Detecting threshold hydrological response through satellite soil moisture data

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Die Erkennung hydrologischer Schwellenwertbeziehungen anhand von Bodenfeuchtedaten aus Satelliten

1 Introduction

Soil Moisture (SM) plays a fundamental role in the hydrological cycle as it governs the partitioning of rainfall into infiltration, runoff and evapotranspiration (Seneviratne et al., 2010). As a result, the understanding of the hydrological processes in experimental basins will strongly benefit from its knowledge. However, long-term SM monitoring with in-situ networks is not straightforward due to the cost of the equipments that usually require frequent maintenance and due to their spatial representativeness. In fact, in-situ stations allow to monitor SM only at specific point locations (and depths), thus arising several issues for their 4-dimensional spatial-temporal extrapolation at basin scale. On the other hand, in addition to soil water balance models frequently employed for simulating the temporal evolution of SM (Brocca et al., 2008; Seneviratne et al., 2010), remote sensing sensors represent a supplementary source of information that could be used for this purpose. Nowadays, satellite SM products are characterized by high temporal resolution (daily) and have also proven their reliability (e.g. Brocca et al., 2011a). Unfortunately, the spatial resolution is low (~ 20 km) and this issue has prevented their application for hydrological applications, especially for small basins (< 100 km²). However, due to the spatial scaling properties of SM (also referred to as "temporal stability"), a very

Zusammenfassung

In früheren Jahren lag der Schwerpunkt der Niederschlags-Abfluss-Transformation in der Festlegung von einzugsgebietsbezogenen, hydrologischen Systemeigenschaften. Eine charakteristische Eigenschaft dafür ist die Schwellenwertbeziehung zwischen aktueller Bodenfeuchte und Abfluss, ab der eine unmittelbare Abflussreaktion erfolgt. In dieser Arbeit werden in vier europäischen Einzugsgebieten Bodenfeuchtedaten aus Beobachtungen, Simulationen und Satellitenaufzeichnungen verglichen und analysiert. Zuerst werden Simulations- und Satellitendaten mit Beobachtungswerten verglichen und deren Eignung zur Beschreibung erfasst. In einem zweiten Schritt werden die Möglichkeiten der einzugsgebietsspezifischen Abflussschätzung an den vier Testgebieten geprüft.

Schlagworte: Bodenfeuchte, experimentelle Einzugsgebiete, Fernerkundung, Schwellenwertprozesse.

Summary

In recent years, the modelling approach to rainfall-runoff transformation has focused on catchment emergent properties, acting as a signature of catchment hydrological response. One of these properties, observed in many catchments worldwide, is the threshold relation between soil moisture and runoff, identified as the critical point at which runoff behaviour rapidly changes. In this study, observed, modelled and satellite-derived soil moisture data are used for analyzing the runoff response of four experimental basins over Europe. Specifically, firstly the simulated and satellite soil moisture data are compared with in situ observations for assessing their reliability. Secondly, the capability of satellite data to detect the differences in the threshold-based hydrological response of the basins is investigated.

Key words: Soil moisture, experimental basin, remote sensing, threshold behaviour.

good agreement between the temporal pattern of some representative point locations and the spatial average over large areas is usually observed (see e.g. BROCCA et al., 2012a). Therefore, coarse-resolution satellite data can be used to analyze the hydrologic behaviour also for small catchments (BECK et al., 2009; PARAJKA et al., 2009; BROCCA et al., 2010; 2011b; 2012b; MATGEN et al., 2012a; 2012b). On this basis, we here investigate the potential of coarse-resolution satellite SM data for hydrological applications in four small experimental basins over Europe. Specifically, satellite data are compared with in-situ observations of SM and their reliability is compared with the results of a soil water balance model. Afterwards, the capability of satellite data to detect the threshold-like behaviour existing between SM and discharge, Q, is analyzed in depth (BROCCA et al., 2011c; PENNA et al., 2011a, b; ALI et al., 2012).

