The Potential of Scatterometer Derived Soil Moisture for Catchment Scale Modelling

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Abstract: Radar remote sensing offers emerging capabilities to monitor global hydrological processes. Only recently, the ERS scatterometer has been used successfully to derive soil moisture information with weekly to decadal temporal resolution. Novel scatterometer systems like NASA's SeaWinds and EUMETSAT's Advanced Scatterometer will provide a flow of operational coarse resolution data for monitoring meso-scale hydrological processes. Currently, concepts of how to integrate scatterometer products in hydrologic models are still vague. The coarse resolution of the data in the range of 10-50 km is often felt to impede hydrological applications. However, by careful consideration of scaling properties of the soil moisture field the remotely sensed information may also be used on a catchment scale (>100 km²). In the paper two examples will be presented which provide a first indication of the usefulness of scatterometer data at the catchment scale. In the first example scaling issues will be discussed based on a comparison with in-situ soil moisture data over the Duero Basin in Spain. In a second example, it will be demonstrate that runoff can be estimated with a forecast range of several weeks by integrating low resolution soil moisture over sub basins of the Zambezi river in Africa.

Keywords: *Hydrology; Soil Moisture; Remote Sensing; Scaling; Runoff*

1. INTRODUCTION

The role of soil moisture in the root zone of the earth surface is widely recognized as a key parameter in environmental processes, including meteorology, hydrology, agriculture and climate change. Unfortunately, with the exception of a few large-scale measurement networks (Robock et al., 2000), continuous information is all but nonexistent. Many feel that the lack of global soil moisture observations is one of the most glaring and pressing deficiencies in hydrologic science (e.g. Blöschl and Sivapalan, 1995).

Radar remote sensing offers emerging capabilities to monitor global hydrological processes. Only recently, the ERS scatterometer has been used successfully to derive soil moisture information with weekly to decadal temporal resolution. Novel scatterometer systems like NASA's SeaWinds and EUMETSAT's Advanced Scatterometer will provide a flow of operational coarse resolution data for monitoring meso-scale hydrological processes.

Despite these technological advances, concepts of how to make best use of this data and how to integrate coarse resolution products in current hydrological modelling are still vague (Enthekabi et al., 1999). Especially the coarse resolution of the data in the range of 10-50 km is often felt to impede hydrological applications.

Use of scatterometer derived soil moisture in agronomical applications led to the feeling that coarse resolution data can be used successfully also on smaller scales. In agronomy scaling requirements are similar to those in catchment hydrology. Irregardless, scatterometer products could be used directly without complex downscaling and data assimilation schemes, leading to improved modelling results (Wagner et al., 2000).

In this paper, two pilot projects dealing with the application of coarse resolution scatterometer derived soil moisture data should indicate ways forward on how to use such data in hydrological science.

2. SCATTEROMETER DERIVED SOIL MOISTURE

Soil moisture data is taken from the Global Soil Moisture Archive 1992-2000 located at http://www.ipf.tuwien.ac.at/radar/ers-scat/home.htm (Scipal et al., 2002). The archive is based on ERS Scatterometer data and comprises indicators of root zone soil moisture with ten day interval and global coverage.

Scatterometers are active microwave sensors characterised by a coarse spatial but a high temporal resolution. To retrieve soil moisture information, scatterometers onboard of the European Remote Sensing Satellites ERS-1 and ERS-2, operated by the European Space Agency were used. The ERS scatterometer operates at 5.3 GHz (C-band) vertical polarization, collecting backscatter measurements over an incidence angle range from 18° to 57° using three sideways looking antennae. The sensor achieves global coverage within 3 to 4 days where each beam provides measurements of radar backscatter from the sea and land surface for overlapping 50 km resolution cells with a 25-km grid spacing at approximately 10:30 am and 10:30 pm for ascending and descending tracks respectively.

