ASSIMILATION OF SATELLITE SOIL MOISTURE DATA INTO RAINFALL-RUNOFF MODELLING FOR SEVERAL CATCHMENTS WORLDWIDE

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ABSTRACT

The assimilation of satellite soil moisture data into rainfall-runoff modelling represents an important issue not only for research purposes but also for hydrological application addressing flood forecasting. Notwithstanding the large effort made in the last three decades, only few studies demonstrated a benefit deriving from the use of satellite soil moisture data in hydrology. This matter can be ascribed to the differences in the quality of the assimilated data, in the climatic conditions and in the data assimilation techniques that have been adopted. Based on that, this study compares different satellite soil moisture products in different catchments worldwide to shed light about the more suitable products and climatic conditions that should be employed for improving runoff prediction. The results reveal that the employed soil moisture products can be conveniently used to improve runoff prediction. However, reliability differs according to the climatic region and the accuracy of satellite retrievals.

Index Terms— Soil moisture, data assimilation, remote sensing, rainfall-runoff modelling

1. INTRODUCTION

In recent years, steady increases in flood damages have led to a growing interest in the development of flood forecasting systems operating in near real-time. Accurate streamflow predictions are of considerable value for mitigating flood damages and flood forecasting systems have been widely approached by using rainfall-runoff models [1, 2]. A large number of rainfall-runoff models are available with different levels of complexity and, sometimes they are used as operational flood prediction tools with a sufficient level of accuracy. However, uncertainties in model structure, model parameters and input/output observations strongly impact the accuracy of the predictions. To reduce this limitation, hydrological data assimilation, especially assimilation of remotely sensed data into rainfall-runoff modelling, has become an important issue for hydrological research and applications. In particular, the assimilation of soil moisture observations has the potential to provide great benefits for runoff prediction in catchments whose hydrologic response is strongly influenced by the initial state of soil wetness [3, 4].

Nowadays, at one hand, soil moisture estimates from satellite sensors and global meteorological models are becoming more readily available with a spatial and temporal resolution that is suitable for hydrological applications [5]. On the other hand, different data assimilation techniques have been developed and proposed for the optimal integration of soil moisture observations into rainfall-runoff modelling. Notwithstanding these large efforts, even after three decades of attempts to improve hydrological predictions through the process of data assimilation, genuine 'success stories' continue to be rare, arguably due to differences in the quality of data and models used in different applications [6]. Some of the most relevant issues that have still to be addressed are: (i) the improvement of the hydrological information retrieval from remotely sensed data, (ii) the choice of the optimum data assimilation method, (iii) the quantitative description of model and observation errors, (iv) the choice of assimilated data and the evaluation of data assimilation effectiveness [7].

The main purpose of this study is to address some of the above issues by assimilating different soil moisture products (from remote sensing and global modelling) into rainfall-runoff modelling for six catchments located in Italy, France, Luxembourg and US. The use of different soil moisture products and study catchments provides an in-depth understanding of the value of soil moisture data assimilation into rainfall-runoff modelling. Specifically, the runoff simulations with and without the assimilation of soil moisture are compared and discussed.

2. STUDY CATCHMENTS

Six catchments located in four different countries are selected for this study (see Fig. 1). Specifically, two catchments in central Italy (Niccone, 137 km² and Assino, 165 km² [2]), one in South Italy (Fiumarella, 33 km² [8]), Luxembourg (Bibeschbach, 12 km² [4]), France (Valescure, 3.7 km² [9]), and US (Lucky Hills, 0.001 km² [10]) are analyzed. For sake of brevity, the reader is referred to the cited references for more details about the characteristics of the catchments and of the available hydrometeorological data. The catchments are characterized by different size and, specifically, by large differences in the climatic conditions (from very arid at Lucky Hills to cold and wet at Bibeschbach). For each catchment, hourly rainfall, temperature and runoff data for the period 2007-2010 are employed.

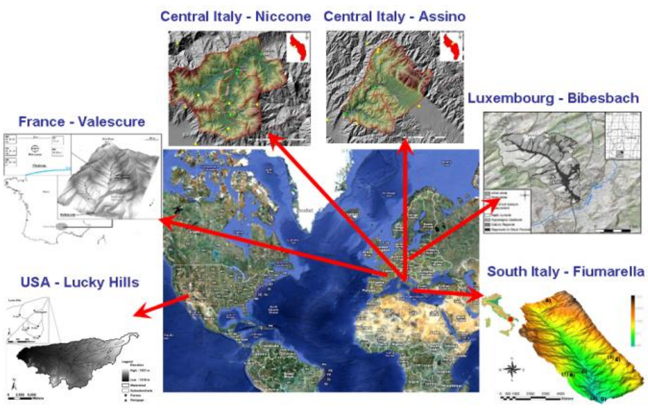

Fig. 1. Location of the six catchments selected in this study.