2 Study catchments and data set

SM and Q data from four experimental catchments were used: Colorso in central Italy (BROCCA et al., 2008), Cordevole in North Italy (PENNA et al., 2011a), Bibeschbach in Luxembourg (MATGEN et al., 2012a) and Villamor in Spain (Figure 1); the main characteristics of each catchment are reported in Table 1. The selected catchments have drainage areas in the range of 1.0 to 12.9 km² and climatic properties between Alpine (Cordevole) and semiarid (Villamor). For each catchment, in-situ observations of both SM and Q (and other meteorological variables) have been collected for many years. Volumetric SM measurements have been collected at different depths (see Table 1) through continuous monitoring sensors based on Frequency and Time Domain Reflectometry (FDR and TDR) techniques. In this study,

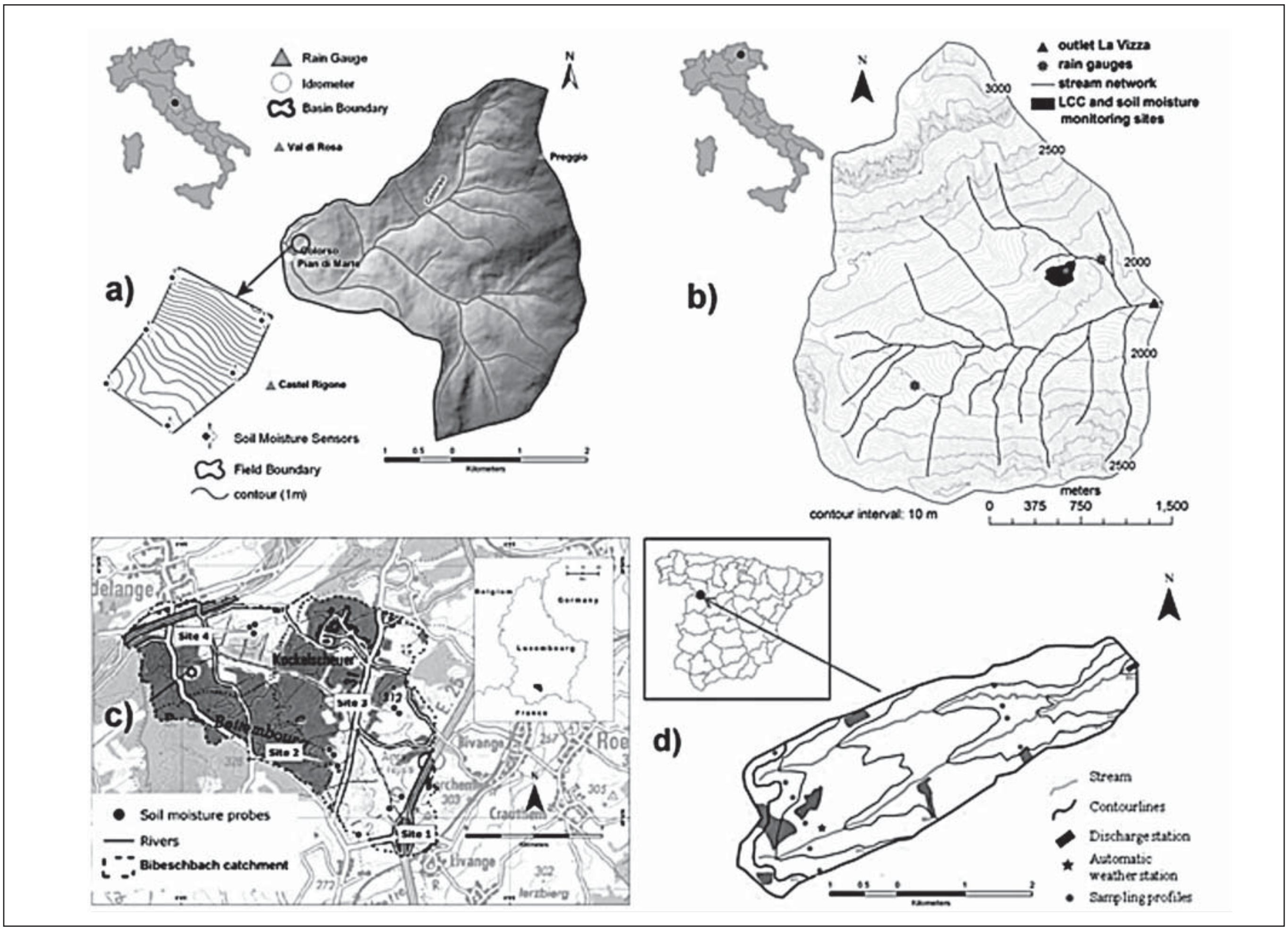

Figure 1: Morphology and hydrometeorological network for the four experimental catchments for: a) Colorso, b) Cordevole, c) Bibeschbach, and d) Villamor catchments

Abbildung 1: Morphologie und hydrometeorologische Messstellen der vier Testgebiete a) Colorso, b) Cordevole, c) Bibeschbach und d) Villamor the period 2007–2011 was used to match the availability of satellite data.

