2). The slowest response within the four catchments belong to the Wimitzbach catchment.

EXPERIMENTS

Experiment 1: test model structures and a-priori parameters with no calibration

First, in order to investigate whether the right model structure and parameters allow to obtain reasonable simulation results without calibration, the following experiment is conducted:

- All models are applied to all catchments using mid-range parameters, i.e., parameters selected at the mid point of the range of values they were developed for (assuming in some cases a logarithmic scale for the range, see Table 4, first 4 columns).
- All models are applied to all catchments using mid-range parameters and information on partition parameters and response time parameters as explained in the previous section (see Table 4, other columns).
- The performances are then compared in terms of ability to simulate the observed runoff.

Figure 6 shows simulated vs. observed discharges for all models in all catchments when the mid range parameters are used (red lines). The figure demonstrates that very different results are obtained with the different model structures even when the parameters corresponding to the model parts representing the same processes are selected equal (see Table 4, first 4 columns).

Figure 7 (top row) shows the results in terms of the Nash Sutcliffe efficiency both for discharges and log-transformed discharges. The efficiencies are low, almost all below the value of 0.5, but surprisingly high if one considers that no calibration at all has been performed. In almost all cases, the model developed explicitly for the catchment (full symbols in Figure 7) outperforms the other models, which seems to confirm our hypothesis that selecting model structures accordingly matters.

Figure 6 also shows simulated discharges for all models in all catchments when the parameters based on runoff generation mechanisms are used (green lines). The figure demonstrates that very different results are obtained with the different model structures even when the parameters are selected in a consistent

