Spaceborne Observation of Catchment Surface Changing Conditions Generating Excess Runoff, Erosion and Flood Risk Downstream

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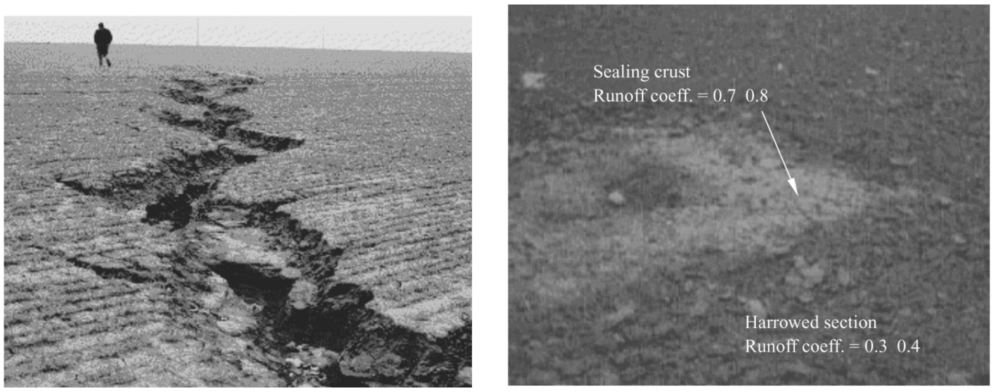
Abstract: The land use and land cover of catchment basins play an important role in the onset of runoff, erosion, sediment load and flood risk in many areas of the world. They control runoff coefficients, concentration time and resistance to erosion processes. Remote sensing and GIS tools have the capacity to provide information on the status of land use and soil protective cover in drainage basins, but this information is not always adaptable to hydrological modeling and forecasting. It has to be translated into parameters and coefficients that hydrological models can understand : Manning coefficients, SCS curve number, soil cover factors in soil loss equations, etc. Optical data such as those from LANDSAT Thematic Mapper are used to map land use classes (forest, crops, bare soils, etc) and soil protective cover by living and dry vegetation, while microwave data such as those from RADARSAT are used to evaluate soil surface roughness and soil moisture. Additionally, they can also be used to evaluate land use classes in areas which are not easily observed by optical data due to cloud cover or poor illumination conditions (wet tropics and northern latitudes). In order to be used reliably in hydrological and erosion modeling, remote sensing data must be calibrated and validated on the ground by appropriate measurements of the surface's spectral, dielectric and geometrical properties. These measurements are then linked to the satellite data which have to be previously geometrically and radiometrically corrected for the effects of topography (altitude, slope, aspect) and atmosphere. This paper presents the team member's experience in applying earth observation data to this type of problems in Canada, Europe and Vietnam.

1 Introduction and Background

Excess runoff has been a major disaster generating cause in recent years in many areas of the world, and especially in Northwest Europe. It occurs in regions having large fields of annual crops on loamy soils, leaving the soil unprotected by vegetation during 2 or 3 months per year. Excess runoff takes place on bare soils forming a sealing crust when exposed to strong rains. This crusting effect increases the runoff coefficient of the surface and therefore the amount and the speed of water sent downstream. This runoff water is also an important erosion and pollution agent, because phosphates move along the slopes with the suspended sediments and end up in rivers and lakes, contributing to silting and eutrophication.

Figure 1(a) shows the initiation of an erosion rill on one of the test sites in Normandy. Low vegetation cover and smooth, crusted surface create the initial conditions for this land degradation process. Land managers and some farmers in Normandy try to reduce these effects by planting grass on these waterways. This conservation practice seems to be relatively efficient to decrease runoff and increase infiltration, but it is sometimes perceived as a reduction of the cash crop producing area. Crusting can also be reduced by tillage or with a harrow in order to increase the surface roughness as shown on Figure 1(b), taken on a test site in Ste-Angèle-de-Monnoir, Quebec, Canada. This action reduces the amount and the velocity of surface runoff, and therefore the erosive power of overland flow.