Scatterometry offers capabilities to infer soil moisture due to the important variation of the dielectric constant of soil with volumetric water content. However, scattering and attenuation properties also depend on various other factors. Potential retrieval techniques must account for the confounding effects of the dielectric properties, surface roughness, vegetation, topography and soil texture. Since the 70's several methods have been developed to retrieve soil moisture from microwave remote sensing data. A large potential is hold by change detection approaches. Change detection has successfully been used to retrieve soil moisture for active (Wagner et al. 1999, Moran et al. 2000) and passive data (deRidder, 2000). Unlike more complex theoretical or semiempirical approaches often preferred for retrieval purposes, change detection is attractive because comprehensive pre-knowledge of surface characteristics is not required, making it a strong technique for global applications.

The Global Soil Moisture Archive is based on the method developed by Wagner et al. (1999). The method allows the retrieval of surface soil moisture information equivalent to the degree of saturation in relative units (ranging between 0 and 100%). To infer root zone soil moisture a simple physical based two-layer infiltration model is used (Wagner et al., 1999). Under the assumption that the effective large-scale soil hydraulic conductivity is constant, an indicator of the water content in the reservoir layer is obtained by convoluting the surface moisture time series with an exponential function. The latter is controlled by the ratio of the layer depth and the pseudo diffusivity that depends on the soil properties. It was empirically set to 50 days by maximizing the correlation between *in-situ* and scatterometer observed soil moisture. Although nowadays more sophisticated methods exist (e.g. Crow and Wood, 2002) the approach is applied in this study as it can easily be coupled with global remote sensing techniques. The resulting index is the Soil Water Index *SWI,* a percentile measure of soil moisture between the critical levels Θ_{min} (dry) and Θ_{max} (wet).

3. SCALE ISSUES

According to Grayson et al. (2002), scale is a key issue in hydrologic applications. It is not only a question of observing relevant features but observing them at the right scale. It is therefore important to ask which processes are captured by coarse resolution soil moisture products and if this information is compatible with model resolution.

Blöschl and Sivapalan (1995) proposed a framework for considering scale issues, defining the scale triplet - spacing, extend and support. According to their notion scatterometer derived soil moisture is characterized by low spacing (25 km), low support (50x50 km²) and large extend (global). Due to the spacing characteristics small scale variability is not captured by the data. Additionally the sub pixel variability is smoothed out during the measurement process integrating information over the entire resolution cell. Such constraints limit a direct integration of Scatterometer products for typical hydrologic balance applications. However, such data sets give a more complete picture on soil moisture in terms of extend and spacing than anything of this kind available today, and it can be reasonably argued that there is considerable information contained in the data.

Entin et al. (2000) discuss spatial characteristics of the soil moisture process and conclude that soil moisture principally acts on two scales. The low scale component influenced by vegetation, soil type, topography acting on the range of centimetres to 100's of meters and the large scale component acting on a scale of kilometres. Clearly, the process observed by low resolution sensors like scatterometers is related to the large scale component. Variability other than the atmospheric related must be introduced by modelling approaches or by additional information obtained by ground sources.

4. COMPARISON OF IN-SITU AND SCATTEROMETER DERIVED SOIL MOISTURE

Comparison of field measured soil moisture for a small catchment in Spain and scatterometer derived soil moisture indicates the high quality of remotely sensed soil moisture information and a possible down scaling strategy.

4.1. Site and Data Description

The Duero Basin is located in the North West of the Iberian Peninsula. With an average annual rainfall of about 400 mm the actual study site is in the semi-arid sector of the Duero basin at 41.1-41.5° N and 5.1-5.7° W (Fig. 1). Because of its geographical position in the central part of the basin, Miocene sediments and fluvial deposits of Quaternary are predominant (sandstones, conglomerates, limestone, gravels, sands, etc). Rainfed crops (cereals and vineyards) cover about 80 % of the land. In this area, the REMEDHUS Network has been operating since June 1999 measuring soil moisture at depths of 5, 25, 50 and 100 cm at 14-days intervals using TDR probes. The total number of stations used in this study is 20 and all are included in agricultural fields. They cover a plain area of about 1300 km^2 in accordance with three physical soil units: sandstones, fluvial terraces and limestone. Sandstones are characterized by a clear textural heterogeneity along the profile, with a sandy upper part and concentration of silt and clay fractions in the half lower part of the profile. For fluvial terraces the texture distribution is more homogeneous with a prevalence of sand fractions (mean about 80 %). Limestone is characterized by the important presence of silt and clay fractions along all profile. Due to the predominance of agricultural land-use and the absence of topographical contrast in the study area, soil texture is considered as the most important parameter affecting the soil moisture field on the small scale.