2.1 ASCAT soil moisture products

Satellite SM data are obtained by the Advanced Scatterometer (ASCAT) sensor, on board of the Metop satellite, which is a real-aperture radar instrument measuring radar backscatter at C-band (5.255 GHz) in VV polarization, operating since 2007. The spatial resolution of ASCAT is 25 km (resampled at 12.5 km) and, for Europe, measurements are generally obtained once per day. The surface SM product is retrieved from the ASCAT backscatter measurements using a time series-based change detection approach developed by WAGNER et al. (1999). The derived surface SM product corresponds to a depth of 2–3 cm. Additionally, to obtain a root-zone SM product, the exponential filter approach proposed by WAGNER et al. (1999), SWI (Soil Water Index), is adopted. It depends on a single parameter, *T*, the characteristic time length. Systematic differences between remote sensing-derived and simulated SM data prevent an absolute agreement between the two time series. For that, the Cumulative Density Function (CDF) matching approach (e.g. BROCCA et al., 2011a) is adopted here to match the CDF of satellite and in-situ observations.

3 Soil water balance model

A parsimonious lumped soil water balanced model is applied for estimating SM temporal variability in the different experimental basins. The structure of the model used in this study was developed by Brocca et al. (2008) and it has been widely tested and applied in different test sites located across Europe, obtaining satisfying performance levels (e.g. BROCCA et al., 2008; 2011a, LACAVA et al., 2012).

The model simulates the SM content for a soil layer for which the following water content balance equation holds:

$$\frac{dW(t)}{dt} = f(t) - e(t) - g(t) \qquad W(t) \leq W_{\max}$$
$$W(t) = W_{\max} \qquad W(t) > W_{\max} \qquad (1)$$

where *t* is time, *W(t)* is the total amount of water in the investigated soil layer (including absorbed and residual water content), *f(t)* is the fraction of the precipitation infiltrating into the soil, *e(t)* is the evapotranspiration rate, *g(t)* is the drainage rate due to the interflow and/or the deep percolation, and W_{max} is the maximum water capacity of the soil layer. The infiltration rate *f(t)* is estimated by using the Green-Ampt equation; the drainage rate *g(t)* is represented by a non-linear relationship able to simulate the steep falling limb that occurs immediately after a rainfall event. The Blaney and Criddle formulation is adopted to estimate the potential evapotranspiration; the actual evapotranspiration rate *e(t)* is a fraction of the potential one according to the degree of saturation, $W(t)/W_{max}$, of the soil layer. The complete formulation of the model can be found in BROCCA et al. (2008).

The model requires as input rainfall and air temperature data, which are routinely measured, and four parameters that need to be calibrated: the saturated hydraulic conductivity (K_s), the wetting front of soil suction head divided by the soil layer depth (ψ/L), the pore size distribution index (λ), and the correction factor for the potential evapotranspiration (*b*).

Table 1: Main characteristics of the four experimental catchments
Tabelle 1: Haupteigenschaften der vier Testgebiete

Catchment	Area (km²)	Soil moisture data period	Sampling depth (cm)	Elevation (m a.s.l.)	Climate	Land use	Lithology
Colorso	12.9	2007–2008	5–15	530	semi-humid	forest and pasture	flysch
Cordevole	7.1	2009 (summer)	0–30	2340	alpine	bare rock and pasture	triassic dolomite and conglomerate
Bibeschbach	10.8	2007–2008	4–7	300	humid temperate	forest and agriculture	loamy soils
Villamor	1.0	2009–2010	0–10	850	semiarid	agriculture	clay loam to loamy sand

4 Results

For each catchment, the reliability of satellite and simulated SM data in reproducing the observed time evolution of SM is investigated. Figure 2 shows the comparison between in-situ, satellite and modelled SM data for the four catchments. The satellite data is represented by the root-zone SM product (i.e., SWI), rescaled through a CDF matching approach, where the value of the T parameter is calibrated by maximizing the correlation R with in-situ observations. A reasonably good agreement between satellite and in-situ observations is observed with R values ranging between 0.810 and 0.910 and Root Mean Square Errors (RMSEs) lower than 0.044 m^3/m^3. As expected, the observations agree slightly better with model results than with satellite data but the improvement in the performance is rather low (less than 5 %).

