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Chapter 8. Variable source areas, soil moisture and active microwave observations at Zwalmbeek and Coët-Dan

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Abstract

This chapter focuses on recent research to identify variable source areas from surface soil moisture dynamics observed at the catchment scale by means of active microwave images from satellites. It is hypothesized that variable source areas can be mapped if we can quantify the temporal variability of the surface soil moisture content. It is difficult to determine the soil moisture content from single synthetic aperture radar images because soil moisture, surface roughness, topography and vegetation all have a great effect on radar backscatter. However, seasonal soil moisture fluctuations can be studied by using multitemporal radar images. Two multitemporal image processing techniques are presented to map variable source areas. The first method computes the temporal standard deviation of radar backscatter. This leads to the definition of the so-called saturation potential index, which compares well with observed saturated areas. The second method makes use of a principal component analysis to separate the dominant effects, like topography, land use and soil moisture, on total radar backscatter. Again this leads to reliable mapping of the spatial patterns of variable source areas. Two humid catchments, the Zwalmbeek in Belgium and the Coët-Dan in France, are used in this study.

Introduction

The variable source area concept is now widely accepted to explain storm runoff production in humid regions. The concept was first introduced by Hewlett and Hibbert (1967): “The yielding proportion of the watershed expands and shrinks depending on rainfall amount and antecedent wetness of the soil”. A major feature of variable source areas is that the area over which return flow and direct precipitation are generated vary seasonally and throughout a storm. The theory was developed because of inadequacies with the Hortonian runoff production mechanism (Horton, 1933) for describing storm runoff in humid catchments. In most humid regions infiltration capacities are high because the vegetation cover protects the soil from rain packing, and because the supply of humus creates an open soil structure. Under such conditions, rainfall intensities generally do not exceed infiltration capacities. Therefore, Hortonian overland flow does not occur on large areas of the catchment.

Research in the 60s and 70s on the variable source area concept was supported by intensive field studies in small watersheds (Hewlett and Hibbert, 1967; Dunne et al., 1975; Dunne, 1978). These authors mapped the spatial patterns of saturated areas and their seasonal fluctuations (e.g. Dunne et al. (1975) show seasonal variation of the saturated zone in a small catchment at Randboro, Quebec). Since then a number of modeling strategies have been developed to explain and predict these spatial patterns of saturated areas (Beven and Kirkby, 1979; Sivapalan et al., 1987; Barling et al., 1994). These modeling efforts recognize the control that catchment topography, soils, antecedent storage capacity and rainfall characteristics exert on the spatial extent of the contributing areas. To link these hydrologic and geomorphologic characteristics of the catchment to variable source areas, static and/or quasi-dynamic wetness indices were introduced. Wetness indices define, at a moment prior to storm rainfall, the readiness of a catchment to produce storm runoff through the saturation excess mechanism.

Routinely collected hydrologic data from catchments generally does not allow full validation of these models. Often validation is solely based on a comparison between observed and predicted streamflow records. This type of validation is insufficient to draw conclusions about the accuracy with which these models describe the temporal and spatial patterns of the contributing areas. More comprehensive validation procedures are required if we want to improve our understanding of these important hydrological processes. At first glance, it therefore seems that the difficulty in collecting information on saturated areas in larger catchments through field work hinders further progress.