(a) (b)

Fig. 1 (a) Initiation of an erosion rill caused by excess runoff in Normandy
(b) Remains of a sealing crust on bare soil compared to a recently harrowed section with a greater roughness

Satellite imagery can help to map these different land surface conditions and to provide hydrologic and erosion models with input data that can refine their spatial distribution. Optical satellites can provide land use maps, especially for identifying crop types, bare soil areas and also anti-erosive measures such as the use of residues for soil protection. But their possible use is limited by the combination of cloud cover and satellite overpasses. Radar satellites such as the Canadian RADARSAT system can see through clouds, and on bare soils, the signal backscattered to the satellite is a function of surface roughness and soil moisture.

These considerations and the interest of end users in Normandy and Canada have given rise to a project called FLOODGEN (FLOOD risk reduction by spaceborne mapping of excess runoff GENerating areas), funded by the European Union and by Canada (King *et al*., 1998). Two components of the runoff/erosion problem have been addressed by the Canadian partners of the project : the question of surface roughness and the question of soil protection by crops and residues.

2 C-Band sar mapping of surface roughness of bare soils

2.1 Introduction

One possible way to estimate surface roughness consists in using active microwave remote sensing. Previous work has shown that the backscattered radar signal is influenced by surface roughness and soil moisture (Ulaby *et al*., 1978). The potential retrieval of surface roughness status represents a crucial step before the assimilation of remote sensing data into numerical models for predicting watershed runoff, especially in winter conditions when no other data could be operationally provided by optical sensors because of frequent cloud cover.

2.2 Methodology and data acquisition

While ERS 1 and 2 acquire data on a fixed orbit with a 23° incidence angle and can observe the same site every 35 days, RADARSAT can be programmed with different resolutions and incidence angles ranging from 24° to 49°, according to user needs. This feature allows a more frequent coverage, up to 2 images per day on the same site if there is no competing site elsewhere. Images of the FLOODGEN test sites have been acquired during winter and early spring when many soils were without vegetation. Simultaneous ground observations and measurements for position (GPS), roughness, moisture and soil cover have been made in order to be able to relate ground parameters with image data. Most RADARSAT images used in the project were provided by the Canadian Space Agency and have been precision geocoded and orthorectified by VIASAT inc. of Montreal, using precision GPS points and digital elevation models.

The plots sampled in the field were then precisely located on the imagery and the backscattering coefficients (σ°) for each of them were extracted from the imagery for statistical analysis. Results of this analysis were then used for image classification. Due to the fact that radar images cannot always separate bare soils from vegetated areas, a mask based on an optical image such as one from LANDSAT or SPOT has been applied on the radar images in order to concentrate the analysis on bare soils only.

2.3 Data analysis

At every incidence angle (23°, 39° and 47°), an analysis of the 1998 and 1999 Normandy data shows that it is impossible to establish a relationship between radar data and soil moisture content over bare soils. This was explained by the low dynamics and high values of soil moisture content (30% to 40%), close to saturation. But the relationships between the backscattering coefficient and the rms of surface heights show that σ° increases with the surface roughness. The mean difference between the roughest areas and smoothest areas is only of the order of 1dB for ERS data at 23°, but of 3.5 dB for RADARSAT at 39°, and of 5 dB for RADARSAT at 47°. Figure 2 shows the relationship between ground measured roughness and satellite data (Coulombe-Simoneau *et al*., 2000).

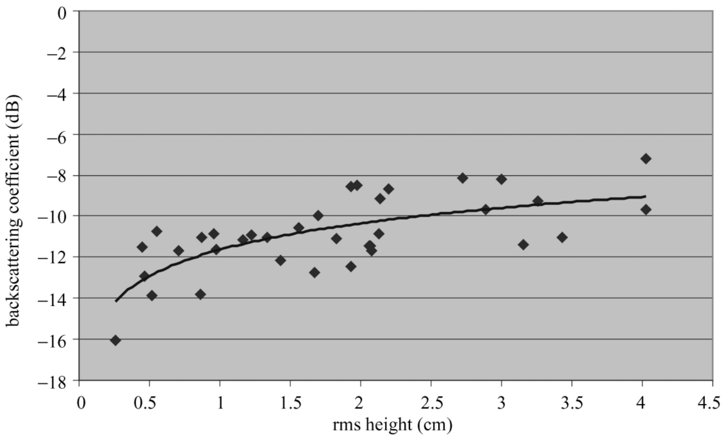


Fig. 2 Variation of the satellite backscattering coefficient σ° as a function of mean surface heights (rms) at 39° for the Normandy site

The results show that the best configuration for a surface roughness measurement requires the use of a SAR image at high incidence angle such as RADARSAT. The relatively good results obtained on the FLOODGEN sites are due to the fact that moisture was high and not very variable. But in order to increase the accuracy of the relation when moisture conditions are more variable, the radar signal related to roughness should be separated from the one related to moisture. This can be achieved with multiple image acquisitions in configurations such as 2 different angles or 2 different polarizations (Dubois *et al.*, 1995, Sahebi *et al*., 2002, Angles *et al*., 2001).