Next, satellite and observed SM data are compared with Q observations for each catchment (Figure 3). For this analysis, in the case of the Colorso catchment the satellite data cover a period that is longer than the one visualized in Figure 2 in order to obtain findings that are more robust. Indeed, ASCAT satellite data are nowadays available for more than 5 years starting from 2007, while for Colorso in-situ observations are only available for a short period. Therefore, the daily discharge data at Colorso basin is higher than hourly observations (Figure 3a), as in 2010 a large flood event occurred. As can be seen in Figure 3, Colorso and Bibeschbach catchments show a highly non-linear behaviour in the relationship between SM and Q, while for Cordevole a smoother pattern is observed (Brocca et al., 2011c). For Villamor, the Q response (< 0.4 mm/h) is much smaller than for the other three catchments, arguably due to its semiarid climatic conditions, soft topography and sandy soils. As a result, the SM-Q relationship appears more scattered. We note that, except for Colorso, the availability of hourly data for in situ observations provides a larger number of pairs with respect to satellite data (mean daily data) and, hence, the SM-Q pattern can be easily identified. Anyhow, also satellite data appear to enable the distinction between the two main states (dry-wet) of river system dynamics in the catchments as well as the description of the differences in the non-linear responses.

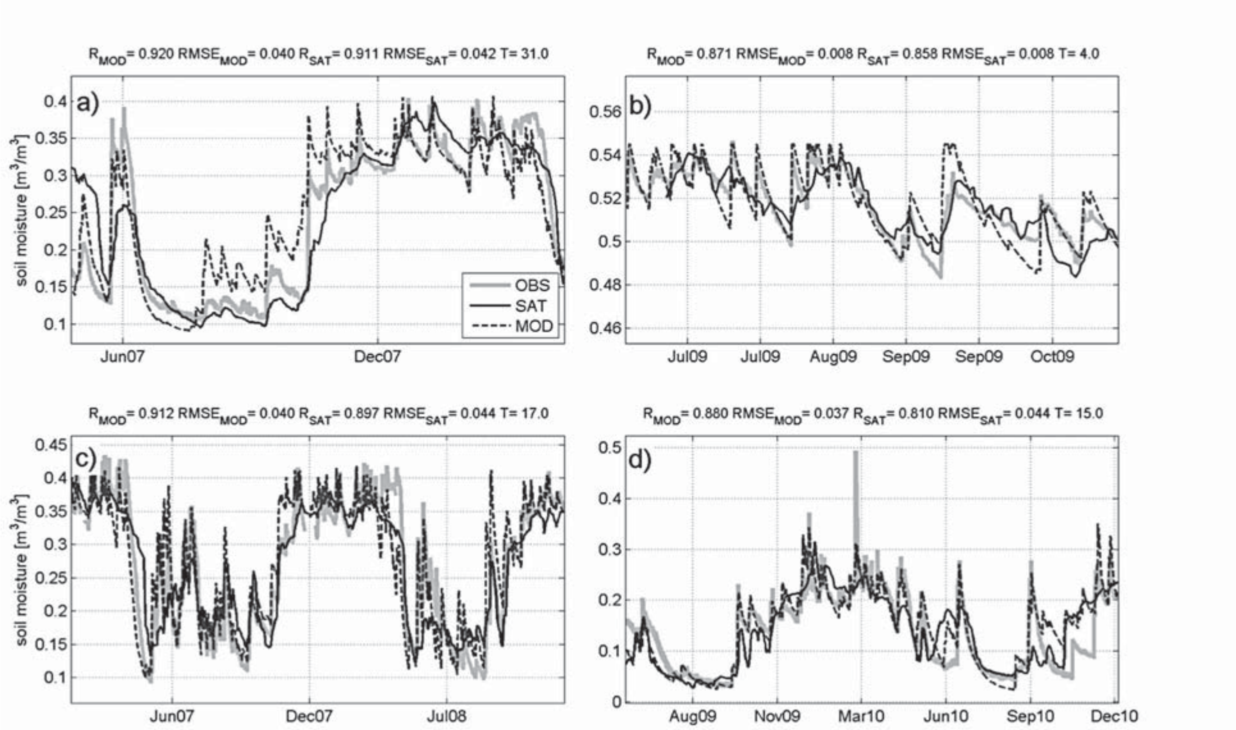

Figure 2: Comparison between in-situ observed (OBS), satellite (SAT), and modelled (MOD) data for a) Colorso, b) Cordevole, c) Bibeschbach, and d) Villamor catchments (R: correlation coefficient, RMSE: root mean square error, T: characteristic time length)

