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Influence of spatial discretization, underground water storage and glacier melt on a physically-based hydrological model of the Upper Durance River basin

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SUMMARY

The SAFRAN-ISBA-MODCOU hydrological model (Habets et al., 2008) presents severe limitations for alpine catchments. Here we propose possible model adaptations. For the catchment discretization, Relatively Homogeneous Hydrological Units (RHHUs) are used instead of the classical 8 km square grid. They are defined from the dilineation of hydrological subbasins, elevation bands, and aspect classes. Glacierized and non-glacierized areas are also treated separately. In addition, new modules are included in the model for the simulation of glacier melt, and retention of underground water. The improvement resulting from each model modification is analysed for the Upper Durance basin. RHHUs allow the model to better account for the high spatial variability of the hydrological processes (e.g. snow cover). The timing and the intensity of the spring snowmelt floods are significantly improved owing to the representation of water retention by aquifers. Despite the relatively small area covered by glaciers, accounting for glacier melt is necessary for simulating the late summer low flows. The modified model is robust over a long simulation period and it produces a good reproduction of the intra and interannual variability of discharge, which is a necessary condition for its application in a modified climate context.

1. Introduction

The impact of global change on regional climates and in turn on water resources is expected to be especially pronounced in mountainous areas and in alpine domains in particular (EEA, 2009). Future hydrological scenarios required for impact studies are classically performed with hydrological models using future meteorological scenarios based on General Circulation Model (GCM) outputs.

For alpine catchments, some key hydrological processes are related to snow accumulation and melt. A number of climate change impact studies have been carried out with temperature-index approaches (e.g. Jasper et al., 2004; Schäfli et al., 2007 for alpine catchments). They usually give satisfactory validation results (Zappa et al., 2003). Input data (i.e. air temperature and precipitation) are easily available from GCM outputs and these parsimonious models are well suited for extensive uncertainties analysis (associated with GCM and downscaling models for the development of meteorological scenarios adapted to the scales of hydrological impact studies). However, they do not account for all of the physical processes involved in the snowpack evolution (e.g. non linearity of some processes with respect to temperature). Physical reasons for changes in snowpack space–time behaviour and for hydrological changes cannot be tracked, and due to their empirical nature, they also lack spatial and temporal transposability.

These limitations are expected to be less poignant for physically based models which compute snow accumulation and melt from energy and mass fluxes between the atmosphere, the snowpack, and the ground. Despite the usual difficulty of providing reliable input data, energy balance snow schemes have been implemented successfully in hydrological models for various hydroclimatic contexts (e.g. Lehning et al., 2006; Etchevers et al., 2001b over the Swiss and French Alps). However, appropriate meteorological input data are not always available for future climate scenarios. The only hydrological applications of such models to the French Alps in a modified climate context were carried out by Etchevers et al. (2002) for the Rhone river basin and Boé et al. (2009) for the entire French metropolitan territory. Both researches used the SAFRAN-ISBA-MODCOU (SIM) hydrological model from Météo France (Habets et al., 2008). Scenarios obtained for the

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French Alps have to be considered with caution due to the poor performance achieved by the model for the present climate in the region (Habets et al., 2008) (e.g. large underestimation of winter and of late summer low flows, large temporal shift between observed and simulated snowmelt spring flood). The present work presents possible improvements of SIM for a more relevant simulation of alpine catchment hydrological behaviour. A description of the Upper Durance River (UDR) basin and of the SIM model principles are given in Section 2. Adaptations of the model are extensively detailed. Results are described in Section 3, with a set of sensitivity tests which were done to evaluate the role of each model modification, and an analysis of the model transferability. A discussion of results, model limitations, and further model improvements follows.