Recently, however, new instruments have become available to the hydrologist, in the form of active microwave remote sensors. Active microwave instruments on board of satellites offer tremendous opportunities to increase our observation capacities of large catchments. First of all, they are all-weather instruments, practically undisturbed by atmospheric conditions. Second, they are day and night instruments since they do not depend upon an additional energy source but produce their own electromagnetic energy to scan the Earth's surface. Third, when using a special technique called "synthetic aperture radar" (SAR), they produce images with the required spatial resolution to be of use for catchment modelers (pixel resolution typically on the order of 10 m). But what makes these instruments truly powerful for observing variable source areas is the sensitivity of the backscattered energy to soil moisture. Recent studies have demonstrated the potential of observing soil moisture by means of SAR instruments (Ulaby et al., 1982; Cognard et al., 1995). The main difficulty with SAR imagery is that not only soil moisture but also surface roughness, vegetation cover and topography have an important effect on radar backscatter. These interactions make retrieval of soil moisture difficult and only achievable under particular conditions, such as bare soil or surfaces with low vegetation cover (Altese et al., 1996). It should be possible to separate the vegetation, roughness, topography and soil moisture effects on radar response using multifrequency and/or multipolarization measurements (Ulaby et al., 1996), but currently operational satellites are not equipped with sensors that provide such data.

In this chapter we present recent research on the use of multitemporal SAR imagery to map the seasonal extent of variable source areas (Gineste et al., 1997; Verhoest et al., 1998). The rational of the proposed technique is based on the observation that the seasonal variability of surface soil moisture content is highly related to the occurrence or absence of contributing areas, as illustrated in Figure 1. At hillslope and catchment scales, soil moisture and its spatial and temporal variability are fingerprints of several hydrologic processes. During rainy periods, flow convergence results in relatively low temporal variability of surface soil moisture in the vicinity of the drainage network. In contrast, areas located at or near hillslope tops will exhibit more pronounced soil moisture variation in time due to successive wetting during rainfall events and drying through evapotranspiration and redistribution during interstorm periods. Therefore, by analyzing the temporal variability of the observed radar signal during a winter season, it should be possible to map the variable source areas at the catchment scale.

The chapter is organized as follows. In section 2 we give a short description of the two experimental catchments used in this study. In section 3 we describe the field survey data that is used to test the accuracy with which the proposed remote sensing techniques predict the spatial patterns of seasonally observed variable source areas. Section 4 gives an overview of the multitemporal SAR data collected over the experimental catchments and lists the different image processing procedures required to prepare the SAR data for multitemporal analysis. Section 5 starts with a review of earlier attempts to map variable source areas from SAR images. We then give a detailed discussion of two new techniques that appear promising for mapping the spatial extent of seasonal saturation-prone areas from multitemporal SAR images. The first method uses the temporal standard deviation of radar backscattered energy to map variable source areas in humid catchments with low relief. The second method, based on a principal component analysis, was developed to overcome the restriction of low relief of the catchments. It is shown that principal component analysis allows separation of the different influencing factors (topography, land use, soil moisture) on the backscattering coefficient, and therefore results in a more robust method of mapping variable source areas. Finally, we summarize the main findings of this research in section 6.

2. Description of test sites

2.1 The Zwalmbeek catchment

The Zwalmbeek catchment is situated about 20 km south of Ghent in Belgium (50°45’48”N to 50°54’16”N and 3°40’17”E to 3°50’15”E). It is a 5th Strahler-order basin with a total drainage area of 114 km^2, and a drainage density of 1.55 km/km^2. Rolling hills and mild slopes, with a maximum elevation difference of 150 m, characterize the topography (Figure 2). Land use is mainly arable crop farming and permanent pasture, but the south of the catchment is partly forested. The degree of urbanization is 10%, and is mainly clustered in three small towns. The soil type in the catchment is predominantly sandy loam (Belgian soil classification), with minor isolated patches of sand and clay. The climatic regime is humid temperate with a mean annual rainfall of 775 mm, distributed almost uniformly over the year, and a mean annual pan evaporation of 450 mm. The catchment is described in detail in De Troch (1977).

