ELSEVIER

Soil Technology 10 (1997) 99–110

SOIL
TECHNOLOGY

Contribution of multi-temporal SPOT data to the mapping of a soil erosion index. The case of the loamy plateaux of northern France

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Received 15 March 1994; accepted 10 April 1996

Abstract

Loamy soils of the northern European loess belt commonly are exposed to erosion caused by concentrated runoff. Such runoff generates mud flows that, when strong, may create major problems because of the damage they cause to infrastructure. Using multi-temporal SPOT data and GIS technologies, a method is proposed and tested for mapping surfaces affected by runoff, as well as for evaluating the effectiveness of such remotely sensed index to infer erosion. This work is part of a major research effort, jointly undertaken by BRGM and INRA, which develops a predictive approach for monitoring erosion at a regional scale. Results have shown that the method for estimating surfaces affected by runoff, is quite reliable for areas underlain by loamy soil. However, the correlation between such surfaces and effective erosion, i.e. soil loss quantitative measurements, remains low, even though it confirms the possibility of using satellite data rather than other sources of information. It became clear that the conditions of low erodibility during the period of our study were a handicap for this type of validation; another problem is caused by the choice of the optimum observation period, which can vary as a result of winter rainfall events.

Keywords: SPOT data; GIS technology; Runoff; Loam

1. Introduction

In the loess belt of northern Europe the past decades have seen a fundamental transformation of the agricultural landscape into an open field system which has led to

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PII S0933-3630(96)00090-6

increased gully erosion by concentrated runoff. Runoff generates mud flows that, when strong may cause major damage to infrastructure (De Ploey, 1989; Boardman, 1990). As a result regional evaluations of soil erosion risk are requested by public organisations which are facing to the necessity to implement cost effective soil conservation plans. In that context several research teams attempt to elaborate small scale erosion hazard map based on multivariate analysis (Madsen et al., 1986; Auerswald, 1988; King et al., 1993). This approach is often limited by the quality or even the availability of the data required to feed these models. Remote sensing from space, is an alternate for obtaining regularly the spatial distribution of certain parameters of the earth's surface, covering large areas with a medium scale cartographic precision (Bocco and Valenzuela, 1993; Jürgens and Fander, 1993; Price, 1993). Since linear erosion is unnoticeable by current satellites it is necessary to infer erosion from indirect phenomena (King and Delpont, 1993). In the case of the loamy plateaux of northern France, such criteria correspond to structural degradation of soil surface called crusting. Surface degradation under rain effect induces a strong reduction of water infiltration capacity and the progressive disappearance of soil roughness limits water retention on soil surface. Runoff water is then concentrated in downstream Thalwegs and acquire a sufficient kinetic energy to form rills and gullies (De Ploey, 1989). In that context, our objective was to test a new method, in a test site 'Hesdin' (4500 ha), to map a soil erosion index suitable to the agricultural land of the loamy plateaux of northern France. This general objective is split up into two particular objectives: (i) determine if a multi-temporal set of SPOT images can map changes of surface roughness which affect proportion of area vulnerable to run off, (ii) verify if the crusted areas may be considered as a relevant spatial indicator of soil erosion risk.

2. Materials and methods

The study area forms part of a limestone sedimentary basin that is covered by up to 5 or 6 m of loamy loess. The landscape consists of successive sub-horizontal to slightly undulating plateaux that have a slight to moderate dip and are incised by narrow valleys. Agricultural production is dominated by large-scale crops such as wheat, potatoes, flax and peas. Soils mostly consist of luvisol (FAO terminology), i.e. loamy soil with a low organic content, strongly vulnerable to structure degradation under rain drop impact. Most of the rain falls between September and March (750–1100 mm/yr). Individual events are generally of low intensity. Our method is summarized in Fig. 2. Bare soils with different surface states were extracted from satellite images, and incisions were mapped from field works. The digital elevation model (DEM) gave the elementary watersheds (EW) that control maximum potential runoff. The two data sets were integrated at the EW level and compared.

