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Exploration of sequential streamflow assimilation in snow dominated watersheds

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ABSTRACT

This paper evaluates Ensemble Kalman filter (EnKF) sequential data assimilation on a semi-distributed hydrological model implementation on two snow-dominated watersheds, focussing strictly on snow accumulation and melt periods while assimilating streamflow for the updating of various state variables combinations. Three scenarios are explored in depth: (1) updating the three state variables that were previously identified pertinent for snow-free hydrological processes: soil moisture in the intermediate layer, soil moisture in the deep layer, and the overland routing reservoir, (2) updating the snow water equivalent, and (3) updating all of the above state variables. Inputs (precipitation and temperature) and output (streamflow) perturbation factors are first identified for each scenario, based on their performance and reliability for simulation with assimilation. The three EnKF implementations are next compared to one another and to an open-loop run, in an ensemble forecasting context. The third scenario outperforms the others in most situations and provides the largest gain in reliability. The ensemble size may also be reduced, from 1000 to 50 members, without much loss in performance or reliability.

1. Introduction

The quality of a hydrological forecast largely depends on the identification of proper (watershed) initial conditions, which may be achieved through various data assimilation techniques. For short-term ensemble forecasting, uncertainty in these initial conditions needs to be taken into account [12]. For instance, Abaza et al. [1], as others before them, obtained under-dispersed ensemble hydrological forecasts in the first few horizons when neglecting the uncertainty of the initial conditions.

Data assimilation combines information from a variety of sources to improve forecast accuracy while accounting for the uncertainty of the measured data and of the prediction model. The literature abounds in data assimilation techniques appropriate for hydrology. The Ensemble Kalman filter (e.g. [14,16,32]), the particle filter (e.g. [29,30,40]), and variational methods (e.g. [34,35,38]) are prominent among them, as detailed by Liu and Gupta [26], Liu et al. [27] and Reichle [33]. Typical assimilated observations include streamflow [34], soil moisture [5,17], and snow [4,10,41], for hydrological models of various level of complexities. Rudolph Emil Kalman developed a sequential filter in 1960 applicable to linear models [25]. Non-linear ones have to be linearized beforehand, exploiting their Jacobian: a variant named Extended Kalman filter (EKF) [22]. But instability under strong nonlinearities and high computational cost when the Jacobian has to be derived limit EKF usage. The Ensemble Kalman filter (EnKF), introduced in 1994 by Geir Evensen, circumvent these limitations, improving the states of non-linear models over the EKF.

This paper evaluates an EnKF implementation for a semi-distributed hydrological model, exploring the effectiveness and the capacity of the EnKF to improve operational streamflow forecasts during the snow accumulation and melt periods. Although there have been many data assimilation studies where snow-related state variables are updated based on snow observations, we have found no other study in which snow-related state variables are updated based uniquely on streamflow observations. For many watersheds, no observations of the water equivalent of the snowpack are available. What this paper aims to show is that assimilation of streamflow in the presence of snow is still possible, but presents specific challenges, and requires different strategies than

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for the warm season. The analysis focusses on the sequential updating of the snow water equivalent, alone or in addition to the three state variables identified beforehand for non-snow-dominated periods: the soil moisture in the intermediate layer, the soil moisture in the deep layer, and the overland routing reservoir.

Watershed, database, model description, and sequential data assimilation are described in Section 2, followed by the experimental set-up in Section 3. Results and discussion are next provided in Section 4 and a conclusion is given in Section 5.

2. Material and methods

2.1. Watersheds and data

The analysis concerns two watersheds located in the Province of Québec (Canada), where hydrological regimes are dominated by a spring freshet and higher flows late into fall. The au Saumon watershed drains 767 km^2 of mostly forested land (gauging station 030282) while the des Anglais watershed drains 643 km^2 of a land mostly occupied by agriculture and forest (gauging station 030907). Fig. 1 illustrates the different characteristics of the two watersheds (land cover, soil texture and gauge station location).

Data include 3-h streamflow time series at the outlet of the watersheds and 3-h rainfall and temperature time series krigged to a 0.1° resolution grid encompassing the river systems (source: Centre d'Expertise Hydrique du Québec, CEHQ).

Hydrological ensemble forecasts are calculated from the global meteorological ensemble forecasts provided by the Canadian Meteorological Center (CMC). It consists of 20-member at a 3-h time step, 100-km resolution for 2011 forecasts and 66-km for 2012 forecasts (at mid-latitudes) and 15-day forecast horizon calculated by the Global Environmental Multiscale model (GEM). Available meteorological forecasts are issued at midnight and bilinearly interpolated to the 0.1° resolution grid of the CEHQ observations.