2.2 The Coët-Dan catchment

The Coët-Dan catchment is located near the town of Naizin, Brittany, France (48°N and 357°10'E). It is a 2nd Strahler-order basin with a drainage area of 12 km^2. Gentle concave slopes (in general less than 5%, especially in the northern part) reflect the brioverian shists substratum with their top overlaid by dystric or aquic eutrochrepts (brown acidic, weakly leached soils) and their bottom by glossaquals (degraded hydromorphic soils) and fluvents (alluvial soils). Agriculture is intensive, and in winter the vegetation cover is particularly low. A land use survey performed in the winter of 1992 revealed that about 22% of the catchment was covered with meadows and young winter cereals (crops 5 to 15 cm high), while about 44% was bare soil, sometimes covered with corn stubble. The mean annual rainfall if about 700 mm, and the mean annual runoff is estimated around 300 mm. For a full description of the hydrology of the catchment see Mérot et al. (1994).

3. Field survey of variable source areas

3.1 The Zwalmbeek catchment

The field data used to investigate the spatial patterns and seasonal extension of the variable source areas are derived from the Belgian soil map (scale 1:20,000). The Belgian soil map was produced during the 1960s and early 1970s for the whole territory, and contains information on soil texture, natural drainage conditions, and profile development. These soil characteristics were derived from auger observations (using augers 1.25 m deep and 5-10 cm diameter) taken in the field with an average density of 2 samples per ha. For our study site this means a total of about 23,000 samples. In addition, soil profile pits were dug with a 1 m^2 area, a depth of 1 to 2 m, and a density of 1 pit each 1.5 km^2. In this study we are mainly interested in the natural drainage conditions of the soils. The drainage map of the Belgian soil map classifies the different soils into classes ranging from well-drained to poorly-drained soils, according to the bore hole field observations (Table 1). These bore hole samples were used to measure the depth to gley and mottle. Gley can be described as a blue-grey waterlogged soil layer in which iron is reduced to the ferrous form. This layer can turn into a soil containing brownish mottles due to oxidation of iron during intermittent dry periods. The occurrence of these features therefore indicate the change in water table height between winter (mottle) and summer (gley). Figure 8b gives the drainage map for the catchment of the Zwalmbeek. As can be noticed from this map, the poorly-drained soils tend to occur in the valley regions of the catchment and correspond to the discharge areas indicated schematically in Figure 1.

Figure 4 shows the rainfall histogram for the winter period of 1995-1996 together with the mean backscattered signal for the whole catchment, calculated from the tandem pairs of the eight ERS-1/2 images.

Table 1. Natural Drainage Classes, Belgian Nomenclature

Drainability Index	Average winter water table depth (= Depth to Mottle) (cm)	Average summer water table depth (= Depth to Gley) (cm)
b	> 125	---
c	80 – 125	---
d	50 – 80	---
h	30 – 50	---
e	30 – 50	> 80
f	0 – 30	40 – 80
g	---	< 40
A (= b + c + d)	> 50	---
D (= c + d)	50 – 125	---

3.2 The Coët-Dan catchment

The field data associated with the study performed in the Coët-Dan catchment were collected in one of the 1st-order subcatchments (drainage area: 1.2 km^2), located in the northwest of the catchment. This survey involved the mapping of the saturated areas during the winter of 1992 by visual inspection (Figure 3) and auger hole sampling. Figure 5 shows the areal extent of the saturated areas as observed on February 15th, 18th and 21st (Salahshour Dehchali, 1993). During the winter period of 1992, rainfall fell between February 8th and February 16th and was followed by a drydown period which lasted till March 3rd (see Figure 12).

4. SAR data collection and preliminary processing

4.1 The ERS-satellite SAR system

The SAR images used in this study originate from the ERS-satellite system. The first ERS satellite (ERS-1) was launched in 1991. This satellite carries several advanced Earth observation instruments, such as the Active Microwave Instrument (AMI) which combines the functions of a synthetic aperture radar and a wind scatterometer. The SAR instrument is a

