Journal of Hydrology 516 (2014) 245–257

Contents lists available at ScienceDirect

Journal of Hydrology

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

# Estimation of soil moisture patterns in mountain grasslands by means of SAR RADARSAT2 images and hydrological modeling

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ARTICLE INFO

*Article history:*
Available online 19 February 2014

*Keywords:*
Soil moisture
Hydrological models
Remote sensing
RADARSAT 2 SAR
Grasslands
Mountain regions

SUMMARY

This paper analyzes the spatial patterns of surface soil moisture of alpine meadows and pastures in the Matsch/Mazia Valley in the Italian Alps by comparing estimations from three different sources of information: (I) RADARSAT 2 synthetic aperture radar (SAR) images; (II) simulations by using the GEOtop hydrological model and (III) ground observations, derived from a network of fixed stations and field campaigns with mobile devices. The aim of this paper is to assess the added value of RADARSAT 2 products with respect to a distributed hydrological model in capturing soil moisture patterns in mountain areas, which is a challenging environment with a high degree of spatial variability. Moreover, the physical controls of the observed soil moisture patterns are analyzed by using the hydrological model. Results show that the model, once calibrated for soil and vegetation parameters, predicts the plot-scale temporal dynamic in station locations and the spatial averages with sufficient accuracy. However, the model output shows lower spatial variability with respect to the ground surveys, with a limited capability of reproducing moist areas in irrigated meadows. Differences arise due to difficulties in knowing soil model parameters and irrigation amounts with accurate spatial detail. RADARSAT 2 soil moisture maps well reproduce the spatial ground surveys, as well as over-irrigated meadows. However, SAR products are limited to slopes with a favorable viewing angle, to bare soil or to grassland areas. Moreover, the signal penetration depth is restricted to the soil surface layer. The major control on RADARSAT 2 patterns is land use. Irrigated meadows in the bottom of the valley have moister conditions, with respect to pastures along the upper hillslopes. In this case, model simulations suggest that differences in soil type could have a relevant impact on soil moisture estimation. A secondary control is topography, with increased moisture in convergent locations with a high topographic wetness index. Results suggest that the capability of RADARSAT 2 products to reproduce small-scale (20 m pixels size) surface soil moisture patterns in mountain grassland areas could complement the ability of the hydrological model to predict variations of soil moisture continuously in space and time. Therefore, RADARSAT 2 products can give useful information to improve spatial parameterization and validation of distributed hydrological models in mountain grassland areas, also in the perspective of implementing data integration procedures for operational soil moisture monitoring.



## 1. Introduction

Soil moisture content (SMC) is a key parameter in many hydrological processes. It controls the infiltration rate during precipitation events, runoff production and evapotranspiration (Rodriguez-Iturbe et al., 1999). Thus it influences both water availability and surface energy budget. As a consequence, accurate spatially and temporally distributed information about SMC is of great importance in hydrological applications, such as flood prediction in the case of extreme rainfall events, water resource management during dry periods, irrigation scheduling and precision farming (Bastiaanssen and Bos, 1999; Heathman et al., 2003). If we focus on mountain regions, and in particular, the drier regions of the Alps, such as Vinschgau (Italy) or Valais (Switzerland), there are areas where irrigation is essential for agriculture as well as for grasslands (Leibundgut, 2004). Moreover,

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http://dx.doi.org/10.1016/j.jhydrol.2014.02.018
0022-1694/

climate change is expected to increase demand for agricultural irrigation over the whole alpine region (Bogataj and Sušnik, 2007). Thus, an improved monitoring of surface SMC, especially in irrigated regions, can provide useful information to avoid increasing problems related to conflicting water uses (Beniston, 2012).

The interacting influences of precipitation, soil properties, vegetation, and topography on SMC have been extensively investigated (e.g. Moore et al., 1991; Grayson et al., 1997; Famiglietti et al., 2008; Rodriguez-Iturbe et al., 1995). However, when we move our attention to mountain areas, such as the Alps, the scale of the spatial and temporal variability is reduced. Because of the extreme heterogeneity in topographic, soil and vegetation properties of this environment, SMC can show very different dynamics over spatial scales of the order of 10–100 m. Therefore, an improved estimation of SMC patterns in mountain regions is needed (Brocca et al., 2013).

The controls on the spatial and temporal distribution of SMC include static (i.e. elevation, slope, aspect, soil properties) and dynamic variables (i.e. climate, snow dynamic, vegetation) (Williams et al., 2009). The superposition of static and dynamic controls can lead to different SMC patterns during wetting, draining, and drying periods (Western et al., 1999). This fact makes the estimation of accurate and reliable SMC temporal and spatial patterns in mountain areas particularly challenging and complex to model.