2.1. Data acquisition

Three SPOT images were acquired for 22 January, 4 March and 14 May 1992 thanks to a SPOT programming campaign. Simultaneously to each period of image acquisition

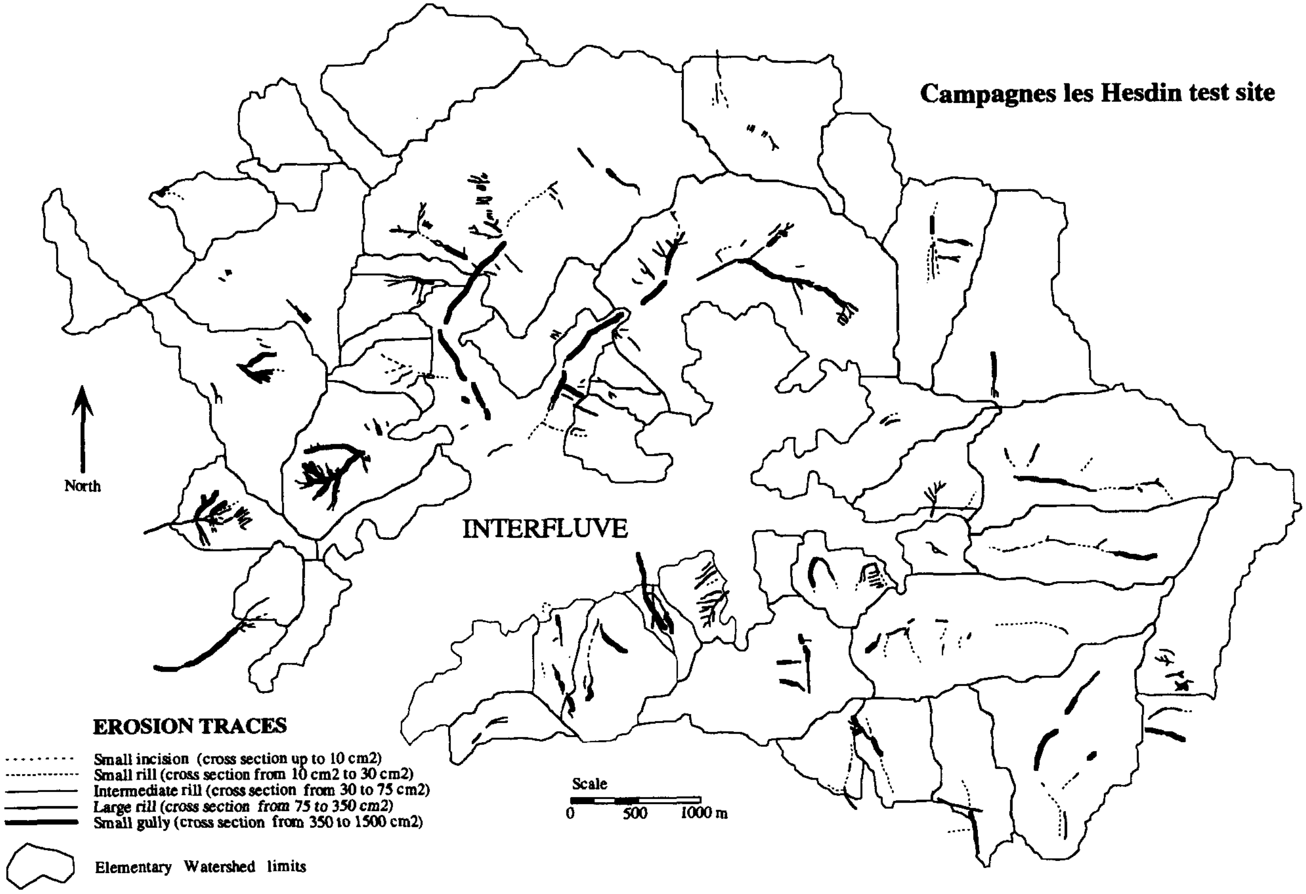

Fig. 1. Map of the elementary watersheds and of the erosion traces observed during the winter of 1992.