3. SOIL MOISTURE DATASETS

The soil moisture products derived from two different satellite sensors, the Advanced Scatterometer (ASCAT) and the Advanced Microwave Scanning Radiometer for the Earth observations (AMSRE), are used. The TU-Wien change detection algorithm [11] and the Land Parameter Retrieval Model [12] are adopted to retrieve soil moisture from ASCAT and AMSRE sensors, respectively. The two products have a spatial resolution of ~25 km and a daily revisit time; the layer depth investigated by the two sensors is less than 5 cm. Moreover, a modelled soil moisture product developed in the context of EUMETSAT's H-SAF (Satellite Application Facility in Support to Operational Hydrology and Water Management) project is employed. This root zone soil moisture product has been developed based on ASCAT surface soil moisture data assimilation into the ECMWF Land Surface Data Assimilation System [13]. The modelled soil moisture product is available for four soil layers (0-7, 8-28, 29-100, 101-289 cm) at ~80 km spatial resolution and daily temporal resolution. The weighted averaged product for the 0-100 cm soil layer is used in this study. In the following, the three products will be named ASCAT, AMSRE and ECMWF and, for sake of simplicity, they are all referred as "satellite data". We finally note that ECMWF data are only available for the period Jun2008-May2010.

As mentioned above, satellite sensors are only sensitive to a very thin surface soil layer. Therefore, their integration in rainfall-runoff modelling, that usually simulates a single soil layer representative of the root-zone, needs a method for obtaining profile soil moisture data from surface measurements. In this study, the exponential filter proposed by [11] is employed as it was already successfully applied in previous applications [4-7]. It should be underlined that the filtering is only carried out for the ASCAT and AMSRE products.

Moreover, the climatology of modelled and satellite (ASCAT, AMSRE and ECMWF) data could be quite different [14]. In order to assimilate unbiased observations, a linear rescaling approach is adopted to match the variability of satellite data with those obtained from the hydrological model [5].

4. METHOD

A continuous rainfall-runoff model, named MISDc [2], is used for the prediction of runoff in the investigated catchments and for the assimilation of the soil moisture products. The model consists of two components; the first one is a soil water balance model that simulates the soil moisture temporal pattern and sets the initial conditions for the second component which is an event-based rainfall-runoff model for flood hydrograph simulation. By coupling the two components through an experimentally derived relationship, the structure of a parsimonious and robust continuous rainfall-runoff model was derived.

The assimilation of soil moisture data into MISDc is carried out by using a simplified nudging scheme [5, 15]. When new observations, SM_{sat}, become available the modelled soil moisture, SM_{mod}, is updated through the following:

$$SM_{ass}(t) = SM_{\mathrm{mod}}(t) + G[SM_{sat}(t) - SM_{\mathrm{mod}}(t)] \quad (1)$$

where t is time, SM_{ass} is the updated modelled soil moisture (after the assimilation) and G is a constant gain parameter. G determines the relative weight of the uncertainties on the model prediction against those of satellite estimates.

For G=1 the observations are assumed without error (direct insertion), vice versa for G=0 the model is assumed perfect (no assimilation). Although the employed nudging scheme is not optimal for a statistical point of view, it is a computationally inexpensive approach which allows analyzing the usefulness of satellite observations in the hydrological practice.

5. RESULTS

The data assimilation experiments require different steps to be carried out: (i) MISDc model calibration for a series of observed flood events, (ii) computation of the linearly rescaled and filtered satellite data that matches the variability of the simulated soil moisture data, and (iii) assimilation into MISDc and evaluation of the results with and without assimilation. The same procedure is applied for the three products and the six catchments.

The MISDc model calibration and validation (first step) is not shown for sake of brevity. Generally, the model is found to satisfactorily reproduce the observed flood event with Nash-Sutcliffe efficiency scores higher than 0.75.

The second step consists in matching modelled (from MISDc) and satellite data. Fig. 2 shows the temporal evolution of the relative soil moisture for three randomly selected catchments as an example. It is evident that all the soil moisture products provide a very good agreement with modelled data with correlation coefficient, R, higher than 0.85 (also for the other catchments not shown in Fig. 2). Anyhow, some differences are visible. The AMSRE product shows a smoother temporal trend with respect to both ASCAT and ECMWF. Moreover, some discrepancies with modelled data are observed, especially in the transition period from dry to wet conditions (Valescure catchment).

