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Impact of temporal resolution of inputs on hydrological model performance: An analysis based on 2400 flood events

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SUMMARY

Hydro-climatic data at short time steps are considered essential to model the rainfall–runoff relationship, especially for short-duration hydrological events, typically flash floods. Also, using fine time step information may be beneficial when using or analysing model outputs at larger aggregated time scales. However, the actual gain in prediction efficiency using short time-step data is not well understood or quantified. In this paper, we investigate the extent to which the performance of hydrological modelling is improved by short time-step data, using a large set of 240 French catchments, for which 2400 flood events were selected. Six-minute rain gauge data were available and the GR4 rainfall–runoff model was run with precipitation inputs at eight different time steps ranging from 6 min to 1 day. Then model outputs were aggregated at seven different reference time scales ranging from sub-hourly to daily for a comparative evaluation of simulations at different target time steps. Three classes of model performance behaviour were found for the 240 test catchments: (i) significant improvement of performance with shorter time steps; (ii) performance insensitivity to the modelling time step; (iii) performance degradation as the time step becomes shorter. The differences between these groups were analysed based on a number of catchment and event characteristics. A statistical test highlighted the most influential explanatory variables for model performance evolution at different time steps, including flow autocorrelation, flood and storm duration, flood hydrograph peakedness, rainfall–runoff lag time and precipitation temporal variability.

1. Introduction

1.1. Importance of short time-step data

The transformation of rainfall into streamflow includes a large number of processes, with various dynamics and characteristic time scales on the order of 1 min to hundreds of years (Blöschl and Sivapalan, 1995). The proper description and simulation of these processes may require short time steps for at least three reasons: (i) because of the short duration of the modelled runoff events (e.g. flash floods); (ii) because of the considerable intra-storm variability that controls some runoff processes and (iii) for numerical reasons especially related to the integration of differential equations in the model structure. This raises the issue of the appropriate time step of data used as input to hydrological models (typically precipitation).

Until the 1990s, hydrologists had to rely mostly on data at the daily step at best, e.g. ground accumulated rainfall amounts recorded once a day by observers. This could cause limitations in the applicability of rainfall–runoff models needing shorter time steps, which had to be run with data disaggregated over the shorter time steps either uniformly or by mass curves (Blöschl and Sivapalan, 1995) or by more sophisticated stochastic generators (Creutin and Obled, 1980). However, over the last two decades, the availability of hourly and even sub-hourly data tremendously increased in many countries, especially with the implementation of automatic rain gauge networks and meteorological radars (e.g. Berne and Krajewski, 2013; Creutin and Borga, 2003). This boosted the development of hydrological models running at short time steps to make use of these available data (e.g. Chu and Steinman, 2009; Hughes, 1993; Jeong et al., 2010; Moretti and Montanari, 2007).

One idea underlying these developments is that data at short time steps contain more information and therefore should contribute to better modelling of the rainfall–runoff relationship. This is supported by several studies that showed that runoff generation is highly affected by sub-hourly dynamics of precipitation, particularly where the infiltration-excess overland flow mechanism dominates the rainfall–runoff response (e.g. Kandel et al., 2005;

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Koch and Kekhia, 1987; Krajewski et al., 1991; Morel-Seytoux, 1988; Paschalis et al., 2014; Woolhiser and Goodrich, 1988). The precipitation controls the high-frequency catchment response, contrary to evapotranspiration whose variations are much more smoothed (Oudin et al., 2006). The temporal distribution of rainfall affects not only the runoff temporal distribution, i.e. flood shape, but also the peak discharge value (Gabellani et al., 2007) and the runoff volume (Viglione et al., 2010). This is due to the nonlinear nature of infiltration (and runoff) processes, with characteristic time scales of a few minutes (Blöschl and Sivapalan, 1995; Kandel et al., 2005). Woolhiser and Goodrich (1988) point out the significance of the rainfall intensity–infiltration interaction using a simple physically based model, concluding that the constant intensity rainfall pattern on an hourly scale cannot be recommended, especially for rapid catchments. Various studies have shown that infiltration excess surface runoff is modelled better using a sub-daily time step rather than daily time-step models, and peak rates of rainfall are recognized as the most important controls for rainfall–runoff modelling (e.g. Kandel et al., 2004, 2005; Socolofsky et al., 2001; Yu et al., 1998).