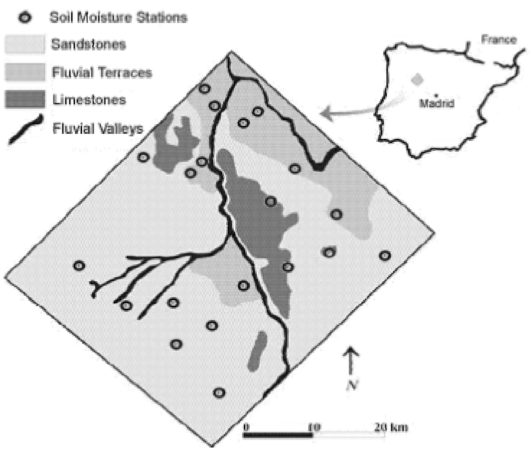

Figure 1. Location of the TDR probes in the Duero basin and soil physical units.

The length of the study period is 21 months from June 1999, corresponding with the beginning of operation of the measurement network, to February 2001, corresponding to the end of ERS-2 data availability. During this period, the rainfall behaviour was very irregular with two marked dry periods: one from November 1999 to March 2000 and another from June 2000 to September 2000. The most important humid period was registered from October 2000 to February 2001.

4.2. Data Preparation

To compare *in-situ* measured soil moisture given in absolute units of plant available water with the *SWI* samples given in relative units, *SWI* must be transformed to absolute units. A simple transformation strategy rests on the idea that actual values in absolute units have to be related to the critical soil moisture levels Θ_{min} and Θ_{max}. From a theoretical perspective, the range in soil moisture is bound to zero and the total water capacity Θ_{twc} (Hillel, 1982). In the field, the practical lower limit is positive due to the inability of plants to extract water below a particular level, commonly called the wilting point $\Theta_{wp.}$ Over the Ukraine (Wagner et al. 1999) empirical analysis of gravimetric soil moisture data confirmed that Θ_{min} can be related to wilting point whereas Θ_{max} can be related in good approximation to a point midway between field capacity Θ_{fc} and total water capacity Θ_{twc}. Following transformation was found to be sufficient to estimate absolute soil moisture in plant available units

$$PAW_{scat} = SWI\left(\frac{\Theta_{fc} + \Theta_{twc}}{2} - \Theta_{wp}\right) \quad (1)$$

To estimate the influence of sub-pixel variability in soil properties the conversion of the *SWI* is once calculated with area-representative values of Θ_{wp}, Θ_{fc}, and Θ_{twc} and once with average values of Θ_{wp}, Θ_{fc}, and Θ_{twc} for each soil class. Area-representative values of Θ_{wp}, Θ_{fc}, and Θ_{twc} are determined by averaging the respective point values of θ_{wp}, θ_{fc} and θ_{twc} from all stations of the basin and for all stations of each soil unit.

In order to compare the TDR measurements with the scatterometer derived soil moisture estimates representing an area of 2500 km^2, the data from the respective sites located within the 1300 km^2 large field and within each unit of REMEDHUS are averaged. The area-average plant available water content based on the field data (PAW_{field}) is derived with

$$PAW_{field} = \frac{\sum_{i=1}^{N} paw_i}{N} \quad (2)$$

where paw_i is plant available water content for station i in volumetric units (vol. %) and N is the number of stations for the entire test site and for each soil class.

4.3. Data Quality

The comparison between the area-average plant available water based in the field and scatterometer data shows a significant coefficient of estimation for average soil moisture profile (0-100 cm) with a R^2 value equal to 0.74 and a mean square error (RMS error) of 2.2 vol.%.