C-band (5.3 GHz) radar operating in VV polarization (Attema, 1991). One of the products generated by the Processing and Archiving Facilities (PAFs) are Precision Images with a spatial resolution of 30 by 30m and a pixel size of 12.5 by 12.5 m. During the winter of 1992, the satellite was put in the so-called "ice-phase", allowing Earth observations at a limited number of locations with a repeat cycle of 3 days. The Coët-Dan catchment was located in one of these areas with 3-day repeat coverage. Between January 28 and March 28, 15 precision images (PRI) were collected over the catchment (Table 2). In 1995, a second satellite (ERS-2) was launched and put in the same sun-synchronous orbit as ERS-1, such that the time difference between overpasses is exactly 24 hours (the so-called "Tandem-phase"). From October 1995 to April 1996, four tandem pairs (8 PRI images) were collected over the Zwalmbeek catchment (Table 2). In both cases, winter-time images were selected in order to minimize changes in soil roughness, due to agricultural activities, and vegetation characteristics, thereby minimizing their effect on the total radar backscatter.

Table 2. Identification of Satellite Images Used in the Analysis of Coët-Dan and Zwalmbeek.

Date	Mission	Orbit	Track	Frame	PAF	Desc./Asc.
Images for the Coët-Dan catchment						
01/28/1992	ERS-1	2807	1	963		Ascending
02/06/1992	ERS-1	2936	1	963		Ascending
02/09/1992	ERS-1	2979	1	963		Ascending
02/12/1992	ERS-1	3022	1	963		Ascending
02/15/1992	ERS-1	3065	1	963		Ascending
02/21/1992	ERS-1	3151	1	963		Ascending
02/24/1992	ERS-1	3194	1	963		Ascending
02/27/1992	ERS-1	3237	1	963		Ascending
01/03/1992	ERS-1	3280	1	963		Ascending
04/03/1992	ERS-1	3323	1	963		Ascending
03/10/1992	ERS-1	3409	1	963		Ascending
03/13/1992	ERS-1	3452	1	963		Ascending
03/16/1992	ERS-1	3495	1	963		Ascending
03/22/1992	ERS-1	3581	1	963		Ascending
03/28/1992	ERS-1	3667	1	963		Ascending
Images for the Zwalmbeek catchment						
10/31/1995	ERS-1	22455	423	2583	D	Descending
11/01/1995	ERS-2	2782	423	2583	D	Descending
12/05/1995	ERS-1	22956	423	2583	I	Descending
12/06/1995	ERS-2	3283	423	2583	I	Descending
02/13/1996	ERS-1	23958	423	2583	I	Descending
02/14/1996	ERS-2	4285	423	2583	D	Descending
03/19/1996	ERS-1	24459	423	2583	I	Descending
03/20/1996	ERS-2	4786	423	2583	I	Descending

4.2 SAR image calibration

After georeferencing the 23 images (8 for Zwalmbeek and 15 for Coët-Dan), the data had to be calibrated in order to be useful for multitemporal analysis. As stated before, in this study we have used SAR PRI (precision image) data. SAR PRIs are subjected to engineering corrections and relative calibration to compensate for well-understood sources of system variability. Absolute calibration of the precision images, on the other hand, has to be performed by the user. The calibration procedure used here is described in Laur et al. (1997). The digital numbers in the PRIs are related to the backscattering coefficient through the following formulas:

$$A_{ij}^2 = DN_{ij}^2 \cdot \frac{1}{K} \cdot \frac{\sin\alpha}{\sin\alpha_{ref}} \cdot C \cdot \frac{PRP}{RRP} \cdot PL \qquad (1)$$