1.2. Modelling at short time steps to evaluate at larger time steps

Given the importance of sub-daily variability of rainfall for runoff modelling, one may be more confident in a model running with short time-step data than a model running with larger time-step data, even when the target model assessment time step is large. However, in the literature there is a limited number of case studies on only a few catchments, where a rainfall–runoff model is run at a short time step and its outputs are used or evaluated at a larger time step (e.g. Finnerty et al., 1997; Hughes, 1993; Jeong et al., 2010; Kannan et al., 2007; Schreider and Jakeman, 2001; Yang et al., 2016). Typically (sub-)hourly or daily time steps are used for running the model and then performance assessment is based on daily or monthly aggregated outputs, respectively. Hughes (1993) discussed the advantages of using fine sub-daily time steps up to 5 min by applying a variable time-step model structure to two semi-arid catchments and a total of six storm events. The results suggested that the simulated runoff volume may be improved as the time step decreases up to 1 h for one catchment and even up to 5 min for the other catchment with higher rainfall intensities and a faster response. Finnerty et al. (1997) analysed the sensitivity of the SAC-SMA model to the spatial and temporal discretization of rainfall inputs while holding the parameters constant. They showed that the runoff volumes cumulated over a 9-month period significantly changed when the time step decreases from 6 h to 1 h. The surface runoff resulted in being the most temporally sensitive model component, which is attributed to the varied averaging of high-intensity short-duration precipitation events that affect surface runoff. Jeong et al. (2010) developed a sub-hourly version of the SWAT model and tested it on a small catchment. They showed the improvement in model performance when sub-daily predicted streamflows (at 15 min and 1 h) are aggregated to daily averages compared to daily simulation results. Similar results were shown also by Yang et al. (2016), using hourly and daily rainfall observations as inputs of the SWAT model for daily streamflow simulation on one medium-sized catchment, while, for the same model, contrasting results were found by Kannan et al. (2007) for the ranking of sub-daily and daily inputs options on one small catchment.

Despite these overall encouraging findings, the common modelling practice is still to choose the model and input data time step equal to the evaluation time step. The assessment of aggregated outputs using shorter time-step data is rarely reported, even among the increasing number of studies examining the time scale dependencies of rainfall–runoff model parameters (e.g. Bastola and Murphy, 2013; Littlewood and Croke, 2008, 2013; Littlewood et al., 2011; Ostrowski et al., 2010; Wang et al., 2009). In these studies, simulation outputs and performance scores at different time steps are sometimes compared at one aggregation time scale, daily or hourly (e.g. Wang et al., 2009) and sometimes without a preliminary aggregation (e.g. Littlewood and Croke, 2008). However, the rankings of model performance at different time steps may depend on the evaluation time scales chosen for comparative analysis. A comparison across a wide range of evaluation time scales could help find general tendencies or specific behaviours emerging at certain time scales.

The case of artificial reservoirs is an example of an application of hydrological models that could benefit from time steps shorter than the operation model time step. For large flood-control or water-supply reservoirs, their management may only require the forecast of daily inflows, but these daily inflow forecasts may be obtained using an hourly model and aggregating the outputs to obtain the daily inflow. This could provide a better description of flood events, which contribute most of the flow volume. Although this approach is still rare in the reservoir operation literature, examples of its advantages can be found. For example, Schreider and Jakeman (2001) applied the IHACRES model at a 4-hourly time step for ten catchments in the Upper Murray Basin, feeding Hume and Dartmouth lakes, two of Australia's four largest reservoirs. They showed that long-term daily forecasts of streamflows used for reservoirs' operational management can be obtained by aggregating the 4-hourly step simulations with the same or higher accuracy than by daily model simulations.

Although this approach of using shorter time steps intuitively makes sense, there are several reasons that may limit the added value of short time-step data when looking at results at larger aggregated time scales. First the model input data, especially rainfall, may have a lower signal-to-noise ratio at shorter time steps due to the greater difficulty validating data and the greater uncertainty in areal averaged rainfalls (Obled et al., 2009; Yu et al., 1997). Second, catchments behave like low-pass filters, which may smooth out the short-term variability of input and limit the sensitivity of outputs to this additional information. This may be especially true when the characteristic time of studied events is far longer than the time step used (e.g. Obled et al., 2009). The model structure itself may also be less appropriate to catch the greater complexity of processes at shorter time steps, as already expressed for example by Hughes (1993). Last, the averaging effect of output data aggregation may also limit the usefulness of using fine time-step input data. Hence, it is useful to investigate the influence of the time step on modelling results, since there may be a compromise between the expected advantages obtained by refining the inputs and the model time step, and the possible limits affecting model efficiency at shorter time steps more than at the larger evaluation time step.

1.3. Scope and structure of the article

The literature review has shown that, despite the general knowledge of the importance of sub-daily variability of rainfall for flood volume modelling, the advantages of using rainfall data at fine temporal resolution for flow simulation are still not well quantified. There is a need for further investigations to evaluate the usefulness of fine time-step information for hydrological model simulations, by comparing different model time-step outputs at common aggregated time scales, using a large set of catchments. A parallel can be made between these investigations on the temporal discretization issue and the studies conducted to investigate the impact of refined spatial discretization of catchments on modelling results, which have received more attention in the literature (see e.g. Das et al., 2008; Lobligeois et al., 2014; Obled et al., 1994).