Advances in Water Resources 44 (2012) 49–65

Contents lists available at SciVerse ScienceDirect

Advances in Water Resources

journal homepage: www.elsevier.com/locate/advwatres

Can ASCAT-derived soil wetness indices reduce predictive uncertainty in well-gauged areas? A comparison with *in situ* observed soil moisture in an assimilation application

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ARTICLE INFO

Article history:
Received 28 April 2011
Received in revised form 20 January 2012
Accepted 21 March 2012
Available online 17 April 2012

Keywords:
Soil moisture
Microwave remote sensing
ASCAT
Hydrological modeling
Data assimilation
Particle Filter

ABSTRACT

Although soil moisture is a key variable controlling the hydrological response of a catchment to rainfall events, the utility of Earth Observation products for soil moisture monitoring in hydrological applications remains controversial. It is not clear under which hydrological modeling scheme remote sensing may have a positive impact on the runoff forecasts and to what degree the practical utility of these data suffers from limitations related to their uncertainty, as well as to their spatial and temporal resolution. More specifically, there is limited understanding of whether remotely sensed soil moisture data can improve forecasts in well gauged catchments, or if their utility is restricted to poorly gauged areas. This paper contrasts the use of space-based and *in situ* based soil moisture monitoring in a data assimilation exercise in the Bibeschbach experimental catchment in Luxembourg. Bi-daily soil wetness indices obtained from ASCAT METOP-A satellite data are used as proxies of soil water storage and have been employed to periodically update the water budget of a lumped conceptual hydrological model. The hydrologic model was specifically developed and calibrated to represent catchment characteristics in terms of observed run-off and soil moisture conditions. Nevertheless, the assimilation of *in situ* soil moisture measurements using a Particle Filter-based data assimilation approach even further improved both discharge and soil wetness forecasts, indicating that continuously recorded *in situ* measurements, even if taken only over a few points within the catchment, are useful for updating model states. On the other hand, the assimilation of the remotely sensed soil moisture data resulted in a negative or only small positive impact. This suggests that for small and well-instrumented catchments, where well-calibrated "à-la-carte" models are available, coarse-resolution remotely sensed soil moisture data add little or no extra value for runoff prediction. It remains an open research question if this result can mainly be attributed to errors in the ASCAT-based profile soil moisture estimates, or if it is mainly related to the stringent hydrological modeling scheme as used in this study. We further illustrate that the efficiency of the approach varies seasonally, with soil moisture recordings being particularly useful for improved flood predictions during transition periods from wet to dry in early spring and from dry to wet in early autumn.

1. Introduction

A key motivation for satellite-based soil moisture retrievals is to improve the effectiveness of operational flood forecasting systems [1]. Soil moisture conditions are known to represent a dominant control on the catchment's response to a given storm event (see e.g. [2,3]). As a result, the monitoring of soil moisture is seen as a key environmental variable that can help to predict abrupt switches in river system dynamics. This is supposed to help to periodically characterise the readiness of a river basin to generate substantial storm runoff volumes during rainfall events.

Although it is perceived that remote sensing-derived soil moisture contains important information about catchment wetness, and that this has the potential to constrain the uncertainty of rainfall–runoff models, even after a decade of attempts to improve

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http://dx.doi.org/10.1016/j.advwatres.2012.03.022

hydrological predictions through the process of data assimilation, genuine 'success stories' continue to be rare. For example, Crow and Ryu [1] experienced significant advantages only at high levels of rainfall errors, and concluded somewhat fatalistically that the primary utility of remote sensing is likely in data sparse regions.

On a more positive note, some previous studies [1,4–6] have shown that the sequential assimilation of different remotely sensed soil moisture products can lead to improved hydrological model-based discharge predictions. However, the improvements are often marginal [6], limited to specific flood events [4] or obtained when assuming high rainfall errors [1]. Brocca et al. [7] and Beck et al. [8] found a good agreement between remotely sensed soil moisture estimates and the soil potential maximum parameter of the Soil Conservation Service – Curve Number method, thereby suggesting that antecedent moisture conditions can be described with proxies of soil water storage derived from satellite observations. Promising results have also been reported by Parajka et al. [9,10] in another offline experiment. Scatterometer-derived surface soil moisture values helped to reduce the parameter uncertainty of the top soil moisture module of their hydrological model. Even though satellite-derived soil moisture did not significantly impact the runoff predictions, Parajka et al. [9] argue that more robust water balance simulations with respect to impact studies can be obtained by considering scatterometer data during model calibration.

The disparity of these outcomes arguably reflects differences in the quality of data and models used in different applications. The quality of soil moisture data differs substantially between different remote sensing products (e.g., soil moisture products from various scatterometer, radiometer or SAR sensors). The quality of ground based information used as model forcings, such as rainfall, has a strong impact on model performance (see e.g. [11,12]), hence assimilation of soil moisture is less effective with more accurate forcing data [1]. Finally, different model structures can perform substantially different (see e.g. [13]), which causes data assimilation to be less effective with models that have a better ability of fitting the data.