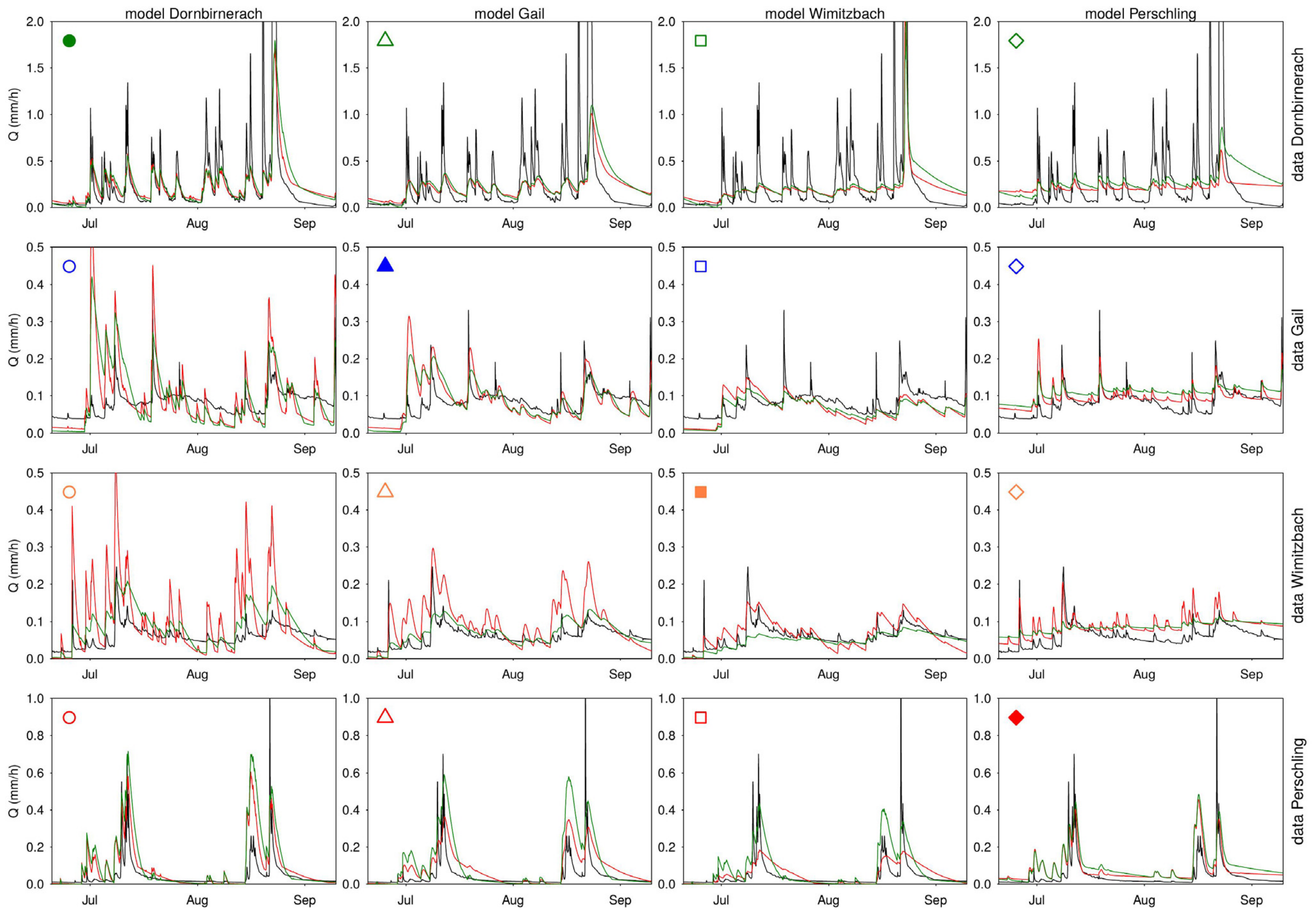


Fig. 6. Observed vs. simulated discharges of summer 2005 in the four catchments with the four models (summer months are shown for which snow accumulation and melt are not relevant). Observed discharges are in black; simulated discharges are in red when the mid-range parameters are used; simulated discharges are in green when the parameters based on runoff generation mechanisms are used (see Table 4).

Table 4. Mid-range parameters and parameters based on runoff generation mechanisms. (D = model for Dornbirnerach; G = model for Gail; W = model for Wimitzbach; P = model for Perschling).

		Mid range				Dornbirnerach				Gail				Wimitzbach				Perschling			
		D	G	W	P	D	G	W	P	D	G	W	P	D	G	W	P	D	G	W	P
ddf	(mm K^{-1} h^{-1})	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
t_s	(°C)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
t_m	(°C)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
SCF	(–)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
p_s	(–)	1/3	1/3		1/2	0.47	0.47		0.69	0.59	0.59		0.67	0.6	0,6		0.6	0.31	0.31		0.44
p_i	(–)	1/3	1/3	1/2	1/2	0.21	0.21	0.47	0.31	0.29	0.29	0.59	0.33	0.2	0.2	0.6	0.4	0.39	0.39	0.44	0.56
p_d	(–)	1/3	1/3	1/2		0.32	0.32	0.53		0.12	0.12	0.41		9.2	0.2	0.4		0.3	0.3	0.56	
e_s	(–)	1/3	1/3		1/2	0.47	0.47		0.69	0.59	0.59		0.67	0.6	0.6		0.6	0.31	0.31		0.44
e_i	(–)	1/3	1/3	1/2	1/2	0.21	0.21	0.47	0.31	0.29	0.29	0.59	0.33	0.2	0.2	0.6	0.4	0.39	0.39	0.44	0.56
e_d	(–)	1/3	1/3	1/2		0.32	0.32	0.53		0.12	0.12	0.41		0.2	0.2	0.4		0.3	0.3	0.56	
k_s	(h)	30	30		30	50	50		50	100	100		100	250	250		250	50	50		50
k_i	(h)	300	300	300	300	250	250	250	250	500	500	500	500	1250	1250	1250	1250	75	75	75	75
k_d	(h)	3000	3000	3000	3000	500	500	500	500	2500	2500	2500	2500	5000	5000	5000	5000	1000	1000	1000	1000
S_{smax}	(mm)	100	100		100	100	100		100	100	100		100	100	100		100	100	100		100
S_{imax}	(mm)			100	100			100	100			100	100			100	100			100	100
o_s	(–)		0.5				0.5				0.5				0.5				0.5		
o_d	(–)			0.5				0.5				0.5				0.5				0.5	
b	(–)				0.05				0.05				0.05				0.05				0.05
k_r	(h)	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10