and

$$\sigma^0 = \frac{1}{N} \sum_{i,j}^{N} A_{ij}^2 \, b \qquad (2)$$

where N is the number of pixels within the area of interest (AOI), i.e., a group of pixels corresponding to a distributed target in the image (e.g. bare soil field) ; i,j are the range and azimuth locations of the pixels within the distributed target containing N pixels ; DN_{ij} is the digital number corresponding to the pixel at location (i,j) ; A_{ij} is the amplitude corresponding to the pixel at location (i,j) ; σ^0 is the backscattering coefficient corresponding to all N pixels within the AOI, which is calculated from the image geometry, the earth surface being represented by a reference ellipsoid (Goddard Earth Model, GEM 6) ; α_{ref} is the ERS reference incidence angle, i.e., 23.0º ; C is a factor that accounts for updating the gain due to the elevation antenna pattern implemented in the processing of ERS SAR PRI products ; PRP is the power of the replica pulse used to generate the PRI product and is given in the header file of the PRI image ; RRP is the replica pulse power of a reference image taken over Flevoland (The Netherlands) ; and PL is the analogue to digital convertor (ADC) power loss. For more details on the calibration we refer to Gineste et al. (1997) and Verhoest et al. (1998).

4.3 Speckle filtering

Radar images of homogeneous rough surfaces always show a granular pattern called speckle. This noise-like phenomenon is the result of changes in the distances between elementary scatterers and the receiver caused by surface roughness, so that the received waves, although coherent in frequency, are no longer coherent in phase. SAR systems rely upon the coherence properties of the scattered signals, making these systems susceptible to speckle to a much greater extent than noncoherent systems, such as side-looking airborne radars (Porcello et al., 1976). The presence of speckle noise in an imaging system reduces resolution, and thus the detectability of a target, and also degrades the quality and interpretability of the scene.

In SAR practice, speckle is suppressed by creating *n*-look images. This reduces the variance of speckle by a factor *n*, but of course deteriorates the spatial resolution by that same factor. During the last decade techniques that do not deteriorate resolution have been proposed for speckle reduction. This filtering reduces the variance of speckle within homogeneous areas, preserves edges and line features in the scene, excludes point scatterers, and preserves the spatial variability. An adapted Lee sigma filter (Gineste et al., 1997) and the Gamma MAP filter (Lopes et al., 1990) have been used in this study to reduce speckle in the 23 SAR images. For more information on these filters, we refer to Verhoest et al. (1998) and Gineste et al. (1997).

5. Spatial patterns of variable source areas through multitemporal SAR analysis

5.1 Introduction

During the last decade, several SAR data analysis techniques have been proposed to map the saturation-prone areas in catchments. Brun et al. (1990), based on helicopter-borne C-band scatterometer data, proposed to map variable source areas by applying a threshold on the backscattering coefficient. The reasoning behind this method is that when ponding occurs the radar signal drops due to specular reflection. They found that a threshold of -7 dB allowed estimation of the spatial patterns in the variable source areas. If the method could be applied successfully it would allow mapping of the extent of saturated areas on each day of radar observations, thereby providing a sequence of variable source area maps. This technique was tested by Gineste et al. (1997) based on the 15 ERS-1 images given in Table 2, but was rejected as an accurate way to map variable source areas. The main difficulty with an absolute threshold is that other surface characteristics that influence radar backscatter, such as

vegetation cover and surface roughness when the terrain is not completely inundated (see Figure 3), are not taken into account.
Another method, proposed by Rignot and van Zyl (1993) and Gineste et al. (1997), uses difference images to overcome the problems occurring with absolute thresholding. These researchers found that a two-date difference image yields more valuable information than the threshold method, but is still limited because the analyzed images should reflect extreme hydrologic conditions (inundated versus dry) before the method becomes reliable. The method of differencing in itself is further susceptible to other problems: changes will not be detected in the same fashion in high intensity regions compared to low intensity areas, which renders the method less reliable. Moreover, the differencing method is not very robust since the radiometric errors introduced in the imagery during SAR processing are multiplicative factors to the total radar intensity, which will not be eliminated during the differencing.

This problem can be overcome by dividing the intensity values of the two dates instead of subtracting them. This ratio method is shown to be better adapted to the statistical characteristics of the radar data, but only works well when the number of looks is very high, since the method is very sensitive to speckle noise (Rignot and van Zyl, 1993).

It is apparent from these trials using change detection techniques that accurate and reliable mapping of saturated areas from one image or from a pair of images is restricted to atypical situations. As an alternative, one can try to analyze a sequence of images taken during a complete season. In the following sections we present two recently developed techniques that appear promising for mapping the spatial patterns in variable source areas during winter seasons.