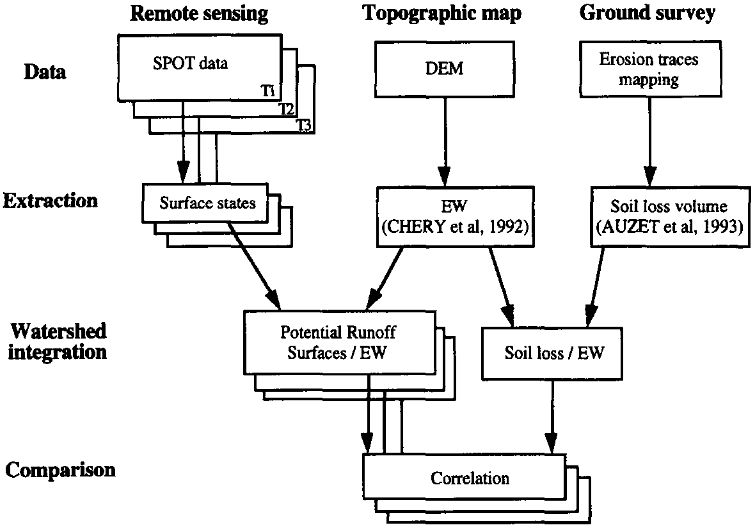

Fig. 2. Methodology.

70 plots, taken to be bare soil i.e. less than 30% of vegetation cover, were investigated to provide field references for the automatic interpretation of satellite data. A surface degradation index was noted, which describes different levels of surface degradation, from raw, recently ploughed soil to sedimentary crust (Table 1). This classification is based on field description of the soil surface aspect (adapted from Boiffin, 1984). All erosion forms observed on the site were mapped in late March 1992, just before spring works, which would have wiped most of the erosion traces. As most traces of erosion disappear from year to year because of tillage, it can be considered that the map effectively shows the erosion features formed during the winter of 91–92 (Fig. 1). Sheet erosion is negligible in comparison with linear erosion (Le Bissonnais, personal communication). The volume of soil loss have been worked out according to the method described by Auzet et al. (1993). The EWs were determined automatically from a DEM generated from interpolation of contours of a topographic map (1:25 000) (Chery et al., 1992). A digital geographic database describes the site, including information on field limits, morphology, geology, pedology and annual land-use (scale: 1:10 000).

Table 1
Classification system of the soil surface states

Code	Surface state description
F0	raw fragmentary state, recent ploughing
F0–F1	intermediary stage, old ploughing
F1	structural crust
F1–F2	intermediary stage
F2	sedimentary crust

Adapted from Boiffin (1984).

2.2. Image classification

Each reference plot was digitised on the false-colour composites to automatically extract the radiometric values for the three original SPOT bands (green, red and near infrared) and two composite channels: normalized vegetation index (NDVI) i.e. measure of green vegetation density, and brightness index (BI) i.e. measure of global luminance intensity. Radiometric data and degradation indices were combined to examine the usefulness of spectral information to discriminate soil degradation states.

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{red}}{\mathrm{NIR} + \mathrm{red}} \qquad \mathrm{BI} = \sqrt{\frac{\mathrm{red}^2 + \mathrm{NIR}^2}{2}}.$$

The method of maximum similarity was used for classifying bare soils. The algorithm uses the reference plot set to statistically describe the spectral characteristics of each soil degradation class (average vector, covariance matrix) and then classify each pixel according to the highest probability rule. Before classification, the 'bare' soil population in each image was isolated. The following objects were masked: (i) vegetation areas where the radiometric signal is not significantly influenced by the underlying soil i.e. soil degradation levels can not be discerned. The vegetation mask was derived from the analysis of the NDVI, (ii) limestone outcrops, which are not sensible to structural degradation, but may be confused with sedimentary crusts. A multi-temporal analysis of the BI allowed a good discrimination between temporary high reflectance surface associated to the sedimentary crusts and the limestone outcrops characterized by a constant high reflectance over time (King et al., 1989), (iii) built-up areas delimited by visual analysis of a false-colour composite.