Simulation with assimilation is performed from January to May 2011 and 2012, after a 2-yr warm-up period. Hydrological ensemble forecasts are issued from February to May. Mean observed streamflow from January to May reaches 25.5 m^3/s in 2011 and 23.5 m^3/s in 2012 for au Saumon and 25.6 m^3/s in 2011 and 13.0 m^3/s in 2012 for des Anglais.

2.2. Hydrotel model

Hydrotel [18,19] is a semi-physical distributed hydrological model. It is operationally used among others by CEHQ [37] to simulate reservoir inflows. It accounts for the variability of the hydrological processes within the watershed, exploiting Relatively Homogeneous Hydrological Units (RHHU): small portions of territory within which the topography, land use, and soil types are considered uniform.

Users must provide Hydrotel with a digital elevation model, a vector map of the river network, a map of the land use, and another one of the soil types. Various approaches are available to the user to represent each hydrological process such as surface and groundwater flows, as well as vertical exchanges. Hydrotel is a three-layer model with four types of state variables associated with snow cover, soil moisture, overland routing reservoirs and river routing reservoirs. Vertical water budgets are computed locally on each RHHU. Variables and flows of the vertical water budgets have been defined to represent approximately the physical macro-processes involved in the infiltration and vertical redistribution of water on the scale of a soil column corresponding to the simulation unit. The principal components of the Hydrotel model are illustrated in Fig. 2. Calibrated parameters were provided by the CEHQ and are routinely used by them for forecasting. In the au Saumon watershed, the Nash coefficient over the global calibration period (2000–2010) reached 0.59, but is only 0.29 in the calibration period of the des Anglais watershed (2008–2010).

2.3. The Ensemble Kalman filter

Data assimilation aims to combine information provided by the observations and the model simulations into an optimal estimate of the hydrological fields of interest, with an objective to deal with uncertainty from measurements, inputs, outputs, and model structure [26,27,33,39].

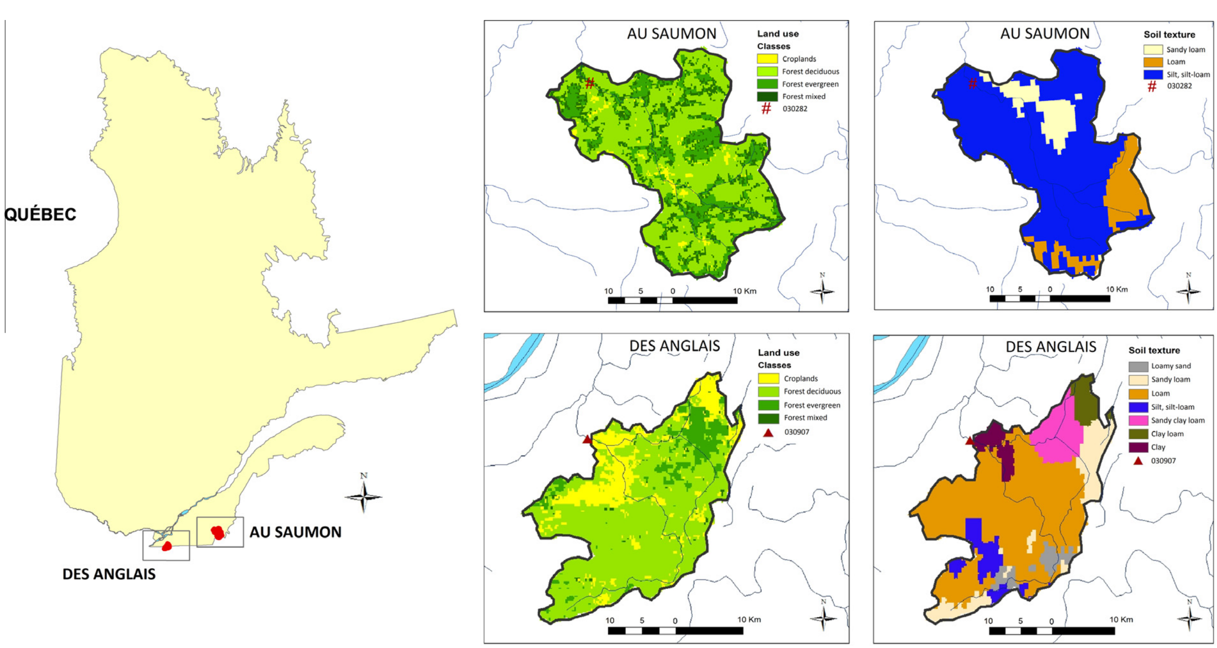

Fig. 1. Localisation of the au Saumon and des Anglais watersheds (Province of Québec, Canada): soil type distribution, land cover distribution, and gauge station.