5.2 Saturation potential index images

Given the strong differentiation in temporal variability of soil moisture as a function of the position along a hillslope (see Figure 1), Gineste et al. (1997) developed a technique based on the backscatter temporal standard deviation as an indicator of the local saturation likelihood during the period of observations. It directly reflects the fact that the more the backscattering coefficient varies in time, the greater is the soil moisture variation, whereas saturation is expected to develop on parts of the catchment that are usually wetter and thus subject to less soil moisture variation in response to the hydrologic forcing conditions. The method uses the logarithmic transform of the backscattering coefficient given by equation (2). Therefore the speckle noise becomes additive and consequently exhibits the same strength regardless of the absolute backscatter level. Moreover, it has been theoretically shown that the possible range of backscatter variation remains about the same (on the order of 5 dB for soil conditions varying from dry to wet) independent of the roughness of the surface (Altese et al., 1996). A measure of the local backscatter temporal variation should thus allow an assessment of the extent to which the soils in the catchments have departed from wet conditions.

Results of this method applied to the Coët-Dan data are illustrated in Figure 5. Indeed, the red areas (indicating low temporal standard deviation) of the derived image mainly appear where saturation has been reported (see Figure 5) and apparently only there. To produce the results given in Figure 5, the original images were speckle filtered twice using the adapted sigma filter, before the backscatter temporal standard deviation was computed. The resulting values can be interpreted as saturation potential indices (SPI). However, the backscatter temporal standard deviation cannot be used directly over the whole catchment as a measure of saturation, as other areas where little variability is to be expected (e.g., areas of dense vegetation such as forests where microwave penetration is impeded) are not discriminated. Another source of discrepancy may arise from human activities in agricultural catchments (compaction of top soil by cattle, harvesting, ploughing). If saturated areas appear locally because of these effects on the soil water regime, they are likely disconnected from the stream and may usually not be considered as contributing to river discharge. One way of removing these areas from the analysis is to combine SPI with static wetness indices, such as the topographic index (Beven and Kirkby, 1979).

The application of the SPI technique to the Zwalmbeek catchment shows similar results, but also reveals another shortcoming of the SPI method. In Figure 6 the effect of topography on the computed SPI is clearly visible as a shift of the predicted saturated areas with respect to the drainage network. Therefore, a more robust technique which can separate the topographic and land use effects from soil moisture influences on the total backscattering is suggested in the next section.

5.3 Principal component analysis

The principal components transformation is a standard tool in image enhancement, image compression, and classification (Richards, 1986; Singh, 1989; Lee and Hoppel, 1992). It linearly transforms multispectral or multidimensional data into a new coordinate system in which the data can be represented without correlation. The new coordinate axes are orthogonal to each other and point in the direction of decreasing order of the variances, so that the first principal component contains the largest percentage of the total variance (hence the maximum or dominant information), the second component the second largest percentage, and so on. Images transformed by PCA may make evident features that are not discernable in the original data — local details in multispectral images, changes and trends in multitemporal data — that typically show up in the intermediate principal components.

PCA is widely used in optical remote sensing but less so in the more recent area of SAR image processing. One example is provided by Lee and Hoppel (1992), who used a modified principal component transformation on multifrequency polarimetric SAR imagery for reducing speckle and for information compression. Another example is given by Henebry (1997) who used PCA on a temporal series of twelve images for the production of a high spatial resolution/low spatial noise image that served as a template for georeferencing. One of the principal components obtained could then be used for land cover segmentation.

Figures 7-9 show the images constructed for the first 3 principal components computed from the 8 Zwalmbeek images. Applying PCA to these eight images leads to the separation of the information into several components that can be attributed to different factors influencing the backscatter. The first principal component accounts for 76.6% of the total variance, the second component for 6.6%, the third for 5.9%, and each of the remaining PCs for less than 4% (Verhoest et al., 1998).