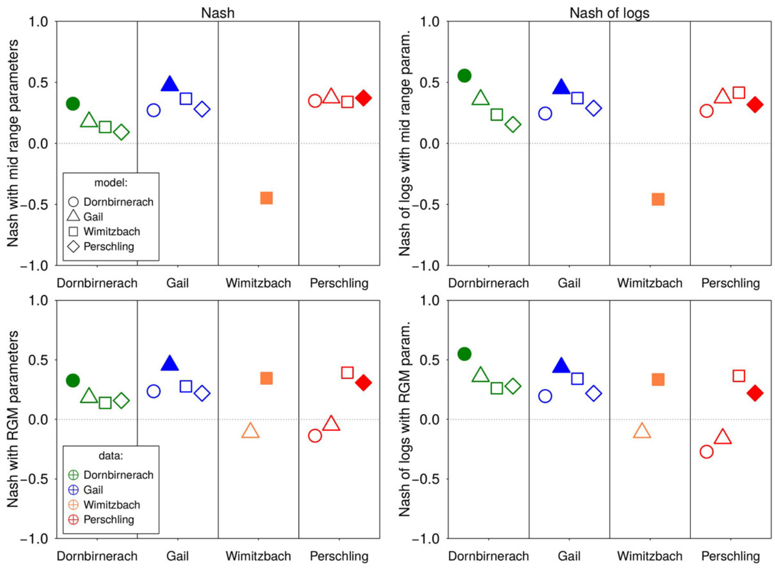


Fig. 7. Validation Nash Sutcliffe efficiencies for all models applied on all catchments when all parameters are selected as mid-range parameters (top row) or based on runoff generation mechanisms (bottom row).

way (see Table 4). Looking at the performances in Figure 7 (bottom row), the results are in most cases similar, between mid-range parameters and parameters based on runoff generation mechanisms, with the exception of the Wimitzbach catchment, where the performance of the mid-range parameters is extremely low for all models with the exception of the case when the right model with the a-priori parameters is used. In almost all cases, the model developed explicitly for the catchment (full symbols in Figure 7) outperforms the other models. This is not the case for the Perschling catchment for which the simpler model developed for the Wimitzbach provides better results.

Experiment 2: test model structure with calibration

In order to investigate whether the model structure per-se allows to obtain better simulation results when calibration is involved, the following experiment is conducted:

- For each catchment all models are calibrated on 6 years of data using as objective function a combination (the average) of the Nash-Sutcliffe efficiency measure applied to the hourly discharge data and to their logarithm.
- All parameters are calibrated with the exception of the ones related to snowmelt, which are assumed known and fix for every catchment and every model (see Table 2). The differential evolution optimisation algorithm (DEoptim in R, Mullen et al., 2011) is used and is run 15 times for each combination of model/catchment/calibration period.
- The performances are then compared for two 6 years calibration periods and for two 6 year validation periods (with the exception of the Wimitzbach/Gurk catchment for which shorter input data series are available).

Figure 8 shows the results in terms of the Nash Sutcliffe efficiency. There is no significant difference of the efficiencies in calibration and validation when all the discharge timeseries is considered. For the Wimitzbach catchment, the very simple model explicitly developed for it seems to perform slightly worse than the other models. This is interesting because the model performs very well for the other catchments, for which its efficiency is as good as the one of other models. Looking at the simulated time series (not shown here), very similar results are obtained with the different model structures because the calibration makes sure that the simulated runoff matches at best the observed one.