Abbildung 2: Vergleich der Bodenfeuchte zwischen Bodenmessungen (OBS), Satellitenmessungen (SAT) und Modellsimulation (MOD) für die Gebiete a) Colorso, b) Cordevole, c) Bibeschbach und d) Villamor (R: Korrelationskoeffizient, RSME: Quadratwurzelfehler, T: charakteristische Zeitlänge

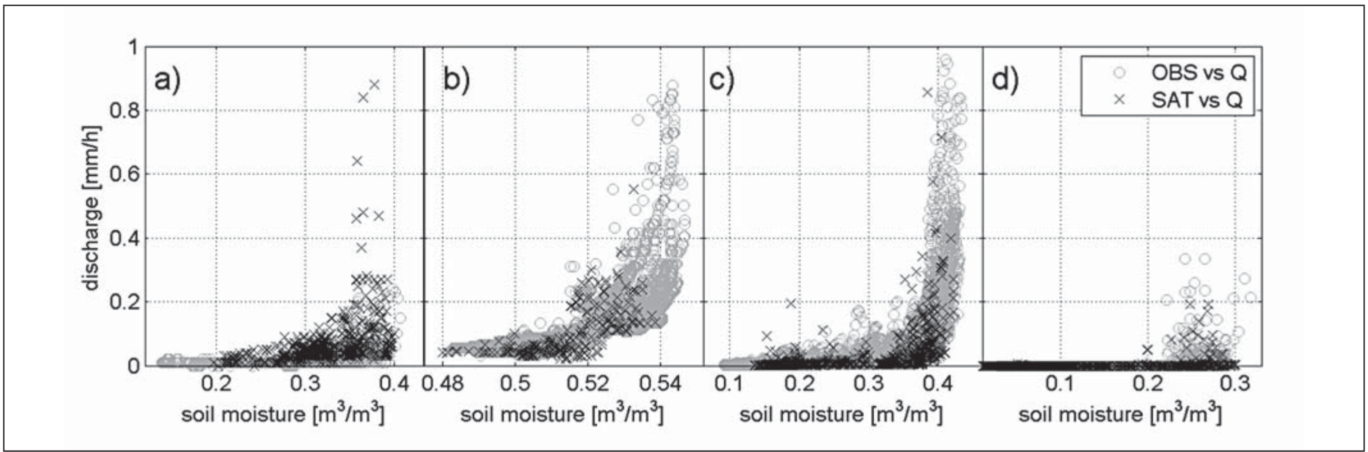

Figure 3: Relation between satellite (SAT) and observed (OBS) soil moisture data with discharge (Q) for: a) Colorso, b) Cordevole, c) Bibeschbach and d) Villamor catchments

Abbildung 3: Beziehung zwischen Abfluss Q und beobachteter (OBS) bzw. Satellitendaten (SAT) der Bodenfeuchte für die Gebiete a) Colorso, b) Cordevole, c) Bibeschbach und d) Villamor

5 Conclusions

The analysis of satellite-derived SM data on four European experimental catchments provides insights on their reliability and capability for identifying the threshold relation between SM and Q. The availability of satellite data at global scale allows performing the analysis for different catchments in contrasting climatic conditions worldwide, also in poorly gauged regions. Moreover, it is worth noting that nowadays long-term satellite SM products have been derived (e.g. Dorigo et al., 2012) and that both the temporal resolution and the accuracy of satellite SM retrievals is going to increase in the near future. All these aspects give a wide range of opportunities for the use of satellite SM data to improve our understanding of the hydrologic response of the basins.

Acknowledgments

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