Figure 7 compares the first component (left image) with a local incidence angle image computed from the digital elevation model of the catchment. The similarity between these two images suggests that topographic effects are responsible for the largest contribution to the total variance in the sequence of SAR images and dominate the backscattering signal. A sequence of images taken with the same radar configuration and footprint (frame and track) will show a very high correlation: slopes facing the satellite will consistently return more energy than slopes turned away from the sensor. The principal component analysis has brought out these hightly correlated features in the first PC.

The left image in Figure 8 represents the second principal component. This image displays a strong spatial organization, with the highest values grouped along the drainage network of the catchment. To test the hypotheses that the information contained in this image is related to the drainage conditions of the catchment, a drainage map for the Zwalmbeek was generated, and is shown in the right image of Figure 8. As can be noticed from this figure, the poorly-drained soils tend to occur in the valley regions of the catchment and correspond well with the areas with high second PC values. This suggests a radar response, brought out in the second principal component, to the soil moisture patterns that result from the drainage characteristics of the basin. These patterns are not attributable to any single event, but reflect the overall response of the soil to the rainfall and interstorm periods spanned by the images, as illustrated by Figure 1.

The third principal component (left image in Figure 9) shows the influence of land cover and land use, as evidenced by its strong correlation with the Landsat-derived map (right image in Figure 9) that highlights the forested areas in the south of the catchment and the few towns on the basin. The land use map is the result of a supervised classification performed on a Landsat TM image of October 12, 1994. The classification resulted in 10 classes, such as woods, urbanized areas and several agricultural fields which are grouped together as shown in Figure 9. In SAR images urban areas typically appear as bright objects, and in a sequence of images such areas, with their relatively static features, will produce a consistent backscattering signal. If there are few changes in major vegetation features over the same sequence of images, each canopy type will also produce a typical and temporally consistent radar response.

The fourth and subsequent principal components account for a very small fraction of the total variance in the sequence of SAR images, and they do not seem to reveal significant features. These PCs are characterized mostly by noise (including speckle).

As was already mentioned, the second component shown in Figure 8 is strongly related to the soil moisture response expected from rainfall and drainage/redistribution episodes and reflects the drainability of the soil. This can be further illustrated by investigating the signal's behavior for the negative and positive values of the second principal component. Figure 10 plots, for each SAR image, the average backscatter value of these two classes in the second PC. The negative class generally corresponds to the well-drained soils, which are found upslope, while the positive class mainly coincides with the poorly-drained areas. As was mentioned before, the discharge areas exhibit a lower temporal variability in soil moisture content than the upslope areas, and this is reflected in the lower variability of the radar backscattering for the positive PC2 areas during the winter period. During a drydown period, upslope areas show a larger decline in soil moisture content than near-stream areas, which corresponds to a larger decline in backscattered signal of the negative PC2 areas for the first four datatakes. The large rain event of February 13 is reflected in the large increase in signal for both positive and negative PC2 areas. Over the course of the following 24 hours, soil moisture was redistributed over the basin, leading to a decrease of soil wetness in the recharge zones but little change in the already saturated near-stream zones, as evidenced in Figure 10. Shrinkage of the variable source areas over the following weeks accounts for the decrease of the backscattered signal of the positive PC2 class.

Applying PCA on the sequence of ERS-1 images taken over the Coët-Dan catchment, omitting the frost dates (January 28 and February 21), leads to similar results as obtained for the Zwalmbeek catchment. As the Coët-Dan basin is quite flat (slopes are generally less than 5%), the backscattered signal is less influenced by the topography. Therefore, the first PC does not show the topographic effects on the backscattered signal but rather shows variations in land use. The second PC, as shown in Figure 11, corresponds remarkably to the SPI computed over the catchment. It therefore can be concluded that saturation prone areas can be mapped using the principal component technique on a sequence of SAR images. Again, slicing the histogram of the second PC into positive and negative classes leads to a similar behavior in the radar backscatter as was observed in the Zwalmbeek catchment. In this analysis, the negative PC2 areas correspond to the saturation prone areas observed during the field campaign. Figure 12 shows the large variability exhibited by the positive PC2 pixels which reflects wetting from the first rainstorm in February and the drydown of the soil in those areas thereafter, while the negative areas almost remain at the same level due to their high moisture content.