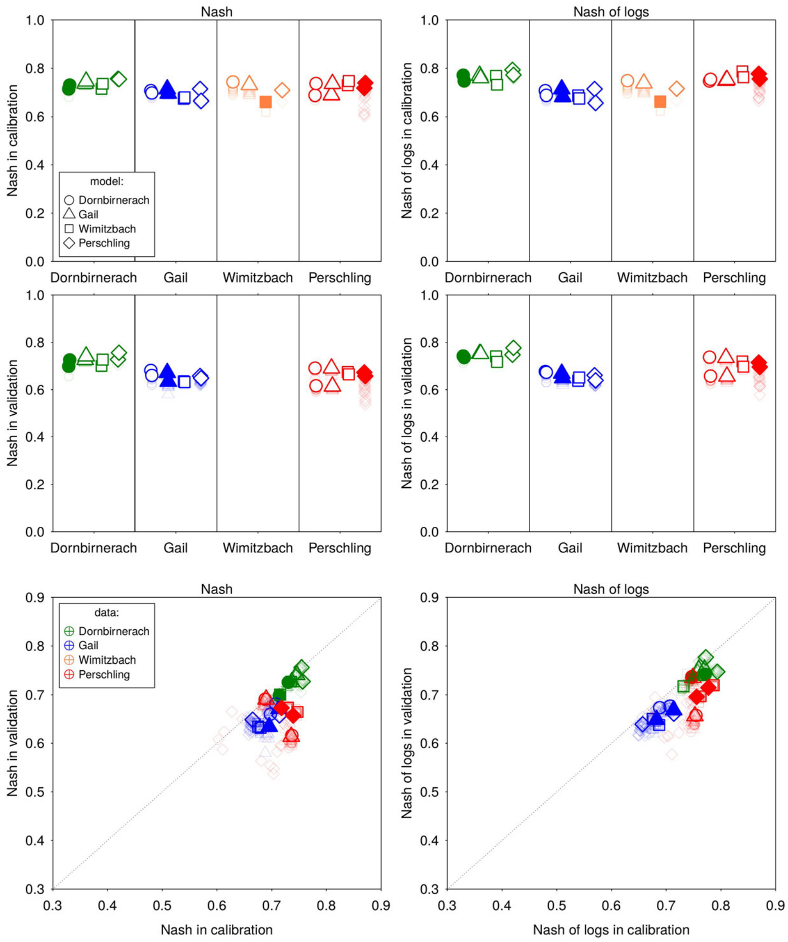


Fig. 8. Calibration and validation Nash Sutcliffe efficiencies for all models applied on all catchments when all parameters are calibrated. The results of the 15 calibrations are shown with light colours, while bold symbols indicate the results for parameters corresponding to maximum efficiencies obtained in calibration (within the 15 runs).

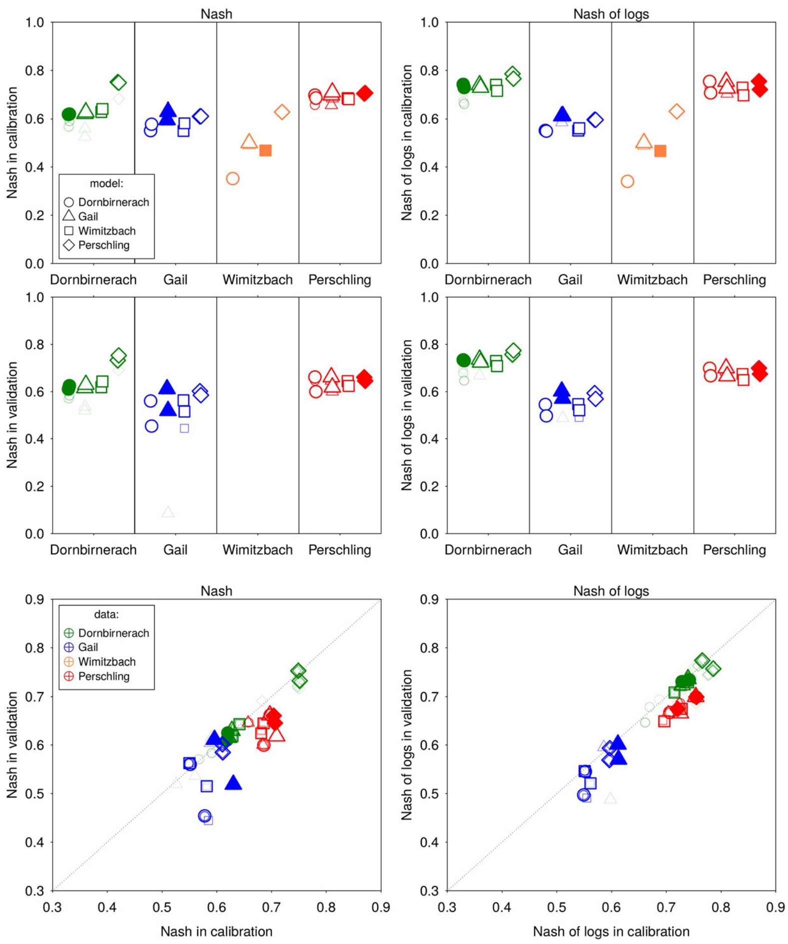


Fig. 9. Calibration and validation Nash Sutcliffe efficiencies for all models applied on all catchments when very few parameters are calibrated (a-priori information is used). The results of the 15 calibrations are shown with light colours, while bold symbols indicate the results for parameters corresponding to maximum efficiencies obtained in calibration (within the 15 runs).

Table 5. Parameters of the model calibrated for the catchments for whom they were developed on two periods, when all parameters are calibrated and when very few parameters are calibrated (a-priori information is used). The non-calibrated parameters are in italic.