4.4. Subpixel variability

Scatterometer and the averaged field measurements are representative of large areas and hence reflect the atmosphere-forcing component of the soil moisture field at the synoptic scale. On smaller scales, soil moisture is affected by soil characteristics, topography and vegetation, causing a variability over a distance of meters that may be as significant as the variability over tens of kilometres. The high spatial variability is evident in Fig. 2, which shows time series of the plant available water content for all 20 stations in the Duero basin. The standard deviation of*PAW* for individual dates ranges between 2.7 and 4.8 vol. %, the average for all dates is 3.4 vol. %. It is a measure of the spatial scaling error when comparing point measurements to the area-average *PAW*.

Results for each soil physical unit indicate distinct differences. In the sandstone unit the bias is generally positive and shows the highest values (Fig. 3). We hypothesize that this is due to the hydraulic discontinuity along the profile, which is also reflected by the difference between wilting point in the soil surface layer and the lower half part of the profile. While the upper part of profile is dry, the lower half part of profile is wetter due to higher water retention capacity (-4 vol. %). The best coefficient of correlation (Fig 3) and lowest bias values are found in the fluvial terraces unit due to homogeneous texture distribution, the upper layer conditions being representative of overall profile. The difference between the water content at wilting point in the soil surface layer and the lower half part of the profile is only –1.2 vol. %. Finally, in the limestone unit, the bias is always negative due to the higher silt and clay fractions (about 50 %) in the upper layer, which can explain the higher water retention in this layer (the θ_{wp} value in the first 5 cm of the soil is equal to 12.8 vol. %).

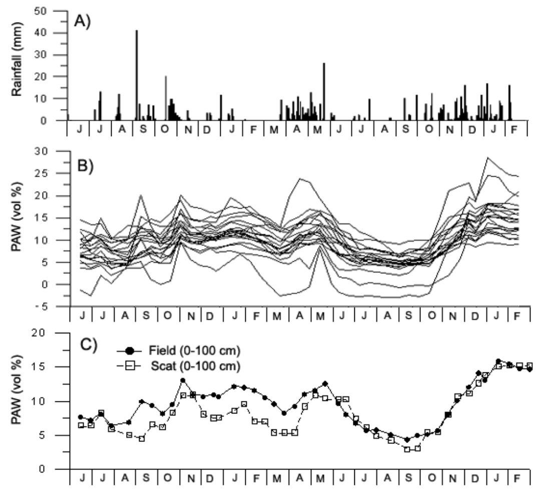

Figure 2. (A) Rainfall; (B) plant available water for all 20 field sites based on TDR measurements; (C) average plant available water based on TDR measurements and scatterometer derived plant available water; for the period June 1999 to February 2001.

Considering that plant available water data partly accounts for texture effects, the scaling error is small, with a high R^2 for all stations and an averaged RMS error of 4 vol. %. The differences in plant available water values in the field, and as consequence between these data and scatterometer estimates can be explained in terms of texture fraction distribution along the profile.

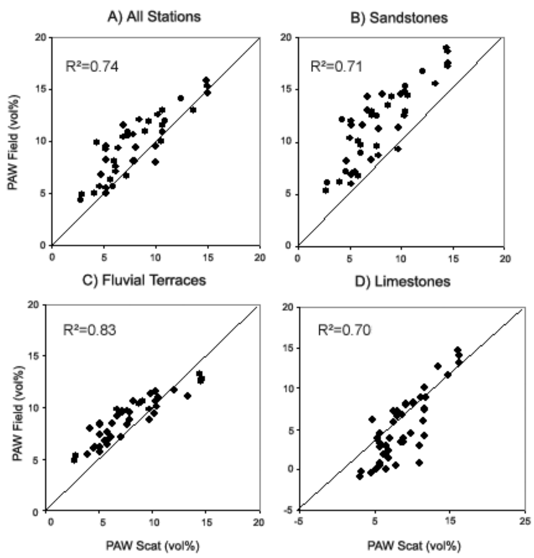

Figure 3. Scatterometer versus field measured plant available water for stations averaged over (A) the entire study site; (B) sandstone unit (C) fluvial terraces unit and (D) limestone unit.