2. Dataset and models

2.1. The Upper Durance River (UDR) basin

The UDR basin is a mesoscale basin (3580 km^2) located in the Southern French Alps. Its outlet is at the Serre-Ponçon lake, which is regulated by a large dam operated for hydropower production by Electricité de France (EDF), with a key role for modulating the water supply in Southeastern France. Contrary to most alpine basins in this region, the UDR discharges are mostly natural upstream of the lake. The climate is much drier than in the Northern French Alps (Durand et al., 2009) due to the influence of the Mediterranean and to the protection from oceanic disturbances by the relatively high Ecrins mountains. Rainfall and snowfall spatial variability is usually high inside the catchment. The Queyras region in the eastern part is the driest, but heavy precipitation can occur when easterly winds, associated with a low pressure system in Genoa Bay, bring humidity from Italy. With altitudes ranging from 700 to 4100 m, the catchment produces highly seasonal flows: minimum and maximum discharges are observed in winter and spring, respectively, mainly due to snow accumulation and melt. Nevertheless, major floods can be observed in fall due to thunderstorms with large liquid precipitation amounts. Winter low flows are observed throughout the season and can last for 3 months or more. At the UDR basin outlet, the corresponding volume (30 m^3/s over 3 months) represent approximately 10% of the average annual yields. Late summer and fall river discharges have a number of marked recession sequences lasting several weeks after the end of the snow-covered period, even for years with negligible precipitation during these seasons. These recessions and winter low flows are probably sustained by various aquifers, as suggested by Lardeau (1977) and Obled (1980). 39 km^2 of the UDR basin are covered by glaciers according to the CORINE Land Cover database (Heymann, 1993). As highlighted by previous works in similar areas (Hingray et al., 2010; Lambrecht and Mayer, 2009), glacier melt is expected to produce a significant contribution to late summer discharges for some UDR subbasins. Late summer discharges observed for right bank tributaries with an upper glacier system are proportionally much higher than those observed for left bank tributaries which are ice-free. Daily discharges measurements are available for eight gauging stations on the Durance river and its main tributaries (Ubaye, Guil, and Guisane, Table 1 and Fig. 1a). For the Serre-Ponçon lake outlet, natural discharges have been reconstructed by EDF for the 1950–2009 period from observed lake levels and dam operations. These nine discharge time series are further used for model evaluation.

2.2. The SIM hydrological model

SIM is used for flood forecasting, drought monitoring, water budget, and climate change impact studies for the entire metropolitan French territory (Habets et al., 2008). It combines a meteorological analysis (SAFRAN), a land surface scheme (ISBA), and a distributed hydrogeological model (MODCOU). The basic simulation methodology is as follows: Meteorological surface variables from SAFRAN are interpolated on a 8 km square grid and are used to force ISBA at the same spatial resolution (SAFRAN and ISBA are described in more details in the following subsections). Runoff and drainage simulated by ISBA are used as input to MODCOU for the simulation of the water transfer and the routing to and within the river network (Ledoux et al., 1989). The transfer of surface flows is simulated through a geomorphologic isochronic approach. Routing in the river is achieved through a cascade of conceptual reservoirs. For our study, SIM is used for the simulation of daily discharges. As the concentration time of the UDR basin is slightly lower than the day, the transfer and routing modules of MODCOU show little sensitivity. The MODCOU hydrogeological module is currently used for simulating deep underground water storage and river-aquifer exchanges in basins with large aquifer systems, i.e. in the Seine River and Rhône River Basins. No such aquifers were identified and simulated for alpine basins. As a result, the MODCOU component of SIM has no effect on simulated discharges in the UDR basin. It was thus omitted in our study, as was also done in Strasser and Etchevers (2005).

2.2.1. The meteorological analysis SAFRAN

The 1958–2006 SAFRAN analysis is used to provide meteorological inputs to ISBA at an hourly time step. Initially developed for avalanche forecasting purposes in the French Alps (Durand et al., 1993, 2009), the SAFRAN analysis has been extended over the entire French territory (Quintana-Segui et al., 2008; Vidal et al., 2010). Temperature, humidity and wind speed profiles are provided for climatically homogeneous areas, at a 6 h time step and at a 300 m vertical resolution: first guess fields come from the

Table 1
River flows measurements stations and main catchment characteristics.

Station	River	Altitude (m)	Area (km^2)	Availability	Operator
Le Monêtier	Guisane	1510	78	1978–2008	DIREN[a]
Val-des-Prés	Durance	1360	203	1975–2008	DIREN
Briançon	Durance	1187	548	1955–2007	EDF[b]
Montdauphin	Guil	950	725	1986–2007	EDF
L'Argentière	Durance	950	984	1952–2008	DIREN
Embrun	Durance	787	2170	1960–2007	EDF
Barcelonnette	Ubaye	1132	549	1958–2008	DIREN
Le Lauzet-Ubaye	Ubaye	790	946	1960–2007	EDF
Espinasses	Durance	652	3580	1950–2006	EDF

[a] Direction Régionale de l'Environnement.
[b] Electricité de France.