	Dornbirnerach		Gail		Wimitzbach	Perschling	
	2000–2005	2005–2010	2000–2005	2005–2010	2004–2009	2000–2005	2005–2010
all parameters calibrated							
p_s	*0.80*	*0.90*	*0.24*	*0.31*		*0.65*	*0.33*
p_i	0.11	0.00	0.56	0.58	0.23	0.35	0.67
p_d	0.09	0.10	0.20	0.11	*0.77*		
e_s	0.30	0.50	0.10	0.35		0.60	0.19
e_i	0.34	0.42	0.20	0.08	0.08	0.27	0.78
e_d	*0.37*	*0.08*	*0.70*	*0.57*	*0.92*	*0.13*	*0.03*
k_s	95	64	441	241		4078	2232
k_i	2936	307	561	452	919	7048	2290
k_d	3460	460	7370	5912	6840	7350	4614
S_{smax}	23	23	17	15		870	31
S_{imax}					38	23	318
o_s			0.03	0.02			
o_d					0.03		
b						0.00	0.00
k_r	5.4	4.9	33.3	23.6	119.5	22.8	11.4
few parameters calibrated							
p_s	*0.47*	*0.47*	*0.59*	*0.59*		*0.44*	*0.44*
p_i	*0.21*	*0.21*	*0.29*	*0.29*	*0.60*	*0.56*	*0.56*
p_d	*0.32*	*0.32*	*0.12*	*0.12*	*0.40*		
e_s	*0.47*	*0.47*	*0.59*	*0.59*		*0.31*	*0.31*
e_i	*0.21*	*0.21*	*0.29*	*0.29*	*0.60*	*0.39*	*0.39*
e_d	*0.32*	*0.32*	*0.12*	*0.12*	*0.40*	*0.30*	*0.30*
k_s	24	17	151	88		4990	2650
k_i	*118*	*86*	*754*	*440*	1859	*7485*	*3974*
k_d	*236*	*173*	*3772*	*2202*	*7437*	*7546*	*4688*
S_{smax}	8	8	17	22		40	41
S_{imax}					94	618	397
o_s			0.00	0.00			
o_d					1.00		
b						0.00	0.00
k_r	3.1	3.2	118.3	40.8	119.9	26.3	13.9

Experiment 3: test a-priori parameters with calibration

In order to investigate whether a-priori information on model parameters allows to obtain better calibration results than by calibrating all parameters, an experiment similar to Experiment 2 is conducted, with the following differences:

- For each catchment all models are calibrated on 6 years of data using as objective function a combination (the average) of the Nash-Sutcliffe efficiency measure applied to the hourly discharge data and to their logarithm.
- The parameters related to the partitioning of water input in the buckets conceptualising the different geological zones, and those controlling the partitioning of evaporation, are set a priori based on the area percentages in Table 3. When the models have less buckets than what the geology would suggest, aggregations are made.
- The parameters describing the response times of the buckets are calibrated by maintaining the proportions shown in the matrix of model parameter ratios in Figure 5. Ratios of response times within catchment response units are used but not ratios between catchment response units.
- All other parameters are calibrated with the exception of the ones related to snowmelt, which are assumed known and fix for every catchment and every model (see Table 2). The differential evolution optimisation algorithm (DEoptim in R, Mullen et al., 2011) is used and is run 15 times for each combination of model/catchment/calibration period.
- The performances are then compared for two 6 years calibration periods and for two 6 year validation periods (with the exception of the Wimitzbach/Gurk catchment for which shorter input data series are available).

Figure 9 shows the results in terms of the Nash Sutcliffe efficiency and is analogous to Figure 8. There is a decrease in Nash Sutcliffe when going from full calibration to runoff-generation mechanisms based parameters (as would be expected) but the difference is not huge and the differences between calibration and validation decreases slightly (points are slightly closer to the 1:1 line in the bottom panels of Figure 9 than in Figure 8). Moreover, the parameters to be calibrated are fewer. Table 5 shows the parameters obtained for the catchments for whom they were developed on the two periods (with the exception of Wimitzbach), when all parameters are calibrated and when very few parameters are calibrated. When a-priori information on some of the parameters is used, in most of the cases also the other parameters get closer, between the two periods, than in the case where all parameters are calibrated. When looking at the simulated timeseries (not shown here), very similar results are obtained with the different model structures because the calibration makes sure that the simulated runoff matches at best the observed one, even though there seems to be some more variability than in the case of calibrating all parameters.

