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Can a regionalized model parameterisation be improved with a limited number of runoff measurements?

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SUMMARY

Application of hydrological models to ungauged basins is both a highly relevant and challenging task. While research has brought forth various approaches for inferring or transferring tuneable model parameters from gauged and calibrated catchments, it has also been recently shown that a few short measurements can support predictions in an ungauged basin by constraining the acceptable range of the parameters. For the present study, we examined a combination of both parameter regionalisation and short-term runoff measurements. More precisely, we attempted to select complete parameter sets from a range of calibrated catchments using a few measurements. Then, we tested a number of ways to combine the hydrographs simulated with these parameter sets with those simulated using a well-established Nearest Neighbour scheme, in order to make use of both actually measured runoff data as well as hydrological similarity. The experimental basis for our study were 49 representative catchments in Switzerland which have been successfully calibrated and regionalised with the hydrological modelling system PREVAH. Results show that even a few short measurements during mean runoff conditions can lead to models that are more efficient than those achieved with hydrological similarity alone. The possible improvement depends largely on the regime type of the catchment examined. Also, the most suitable season to perform measurements varies: In catchments dominated by snow melt or ice melt or both, considerable improvements can be achieved with as few as two measurements during spring or summer, whereas rainfall-dominated catchments show only moderate improvements with no particular season being more suitable for the measurements. Our findings highlight the value of field measurements in mountain areas. The information gained in these regions from short measurements may act as a counterbalance to the sparse operational observation networks.

1. Introduction

Long series of hydrological measurements are the basis for tackling highly relevant questions in water resources management and water-related natural hazards, which concern both the human as well as the natural environment. Since direct measurements are available for only a limited number of sites, predictions in ungauged basins are an important albeit challenging task. This is highlighted by the attention the topic has received through the International Association of Hydrological Sciences (IAHS) decade on predictions in ungauged basins (PUB) (Hrachowitz et al., 2013).

In this context, the value of short runoff measurements gathered during a targeted field campaign has been recognised recently. Rather than relying on long data series for calibration of conceptual models or attempting a fully physical parameterisation of the catchment, using short measurements might lead to a feasible way of achieving improved predictions for ungauged sites (see Beven, 2002). Developing this approach, Seibert and Beven (2009) demonstrated that even a relatively small number of runoff measurements help in constraining model predictions, provided that these measurements are timed sensibly. The value of additional data from groundwater levels (Juston et al., 2009), glacial mass balances (Konz and Seibert, 2010) and soft data (Seibert and McDonnell, 2013) has been shown in similar studies. Related analyses were also performed by Perrin et al. (2007, 2008) who relied on short, partly continuous series of runoff data to select parameters from a vast library of predefined sets. Drogue and Plasse (2014), finally, showed that runoff measurements at random times can improve distance-based regionalisation approaches.

In the present study, we examine whether a successful regionalisation (i.e. one that performs only slightly worse than a calibrated model) can be further improved with a number of

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short measurements. This question was studied thoroughly for the Nearest Neighbour regionalisation developed for the conceptual, process-oriented hydrological modelling system PREVAH (Precipitation-Runoff-EVApotranspiration-HRU related model; Viviroli et al., 2009a). The Nearest Neighbour scheme was chosen since it is based on extensive model calibration for 140 sites with long gauge data series. It therefore offers a large pool of model parameter sets and, at the same time, extensive data to scrutinize the value of the measurement data introduced. The latter is of particular importance since results may differ from catchment to catchment and from year to year, resulting in misleading findings if only a few cases are examined (Seibert and Beven, 2009). All of our parameter sets are derived from calibration and provide functional and mutually adjusted parameter combinations. In contrast to purely random ("Monte-Carlo") parameter sets, they have the large advantage that they do not contain many implausible parameter combinations and are thus a computationally effective basis for our experiments (see e.g. Bárdossy, 2007; Khu and Werner, 2003; Perrin et al., 2008; Viviroli et al., 2009b). We tested our approach for 49 out of the abovementioned 140 calibrated catchments, these 49 having continuous series of at least 20 years of runoff measurements at the hourly time-step, which allowed for a thorough analysis and assessment.

2. Experimental basis

2.1. Hydrological model

2.1.1. General description

All simulations for this study have been performed with PREVAH (Precipitation-Runoff-EVApotranspiration-HRU related model; for definition of HRU see below) (Viviroli et al., 2009a). PREVAH is a conceptual, process-oriented hydrological modelling system which has been developed based on the HBV model (Bergström, 1972; Lindström et al. 1997) and relies on the aggregation of gridded spatial information into hydrological response units (HRUs, see Ross et al., 1979; Gurtz et al., 1999). These HRUs unite areas of a basin where similar hydrological behaviour is expected, thus representing a computationally efficient, dynamic spatial discretisation: With increasing variability of the physical catchment characteristics, the size of the HRUs decreases, while the number of HRUs increases (for details, see Viviroli et al., 2009a). Raster cells of 0.5×0.5 km^2 have proven reasonable as a basis for generating HRUs (Viviroli et al., 2009b).