2.4 Classification of roughness classes

Soil surface roughness is one of the key parameters involved in the runoff process, whose measurement is of primary importance in the problem of modelling excessive runoff risk. By inversion of the relation obtained above, a pixel by pixel classifier separated the bare soils of the test area into three categories: (1) smooth areas (high runoff potential), (2) medium rough areas (moderate runoff potential) and (3) rough areas (low runoff potential). Figure 3 illustrates the result of this classification procedure with the 1999 RADARSAT image. Compared to observations, the classified RADARSAT images show good agreement with the test fields. The final product provides the localisation and quantity of various state of soil roughness inside a catchment basin. The overall classification accuracy is of 80%. The misclassification rates for individual categories are less than 20% except for the middle class (40%). Some sophisticated runoff models such as STREAM (Le Bissonais, 1991) may require more classes, but end users agreed that even these crude classes were better than roughness guesses from cropping calendars and helped them in runoff forecasting.

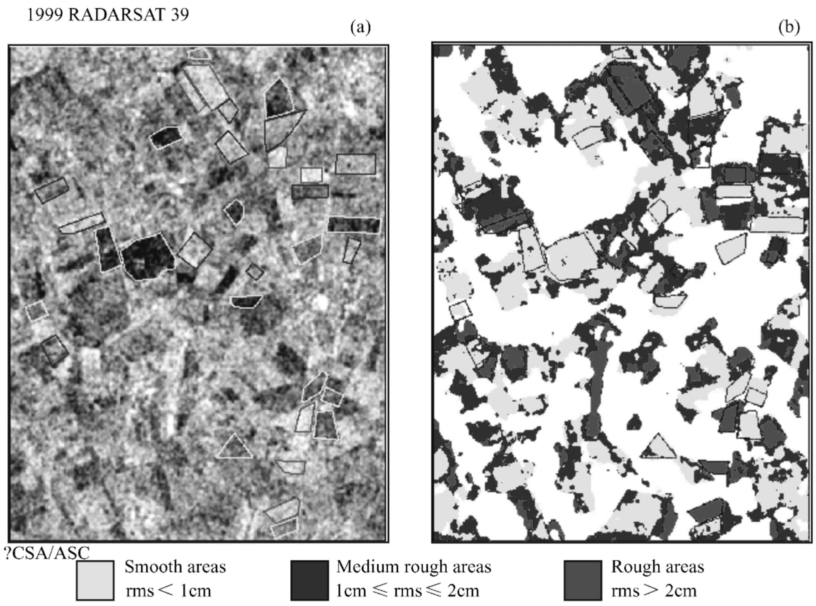


Fig. 3 Segment of RADARSAT image and the corresponding classified image. Image dimension is 4.7km (horizontal) by 6.2km (vertical)

2.5 Conclusion for roughness mapping with RADARSAT

The retrieval of physical parameters of the soil surface such as surface roughness is important for environmental management in hydrology and agriculture, as they appear to be among the major parameters for runoff forecasting on a watershed. In this study, the possible use of synthetic aperture radar (SAR) for mapping soil roughness classes over bare soils shows that RADARSAT at high incidence angles provides a better way than ERS to discriminate among the different roughness classes (smooth, medium rough and rough areas) of agricultural fields. However, when all the fields have a very high roughness, as is the case in the Solnan, another FLOODGEN site, tillage orientation has also an important effect on backscattering, allowing the orientation to be extracted from RADARSAT imagery at high incidence angle (Smyth *et al*., 2000).