DISCUSSION AND CONCLUSIONS

Because of the diversity of hydrologic processes in different catchments, models need to be adjusted to the particular situation to accurately portray the hydrological fluxes. The standard procedure in hydrology is to adjust the model parameters to the local situation but to choose the model structure based on software availability, convenience or other logistic considerations (Holländer et al., 2009). However, because of the wide variety of processes, choosing a suitable model structure for a particular setting may be just as important, if not more important, than choosing suitable model parameters. The main hypothesis we have investigated is that a single model structure cannot capture the wide variety of hydrological processes and ad-hoc model structures are therefore needed. More generally, our aim is to understand the mapping between landscape structure and hydrological model structure through the identification of dominant processes.

In this paper we have developed hydrologic models based on field-mapped runoff generation mechanisms as identified by a geologist. For four different catchments in Austria, we have identified four different lumped model structures and constrained their parameters based on the field-mapped information. A repeatable framework for quantifying expert judgement as a-priori information on model parameters has been developed. In order to understand the usefulness of geologic information, we have then tested their capability to predict river discharge without calibration and using the standard split-sample calibration-validation procedure (see e.g., Klemes, 1986). All models have been compared against each other.

Choosing a suitable model structure in a particular catchment may not only help improve model performance, it may also be helpful in estimating the parameters from runoff data. For example, van Werkhoven et al. (2008, 2009) found that an appropriate choice of the model structure simplifies parameter estimation as the plausible parameter range is narrower if the model structure corresponds to the actual controls. Consistently with these studies, our results show that, when no calibration is involved, using the right model structure for the catchment of interest is valuable. This has to do with the fact that the models have been developed in a way that, when reasonable parameter values are used (e.g., mid range values), the catchment response is consistent with what is expected by the modeler (e.g., in terms of smoothness or flashiness of catchment response). A-priori information on model parameters does not always improve the results but allows for more realistic model parameters.

When calibration is performed, the differences between model structures do not result in difference in model performances. This is because calibration compensate for the structural differences (Beven, 2006; Blöschl, 2006). When a-priori information on some of the parameters is used, in most of the cases also the calibrated parameters get closer, between the two calibration periods, as compared to the case where all parameters are calibrated. There seems to be value in estimating the parameters from runoff generation mechanisms, that can be expected to be more realistic and lead to more robust in prediction. However, even when constraining many parameters with a-priori information, the within model results do not differ significantly. This is in contrast with our expectation of finding a stronger difference between results with different model structures when very few parameters are calibrated. Apparently the tuning of these few parameters is able to compensate for other differences. One of the reasons that may have determined this lack of difference between models, when calibration is performed, is the fact that information on runoff generation mechanisms has been used to develop lumped rainfall-runoff models. Since the available information is distributed in space, conceptualising the model in a spatially explicit way may have resulted into a better characterisation of the geology-related processes and in more distinct results between different models, even when calibration is performed (Grayson and Blöschl, 2000).

In this paper, a-priori information on runoff generation mechanisms has been used by selecting some of the model parameters (or parameter ratios) as fixed/exact values. Better performances may have been obtained by constraining these parameters by ranges or distributions. Ideally, a Bayesian framework could be used instead to formally account for a-priori information (see e.g., Kavetski et al., 2006a,b) and fuzzy numbers could be used to account for the imprecision of the information (see e.g., Salinas et al., 2016). The investigation of these hypotheses is left to further studies. Also, we have not looked here at how strong the input interpolation, the estimation of evapotranspiration and snowmelt modelling have influence the results. Sensitivity analyses will be performed in further studies in order to evaluate this and what are the parameters controlling the runoff goodness-of-fit for the different models.

Even though our results have not shown a significant advantage of selecting ad-hoc models and parameters when calibration is performed, the results obtained without calibration suggest that there is potential of this approach for ungauged catchments, where no calibration is possible and so a priori selection of models and parameters is necessary (Blöschl, 2005; Blöschl et al., 2013). For the same reasons, the modelling framework proposed in this paper has a potential to be suitable for investigating the effects of changes in controls (e.g., land use) in changing runoff regimes in the future (Ehret et al., 2014). Models selected by runoff generation mechanisms are expected to be more robust and more suitable for extrapolation to conditions outside the calibration range than models that are purely based on parameter calibration to runoff data.

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