2.3. Integration by elementary watershed

The EW is a determining factor to describe the specificity and complexity of the erosion process of loamy soils of northern France. An EW is defined as a first-order hydrological catchment basin, corresponding to the water collection area of the last branch of a temporary drainage network (Boiffin et al., 1988). It represents the basic spatial and hydrological unit where the phenomena expresses itself in the nature, making the geographic link between surfaces contributing to runoff and effective erosion (incisions) which is observed locally downstream (King and Le Bissonnais, 1992). It is

Table 2
List of variables generated from the integration process

Var. name	Variable description	Indice of date
1	no degraded soils (%)	Jan. March May
2	transition degraded soils (%)	Jan. March —
3	degraded soils (%)	Jan. March —
2–3	2 + 3 (%)	Jan. March —
SL	estimated soil loss (m^3/ha)	entire winter

(%) surface percentage of EW.

then essential to integrate both data set at that scale to compare them. Such integration is made easier by digital processing techniques of georeferenced data from geographic information systems (GIS), as described by King et al. (1993). A new set of variable was then generated (Table 2). To these variables must be added the percentage of built-up area, as well as the number of fields and the average plot size for each EW.

2.4. Correlation analysis

Correlation analysis studied the relationships that might exist between the proportion of degraded soil and the intensity of erosion, as well as the effect that the period of image acquisition has on such relationships. Several EWs, which contain a characteristic that might strongly modify the erosion process encountered in this type of environment were discarded from the correlation analysis (e.g. high built-up area proportion, minimum plot and EW size). Nevertheless 80% of the initial surface has been preserved.

3. Results

3.1. Radiometric behaviour of soil surface state

The five surface state classes described in the field can be divided into three groups of distinct radiometric behaviour (Fig. 3). The three groups are grouped along the very classical 'soil axis' in the following manner: (1) Group 1: no degraded soil, F0; (2) Group 2: transition degraded soil, F0–F1, F1; (3) Group 3: degraded soil, F1–F2, F2. This result confirms the relationship between NIR reflectance recorded by SPOT and the degree of closure of the soil surface, which itself is related to roughness of the soil (King et al., 1989; Courault, 1989). The confusion between classes within the groups has clearly shown the existing limits to further radiometric discrimination of surface states. This limitation can be explained by the following points:

(i) other soil properties that may influence the soil radiometric response have not been taken into account such as humidity, texture or organic matter content;

(ii) the descriptive classification system used to differentiate the surface states introduces a certain degree of subjectivity;

Table 3
Classification matrix of confusion: January data

Classification/Field survey	Class 1	Class 2	Class 3	Prod. Acc.	Total
Class 1	896	287	0	75.7	1183
Class 2	139	680	100	74.0	919
Class 3	44	17	667	91.2	728
User's Acc.	83.0	69.1	87.0	—	100
Total	1079	984	767	100	2830

Producer's accuracy (PA); pixels well classified in a class/all pixels classified in that class.
User's accuracy (UA); pixels well classified in a class/all pixels surveyed in that class.
Overall accuracy: 79.2%.

(iii) the difficult integration of intra-plot variations of surface states in the field; 2–3 field observations are assimilated to an average reflectance value for a large group of pixels.

3.2. Classification of bare soil

The radiometric behaviour of bare soil is the basis for a multi-spectral classification over all the test site. This classification gave very good results for 1992 (Table 3), which were evaluated mainly according to 'producer's accuracy' (PA) and 'user's accuracy' (UA). The results were very similar for March: Class 1: 98.4% PA and 82.2% UA; Class 2: 79.9% PA and 88.4% UA; and Class 3: 88.5% PA and 97.2% UA. For May, however, practically all bare ground was at the same stage of spring sowing with very few encrusted parcels and, moreover, a very large part of the surface being studied was covered by vegetation. This made it impossible to map the various stages of degradation. This classification analysis shows how a multi-temporal cartographic evaluation can be made of soil surface degradation. This evaluation then serves as a support for the integration for each EW.