In order to take into account the different processes controlling SMC dynamics and include spatial details, physically-based and spatially distributed hydrological models are needed (e.g. Fatichi et al., 2012; Ivanov et al., 2004; Wigmosta et al., 1994; Rigon et al., 2006; Bixio et al., 2000; Ewen et al., 2000). However, such models integrate a large number of parameters and require detailed information on soil and land cover properties as well on meteorological forcing, often facing the problem of over parameterization and equifinality (Freer and Beven, 2001). At the same time, field campaigns to provide validation data are labor-intensive and often limited to small areas. For this reason, SMC retrieval from remote sensing in an alpine context is a promising source of detailed spatially distributed information to assess the spatial consistency of distributed hydrological model predictions (Manfreda et al., 2007).

In the last few years there has been an increasing interest in the estimation of surface SMC at local scales using active microwave techniques such as Synthetic Aperture Radars (SARs) (Barret et al., 2009). In fact SAR images have the potential of providing data at high spatial resolution ($\sim$10–20 m), as is particularly needed in mountain areas. Moreover, SAR sensors, being active instruments with their own source of energy, can acquire images in all-weather conditions and with no difference between day and night. Currently, only a few satellites offer products with a spatial resolution of the order of 10–100 m, which is needed in mountain areas. For example RADARSAT 2 has a resolution of about 10 m, but a time repetition frequency of 21 days. With upcoming satellites such as Sentinel 1, the time repetition frequency will be increased (1 acquisition every 12 days with the first satellite and every 5 days when the second satellite is launched). However, one main disadvantage of SAR sensors is related to the fact that their signal is influenced by soil moisture as well as by vegetation and surface roughness. This effect makes the retrieval process, by which it is possible to obtain SMC values from the SAR signal, a so-called "ill-posed" problem. In such problems, different combinations of soil features (SMC, vegetation, roughness) can give rise to the same SAR signal.

Up to now, many works have addressed the retrieval of SMC from SAR data (Barret et al., 2009). The proposed methodologies exploited polarization and multi-angle features (Srivastava et al., 2009) or temporal time series of SAR images in order to disentangle the effect of vegetation and roughness from that of soil moisture (e.g. Pierdicca et al., 2010; Balenzano et al., 2011; Hornacek et al., 2012). However, mountain areas are often masked in most approaches because of layover and shadowing issues or have been considered only in a few pioneer studies (Brocca et al., 2013; Paloscia et al., 2010). In mountain environments, besides the effects of vegetation and surface roughness, which introduce ambiguities and non-linearity in the SMC retrieval process (Ulaby et al., 1979, 1986), topography is another important factor to be taken into consideration. The distortion effect introduced in the image by topography cannot be fully eliminated during the calibration of the SAR data (Luckman, 1998). This limits the spatial coverage, because of layover and shadowing effects. The residual contribution of topography in the SAR signal further increases the complexity of the SMC retrieval in alpine areas. For this reason, robust estimation techniques are needed, being mainly based on the use of iterative methods or non-linear machine learning techniques, such as the Support Vector Regression (SVR) technique (Bruzzone and Melgani, 2005; Pasolli et al., 2011a,b).

Pasolli et al. (2011a,b) developed a robust and customized technique for addressing the retrieval process in alpine grassland areas, based on the exploitation of the Support Vector Regression (SVR) technique with ancillary data. The proposed approach makes use of a high-resolution digital elevation model, land cover maps and NDVI maps from optical images, to disentangle the topography and vegetation effects from the radar signal. The methodology has proven successful in estimating SMC spatial patterns for alpine meadow and pastures.

In order to properly integrate different sources of information, such as satellite data with models and ground measurements, a clear comprehension of the possibilities, but also of the limitations, of new generation satellite SAR sensors as well as of hydrological models to capture SMC patterns for alpine areas still needs to be addressed. More in detail, an extensive analysis is required for comparing high-resolution remote sensing products with ground measurements and advanced hydrological model outputs in mountain areas and for assessing the benefits of such new products in terms of model parameterization and validation. This kind of analysis should be considered as preliminary work, which is required before implementing a successful data integration or assimilation strategy (Pasolli et al., 2011c,d).

In this contribution we compare the spatial dynamics of surface SMC (0–5 cm depth) of alpine meadows and pastures in the establishing Long Term Ecological Research area (LTER) "Matsch/Mazia Valley" (South Tyrol – Italy), at different spatial scales and with different techniques: (I) ground observation from fixed stations and from field campaigns with mobile ground sensors; (II) SMC retrieved from RADARSAT 2 SAR images; (III) numerical simulations using the hydrological model GEOtop 2.0 (Endrizzi et al., 2013).

The main aim of this paper is to evaluate the strengths, weaknesses and consistency of these three sources of information and to determine which features of the spatial and temporal patterns of soil moisture they are able to detect in alpine grasslands and meadows, and in particular, to:

- Understand the physical controls of the observed SMC patterns in model and RADARSAT 2 maps and their consistency with respect to ground observations.
- Assess the added value of RADARSAT 2 SMC maps with respect to the outputs of a distributed hydrological model in capturing SMC patterns in mountain grassland areas.

The rest of the paper is organized as follows. Section 2 introduces the study area on which our analysis is focused, the available ground observations, the description of the SMC retrieval algorithm and of the hydrological model. Section 3 evaluates the