In addition to this, there are intrinsic limitations to the use of remotely sensed soil moisture data in hydrological modelling. They include, most notably, the spatial mismatch between pixels of remote sensing products and the spatial domain of hydrological models [14] and incommensurability errors due to the difference between the nature of remotely sensed soil moisture at ca. 0–5 cm depth and profile-averaged soil moisture that is commonly simulated with rainfall–runoff models [15]. Assumptions thus need to be made with respect to the vertical distribution of soil moisture in the soil profile in order to retrieve profile-averaged soil moisture from surface soil moisture measurements. Most hydrological models compartmentalise soils in two or more layers, which makes it difficult to map satellite-derived soil moisture to any state variable. Another challenge of hydrological data assimilation relates to the fact that storage fluctuations can be effectively predicted with basic atmospheric forcing data such as precipitation and air temperature [5]. Since these data are readily available in most instrumented catchments, hydrological models are able to simulate the water balance reasonably well, thereby not leaving much room for further improvements.

Bypassing these limitations, the synthetic experiment of Walker and Houser [16] has shown that daily near surface soil moisture observations with a RMSE of 0.05 m^3/m^3 and a spatial resolution finer than the one of their land surface model positively impacted soil moisture forecasts. Albeit the merits are less obvious for flood forecasting applications using real data, the assimilation into hydrological models of soil moisture data that satisfy the repeat time, spatial resolution and accuracy requirements given by Ref. [16] may significantly reduce model uncertainties caused by errors in model structure, parameters and input data and lead to improved discharge predictions.

Nowadays, these requirements can be met with several spaceborne sensors. In particular, the advanced scatterometer (ASCAT) onboard METOP-A provides bi-daily soil wetness estimates at a spatial resolution of ca. 50 km (re-sampled to 25 km) that were shown in a number of case studies to be highly correlated with *in situ* measurements of volumetric soil moisture. The published RMSE values are 0.014 m^3/m^3 [17], 0.035 m^3/m^3 [18] and 0.06 m^3/m^3 [19] with respect to field measurements. Further improvements are expected to come from the microwave imaging radiometer with aperture synthesis (MIRAS) sensor from the Soil Moisture and Ocean Salinity (SMOS) satellite platform launched in 2009. The targeted accuracy of the retrieved surface soil moisture is 0.04 m^3/m^3 [20,21], which is a significant improvement over the accuracy level of 0.06 m^3/m^3 of the soil moisture product retrieved from the Advanced Microwave Scanning Radiometer (AMSR) [22].

Brocca et al. [14] assimilated ASCAT-derived soil wetness indices into a continuous water balance model that is coupled to an event-based rainfall–runoff model, using a non-optimal nudging scheme to update modelled saturation degrees. They found significant improvements of model performances in five catchments of varying sizes. As expected, the main effect of the assimilation is to update the simulation of antecedent moisture conditions, which, in this case study, led to the reduction of the pre-assimilation bias in runoff predictions.

The aim of this paper is to provide further insights in the utility of ASCAT-derived soil wetness indices for improving hydrological predictions in well gauged catchments. The use of these data is compared to *in situ* measurements in an assimilation exercise, where we applied a Particle Filter-based assimilation scheme to a single lumped conceptual rainfall–runoff model specifically developed for this purpose. More broadly, we examine the potential of soil moisture data for defining appropriate hydrologic model structures, for inferring model parameters and for periodically updating modelled state variables.

2. Study area

2.1. Basin characteristics and measurement network

The study area is the Bibeschbach experimental catchment (10.8 km^2), located in the Southern part of the Grand Duchy of Luxembourg. The basin is characterised by a humid temperate climate with a mean rainfall of about 740 mm/year, spread uniformly over the year, mean annual runoff of 452 mm/year and a mean annual temperature of 9 °C. The topography is characterised by a gently sloping landscape (mean slope of 6.4%) with a local relief of approximately 100 m. The catchment is covered by 46% forest, 46% agriculture (i.e., grassland and cropland) and 8% impervious areas (Fig. 1). Oligocene to Pleistocene table-land loams and Lias marls are the two lithologies that mostly characterise the geology of the catchment. Investigations at several locations indicate that soils are mainly shallow with a soil depth averaging 50 cm. While the topsoil layer is rather permeable due to a reduced amount of clay particles and an intense bioturbation, a textural B horizon limits water infiltration at approximately 50 cm depth. This effectively impermeable layer promotes the lateral movement of water in the topsoil layer.

Precipitation, discharge, soil moisture and air temperature are measured *in situ* from January 2006 to January 2009 every 15 min and aggregated or averaged to a common time step of 1 h. Air temperature is used to calculate the potential evaporation and transpiration *via* the Hamon formula [23]. Discharge is