3.3. Correlation of surface conditions and soil loss

To find a significant correlation between observed facts and remotely sensed indications, we tested several hypotheses: (i) only degraded surfaces (variable 3) will influence runoff in each EW and (ii) both degraded and intermediate surfaces (variable 2-3) will contribute to runoff. The correlations between these different variables and soil loss (SL) are not only made separately at each observation date, but also by searching for a cumulative effect of the contributing March surfaces on those of January. The corresponding variable (Σ) integrates the surfaces of classes 2 and 3 of January, and the new surfaces that appeared in classes 2 or 3 between January and March. This variable is obtained by logical combination of the two classified images. A significant increase can be seen in surfaces contributing to runoff, with an average increase of 23% and a variation between 0 and 49%. A single significant relationship was identified between the percentage of surfaces contributing to runoff and soil loss (Table 4), which concerns surfaces that were degraded before January. It appears that surfaces which were observed to be degraded in March are not related to the volume of soil loss. Also, notwithstanding the increase between January and March in surfaces that could contribute to runoff, Σ–SL gave an inconclusive result with $R = 0.39$. This result seems to

Table 4
Correlation coefficient (R) between crusting areas and soil loss

Variable date	Class 2	Class 3	Class 2+3
January	1.29 [a]	0.4 [a]	0.48 [b]
March	0.29 [a]	−0.06 [a]	−0.39 [a]
Σ	—	—	0.39 [a]

[a] No significant. [b] $P < 0.05$.

confirm that the development of rills and gullies is dominated by surfaces that were degraded before January.

4. Discussion

In the light of the results obtained during our work, three questions require discussion and further work:

(1) How reliable are estimates of surfaces contributing to runoff (SCR) when using satellite images?

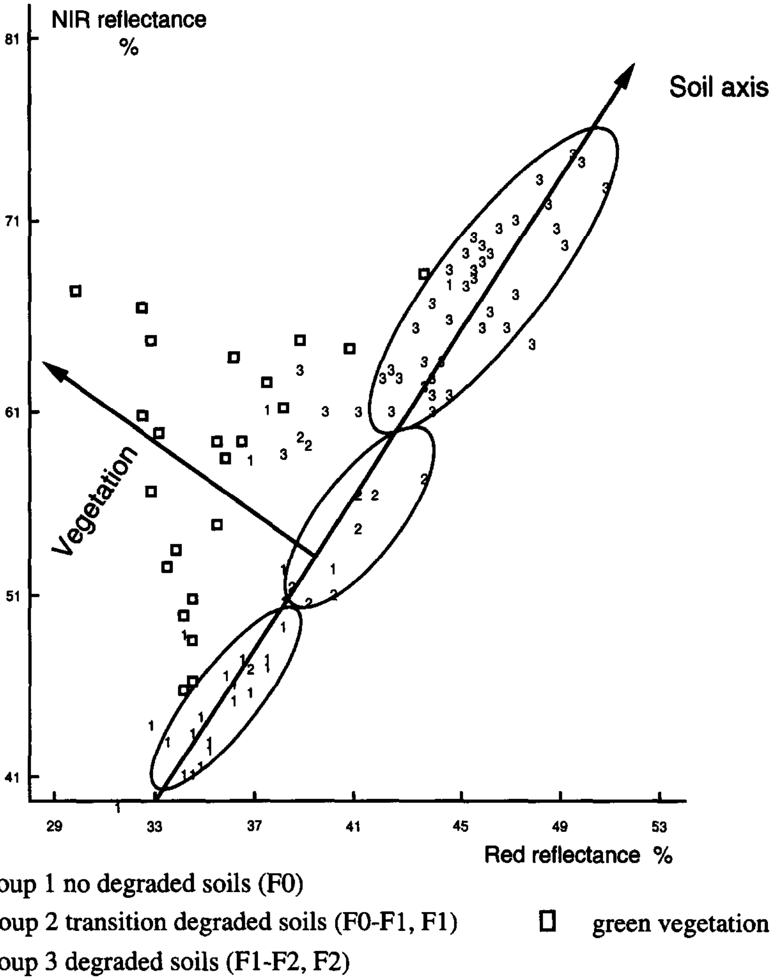

Fig. 3. Scattergram near infrared versus red reflectance: radiometric behavior of the different soil degradation stages (January data).