PREVAH has already been used successfully in a large number of catchments and for a broad range of topics in Switzerland and abroad (see Viviroli et al., 2009a for an overview). Recent applications include flood estimation (Viviroli et al., 2009b,c; Viviroli and Weingartner, 2011), studies of climate and land use change impacts on flood and low flow hydrology (Addor et al., 2014; Bosshard et al., 2014; Köplin et al., 2012, 2013, 2014a,b; Meyer et al., 2011; Schattan et al., 2013) as well as flood, drought and water resources forecasting at various lead times (Addor et al., 2011; Fundel and Zappa, 2011; Fundel et al., 2013; Jörg-Hess et al., 2014; Liechti et al., 2013; Romang et al., 2011; Zappa et al., 2014).

The basic parameterisation of PREVAH relies on the topographic analysis of a Digital Elevation Model (DEM), on land cover characteristics and on maps of soil types. Each HRU is provided with a set of parameters based on information derived from the DEM (elevation, aspect and slope) and the soil map (plant-available soil field capacity, soil depth, hydraulic conductivity). Information on land cover provides additional values required for determining evapotranspiration (albedo, root depth, interception storage capacity, vegetation height, leaf area index and minimum stomatal resistance of the various vegetation classes). Non-vegetated surfaces (snowpack, glaciers, rock, large water bodies and urban areas) are parameterised separately (Gurtz et al., 1999). Meteorological and geophysical pre-processing is handled by a suite of comprehensive tools (Viviroli et al., 2007, 2009a).

2.1.2. Model input, model parameters and parameter estimation

For the present study, PREVAH was run at an hourly time-step, being forced by series of six observed climatic variables at the same time-step, namely precipitation, air temperature, global radiation, relative sunshine duration, wind speed and relative humidity. All of these variables were interpolated in space with Detrended Inverse Distance Weighting and Ordinary Kriging (see e.g. Garen and Marks, 2001; Isaaks and Srivastava, 1989; for elevation effects and detrending, see also Goovaerts, 2000) and averaged to 100 m elevation bands. The catchment-specific tuneable parameters of PREVAH are found in Table 1.

To calibrate the tuneable parameters against observed runoff, PREVAH provides an automatic global search algorithm based on an iterative procedure that sequentially treats the parameters pair-wise and narrows down the considered parameter space step by step (Zappa and Kan, 2007). Although being straight-forward, the algorithm leads to stable efficiencies and plausible flow components by evaluating multiple efficiency criteria (for details see Viviroli et al., 2009b). In the model version used here, the parameter for soil moisture recharge (BETA) was not calibrated, but computed from soil depth and altitude for each HRU (for details see Viviroli, 2007). Details of the model's physics, structure and parameterisation are reported in the comprehensive description by Viviroli et al. (2007).

2.2. Regionalisation

The baseline parameterisation was derived from a Nearest Neighbour regionalisation approach. This approach essentially consists in identifying a calibrated donor catchment that is as similar as possible to the ungauged target basin in question. All tuneable model parameters are then transferred from the donor to the target as a complete, unaltered set, preserving the mutual adjustment of the calibrated model parameters (Kokkonen et al., 2003; Young, 2006). Catchment similarity can be determined, for example, from spatial proximity (see Patil and Stieglitz, 2012 and references therein) or, as done in this study and explained in more

Table 1
Catchment-specific tuneable parameters of PREVAH as used in the present study (for details see Viviroli et al., 2007).

Abbreviation	Description	Unit
BETA	Non-linearity exponent for soil moisture recharge	(–)
CG1H	Storage time for quick baseflow	(h)
ICERMF	Radiation melt factor for ice	(mm h^{-1} K^{-1} W^{-1} m^2)
ICETMF	Temperature melt factor for ice	(mm d^{-1} K^{-1})
K0H	Storage time for surface runoff	(h)
K1H	Storage time for interflow	(h)
K2H	Storage time for slow baseflow	(h)
PERC	Percolation rate	(mm h^{-1})
PKOR	Water balance adjustment factor for rainfall	(%)
RMFSNOW	Radiation melt factor for snow	(mm h^{-1} K^{-1} W^{-1} m^2)
SGR	Threshold for generation of surface runoff	(mm)
SLZ1MAX	Maximum storage available for fast baseflow	(mm)
SNOKOR	Water balance adjustment factor for snowfall	(%)
T0	Threshold temperature for snowmelt	(°C)
TMFSNOW	Temperature melt factor for snow	(mm d^{-1} K^{-1})