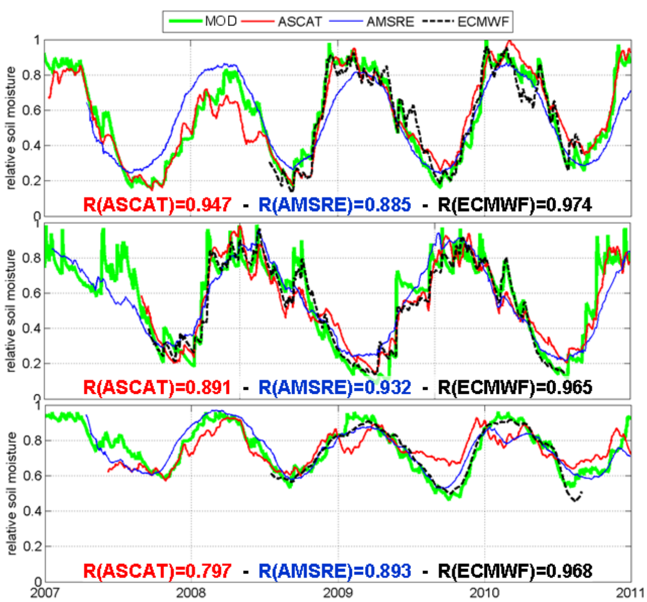

Fig. 2. Comparison between modelled (MOD) and linearly rescaled (and filtered) satellite data for Niccone (upper panel), Valescure (middle) and Bibeschbach (lower) catchments (R: correlation coefficient).

In the last stage, the rescaled (and filtered) satellite data are incorporated into the MISDc by using Eq. (1) and considering the *G* parameter varying between 0 (perfect model) and 1 (perfect observation). Fig. 3 shows the Nash-Sutcliffe efficiency, NS, the peak discharge, E Qp, and volume, E Vol, errors (in percentage) versus *G* for all the investigated catchments and satellite products. By inspecting this figure, a clear picture of the data assimilation performance for each product and catchment can be depicted. It's worth noting that for the ECMWF product the analysis period is shorter than ASCAT and AMSRE.

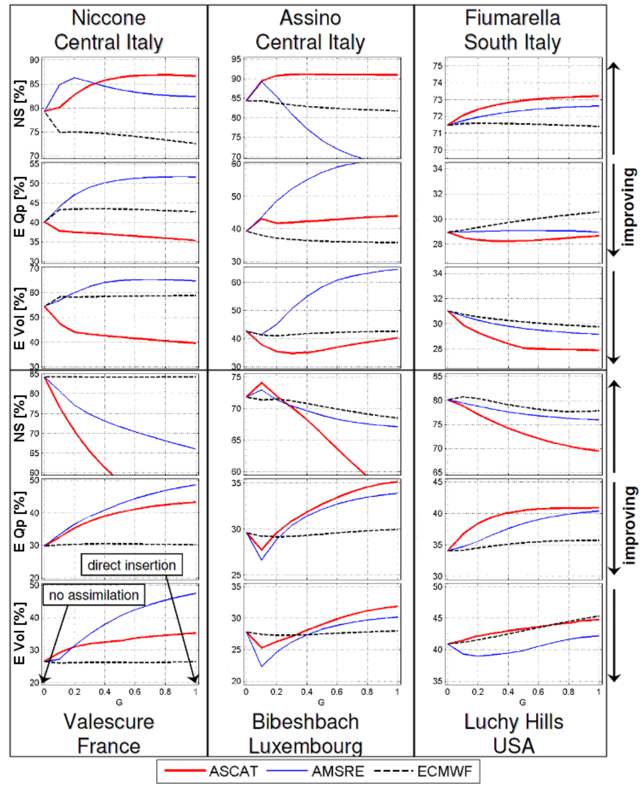

Fig. 3. Data assimilation performance as a function of the gain parameter, *G*, in terms of Nash-Sutcliffe efficiency, NS, peak discharge, E Qp, and volume, E Vol, error versus *G* for all the investigated catchments and satellite products. Note the different y-axis range for the different subplots.

The overall results can be summarized in:

- the assimilation of the ECMWF product has a slight impact due to the limited time period for which the data are available;
- for central Italy catchments, the assimilation of ASCAT and AMSRE provides a significant improvement in model performance (NS increase of ~9% after the assimilation) [5];
- in the Fiumarella catchment. only a slight improvement can be seen (NS increase of ~2%);
- in the Valescure catchment, the model performance deteriorates through the products assimilation (NS decrease) likely due to the difficulties of satellite data to retrieve soil moisture over mountain areas [16];
- in the Bibeschbach catchment, the assimilation impact is limited (NS increase of 2%) due to the presence of snow that also affects the soil moisture retrieval [6];
- in the Lucky Hills catchment, no impact is observed due to, besides the catchment size, the limited variability of the wetness conditions prior to rainfall events (very arid conditions) [10].

6. CONCLUSIONS

The assimilation of two different satellite soil moisture products, ASCAT and AMSRE, and a modelled product, from ECMWF, in different catchments worldwide is carried out. Generally, it is shown that these soil moisture estimates can have a positive impact on runoff prediction. However, the assimilation performance are significantly affected by: 1) the accuracy of the satellite soil moisture retrievals that is lower in mountain (Valescure) and snow-affected (Bibeschbach) catchments, 2) the length of the observation period used in the analysis (as shown for the ECMWF product), and 3) the catchment climatic conditions (Lucky Hills).

Therefore, the recent availability of accurate satellite soil moisture products opens new challenges in the hydrological research. Specifically, it's our opinion that the enhancement of the rainfall-runoff models structure is strongly needed for a better utilization of this new data source.

7. ACKNOWLEDGMENTS

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