6. Conclusions

Remote sensing offers great potential for mapping saturation prone zones within a watershed. For two humid catchments in Western Europe, several methods based on change detection techniques have been tested for this purpose. Applying a threshold on the backscattering coefficient is not succesful in delineating saturated areas since the choice of an absolute threshold cannot take account of the several surface characteristics that influence the backscatter. Other simple methods consist of differencing or ratioing SAR images. The differencing technique yields more valuable information than the threshold method, but still is limited due to statistical problems related with the speckle in SAR images.

Based on the observation that soil moisture variability is a function of its position along a hillslope, the saturation potential index was introduced. This index is based on the temporal standard deviation of the backscattering coefficient at a certain location which is directly related with the variation of soil moisture at that spot. This index leads to good results for the Coët-Dan catchment. However, for the Zwalmbeek catchment, which has a more pronounced topography, influences of the change in local incidence angle were introduced in the SPI. This problem can be overcome by performing a principal component analysis on the sequences of images. This technique can separate topography and land use effects from the soil moisture influence on the total backscattering. In particular, it was possible to detect changes between scenes in the second principal component that could be linked to soil moisture variations. The soil moisture patterns observed are consistent with the rainfall-runoff dynamics of a watershed and coincide with the saturation prone areas derived from information on the natural drainage condition of the soils in the Zwalmbeek catchment.

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Figure 1: Redistribution of soil moisture along a hillslope resulting in recharge areas with high temporal soil moisture variability and discharge zones with low temporal soil moisture variability (σ_θ^2: temporal variance of soil moisture).

Figure 2: Photograph of part of the Zwalmbeek catchment.

Figure 3: Photograph of part of the Coët-Dan catchment.

Figure 4: Daily rainfall for the 1995-1996 winter period observed at the Zwalmbeek catchment. Also indicated by the dashed line and right-hand scale is the average radar backscatter σ^0 for the catchment calculated for each tandem pair of ERS-1/2 images.

Figure 5: Saturated areas observed from field campaigns on February 15, 18, and 21 for the Coët-Dan catchment. The right image shows the saturated potential index (SPI) for the Coët-Dan basin, calculated on the sequence of ERS-1 images taken during the winter period of 1992. The SPI varies from low (red) to high (blue).

Figure 6: Saturated potential index (SPI) calculated on the sequence of 8 ERS images for the Zwalmbeek catchment, ranging from low (blue) to high (red). The stream network (black) is given in overlay. Notice the shift of the low SPI with respect to the river network.

Figure 7: First principal component image calculated for the Zwalmbeek catchment (left) and an image of the local incidence angles calculated from the digital elevation model of the catchment (right). The stream network (black) is shown in overlay in both images.

Figure 8: Second principal component image calculated for the Zwalmbeek catchment (left) and the drainage map for the catchment (right). The drainage classification scheme is explained in Table 1.

Figure 9: Third principal component image for the Zwalmbeek (left) and a classified Landsat image with forested and urbanized regions in the catchment highlighted (right).

Figure 10: Average radar backscatter values for the negative and positive PC2 values for the Zwalmbeek catchment.

Figure 11: Second principal component calculated for the Coët-Dan catchment. The stream network (black) is given in overlay. (Red: negative values, blue positive values).

Figure 12: Daily rainfall for the Coët-Dan catchment during the winter period of 1992. Also indicated by the solid line is the average backscatter over the basin (expressed in digital numbers) and by the dashed lines the average radar backscatter values for the negative and positive PC2 values.