This simple operational processing of radar images for retrieving soil surface roughness will allow applications to improve the characterisation of the roughness classes in a watershed so that it should be possible to assess the areas contributing to quickflow and to use them in spatial modelling of excessive runoff. However, the study sites of the different FLOODGEN teams vary significantly, and these results cannot be extrapolated on all sites. For example, on the Ruwer site (Germany), terrain slope effect is very strong due to the local topography and it masks the effect of roughness on radar imagery. On the Lombardia site (Italy), the very small agricultural field size and the proximity of buildings and roads generates much noise in the radar imagery, making extraction of radiometric values less reliable. Therefore, the extraction of roughness based on relations found in this work is applicable only in areas of open fields with gentle topography. These conditions prevail in many agricultural areas of Northwest Europe. Similar approaches are presently tested on recently deforested lands in Vietnam.

3. Optical observation of crop residue cover as a way to control erosion and runoff

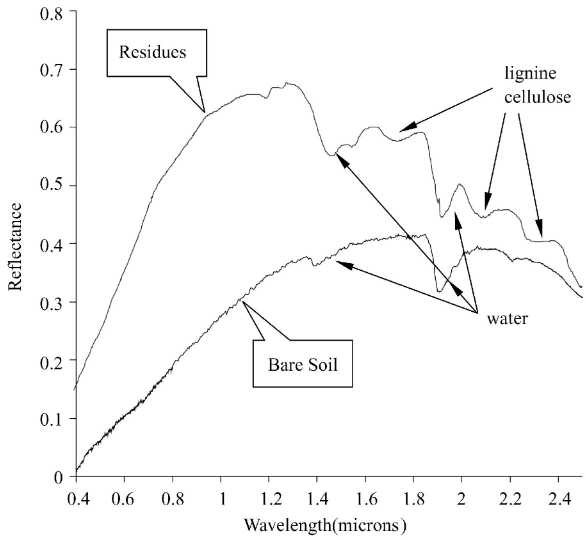
3.1 Crop residues are an efficient way to reduce erosion and runoff

Several agricultural practices have been developed to reduce runoff and erosion. Terraces, contour tillage, reduced till and no till are among the practices used. Application of crop residues to protect the soil from raindrop impact and to reduce the speed of runoff is one of the techniques under development. Field based experiments conducted in Ontario, Canada (Ketcheson and Stonehouse, 1989), and others in Switzerland, have shown that a residue cover of 30% can reduce the erosion rate by 80% and also reduce the runoff by a significant amount. In some areas, crop residue application is subsidised by the states, and therefore it is important to be able to assess the amount of land covered by residues.

3.2 Mapping of crop residues is possible with optical sensors operating in the SWIR spectral range

Crop residues have a brownish colour relatively close to that of bare soil. Therefore, the usual remote sensing satellites such as SPOT, operating in the visible (VIS) and near infrared (NIR) range of the electromagnetic spectrum, have a tendency to confuse bare soils with crop residues. Classical vegetation indices such as NDVI do not make the difference either because they are based on the difference between chlorophyll absorption in the red band and cell structure reflection in the NIR band. Senescent vegetation does not absorb the red radiation anymore. Figure 4(a) shows the colour similarity of the soil and the residues.

(a)



(b)

Fig. 4 (a) Note the difficulty to separate visually the residue colour from the bare soil
(b) Reflectance spectra of bare soil and cereal residue. Lignine and cellulose absorption bands help to discriminate residues from bare soil

New optical sensors looking at the short-wave infrared (SWIR) range can however make the difference between residues and bare soils. This is due to specific absorption features of cellulose and lignine, major components of crop residues, in the SWIR range. In order to investigate the capability of the new sensors to map crop residues, field spectra-radiometric campaigns have been conducted over several FLOODGEN sites. These campaigns have shown that the residues can be distinguished from bare soil by using either an approach based on spectral indices in the SWIR and NIR range or an approach based on spectral mixture analysis (SMA) (Biard and Baret, 1997; Arsenault and Bonn, 2001. Figure 4(b) shows reflection spectra of bare soils and cereal residues on one of the test sites. Spectra of cereal residue and bare wet loamy soil are represented in green and red respectively. Even if both show the same water absorption bands, residues show also absorption by cellulose and lignine in the SWIR part of the spectrum. These features help to discriminate residues from bare soil and to map them from satellite data if SWIR bands are present.

Combination of such maps with cadastral information can help authorities to enforce and verify soil conservation subsidy policies. Furthermore, these digital maps can then be imported into geographic information systems (GIS). This operation can improve the accuracy of runoff modelling or soil loss prediction in models such as ANSWERS, STREAM, LISEM or the Universal Soil Loss Equation where the C factor accounts for the vegetative cover.

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