5. RUNOFF ESTIMATION FROM SCATTEROMETER DERIVED SOIL MOISTURE

In a pilot study it was tested if Scatterometer derived soil moisture can be used to determine runoff of the Zambezi catchment in Africa for improved flood early warning.

5.1. Site and Data Description

The climate of the Zambezi catchment generally underlies the movement of the Intertropical Convergence zone ITC, resulting in distinct dry and a wet seasons during the year. The study period, ranging from 1992-2000, was characterized by a wet period from 1992 to 1994, followed by a rather dry period from 1995 to September 1997. The end of the study period was characterized by extreme wet conditions with disastrous floods in the years 1997 and 2000.

The Zambezi River Authority in Zambia provided discharge and water level data of five gauging stations - Chavuma Mission (discharge), Lukulu (water level), Matongo (water level), Senanga (water level), and Nana´s Farm (discharge) - of the catchment-basin of the Zambezi river in southern Africa. The observations cover the years 1992 to 2000 with a daily sampling. To retrieve matching data sets daily hydrological data was averaged over a ten day period.

Although runoff is a point measure it integrates information on the hydrologic status of an entire catchment. To get a representative indicator *SWI* samples have been averaged over all grid points of the entire catchment.

5.2. Results

Fig. 4 shows time series of discharge and area averaged *SWI* for the gauging station Nana's Farm. Similar trends in both data sets are evident. Also evident is a clear shift between the two data sets which relates to the response time of the river systems to changes in the hydrological conditions of the catchment. Correlation analysis revealed that the shift varies throughout the river systems. For upstream gauging stations a 30 day shift is estimated, for downstream stations this value increases to 60 days. Taking the shift into account, a significant non-linear coefficient of correlation between observed runoff and the area averaged SWI in the order of 0.9 is estimated (Fig. 5).

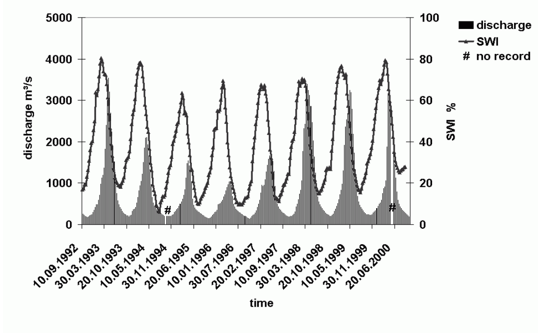

Figure 4 Discharge and Area Average SWI Time Series for the station Nana's Farm.

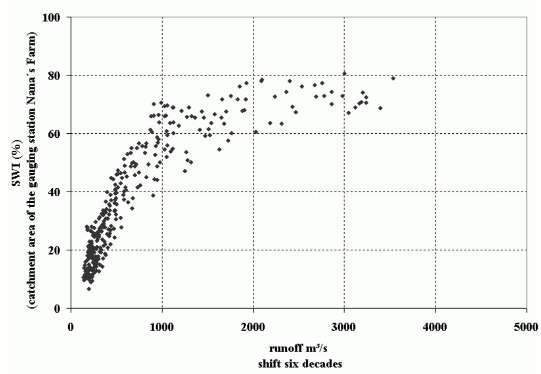

Figure 5 Scatterplot of discharge and area average SWI – discharge samples have been shifted 60 days to maximize correlation.

6. CONCLUSIONS

Current and future low resolution active microwave and passive sensors will provide a flow of global high quality coarse resolution hydrologic parameters. Concepts of how to make best use of this data and how to integrate coarse resolution products in current hydrological modelling are still vague.

Based on two simple examples possible ways forward to use the coarse resolution data in hydrologic applications was illustrated. Already simple strategies allow to apply respective data directly for hydrological research and applications. More sophisticated downscaling and data assimilations schemes developed in future will raise the potential of such data sets.

7. ACKNOWLEDGEMENT

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