(2) Can such estimates be used as a predictive indicator of soil loss, when considering the erosion conditions of the winter of 1991–1992?

(3) What are the implications of the erosion process characteristic of northern France on the choice of pertinent satellite data?

The method for estimating SCRs using satellite images was based on the relationship between surface roughness and reflectance (Courault, 1989) and is quite suitable for loamy soil (Fig. 3; Table 3). This approach opens possibilities for acquiring the same type of parameters derived from satellite images for estimating surface states, which Auzet et al. (1993) related to erosion. Ongoing research is based on such relationships for developing a predictive approach to erosion (King and Le Bissonnais, 1992). Here, the question to be answered is whether or not the estimates of SCRs from remote sensing can be used as predictive indicators.

The results should be placed in the framework of conditions for establishing the relationship between SCRs and soil loss (Auzet et al., 1993). This relationship was established from data collected over 20 watersheds during three successive winters (60 data points), and gave a correlation coefficient (R) of 0.73. It was also shown (op. cit.) that year-to-year variability is quite large, as the results vary between 0.37 and 0.82 for each winter taken individually. It can be seen that the correlations improve with increasing average annual erosion intensity, as shown by an increase in soil loss. For instance, the year 1990/91 ($R = 0.82$) was characterized by a sediment production that varied from 0 to 12 m^3/ha, whereas the year 1989/90 ($R = 0.37$) had a variation of only 0 to 3 m^3/ha. In our case, soil loss varied between 0 and 1.8 m^3/ha; which was an even lower figure. It is thus clear that the conditions of minimal erosion during our study period are a handicap for the type of validation we recommend, and may explain most of the poor correlations we obtained. Our method should be reproduced under different climatic figures and should be extended to various test sites to obtain a better representativity of the regional erosive conditions. Moreover, our results are very similar to those obtained by King and Le Bissonnais (1992) on the same site, but using an entirely different method. They obtain estimates of SCRs by the spatial combination of two types of data that were systematically collected: texture of soil that has a propensity for crusting, and land-use during the winter considered. The correlation between these estimates and effective erosion is shown in Table 5. It shows that the estimate based on the analysis of satellite images seems to be more suitable for discerning the part of surfaces that contribute to runoff, and confirms the interest of our method.

Nevertheless, it is not reasonable today to use such method to evaluate soil erosion at a large scale. We think that it is possible to obtain a rough stratification of the landscape at a regional scale. This would permit to identify areas which need to be closely

Table 5
Comparison of the two models of spatial assessment of erosion risk

Methodology	King and Le Bissonnais (1992)			this work
Winter	89–90	90–91	91–92	91–92
R	0.37	0.45	0.30	0.48

monitored and where priority investments should be planned. Afterwards more detailed studies can be undertaken. Moreover an improvement of this method should be sought through the integration of synthetic hydrologic parameters which would take into account the water collection process within the EWs. Soil surface degradation is essential for runoff triggering. But prior to generate erosion runoff must be concentrated through a dense and continuous network of collectors including field boundaries, wheeltracks, headlands and Thalwegs (Boiffin et al., 1988). The concentration of water through the drainage network, natural or artificial increases the erosivity as a function of the flow rate (Morgan et al., 1990; De Roo, 1993). For example a high discontinuity in the flowing pattern may reduce the flow energy and then the soil loss. In further works it should be important to design and integrate a set of relevant indexes that would weight the SCRs according to the EW characteristics (form, drainage network density and characteristics) and the spatial organisation of the crusted plots within the EWs (contiguity analysis, average size of crusted plots). Another point deals with the geographic definition of the EW. An EW is not a functional unit isolated and independent. It exits logical relationships between the EWs. Runoff produced within an EW may induce soil loss in another located downstream.

Our multi-temporal approach aimed at extracting a cumulative evaluation of SCRs during winter and spring. The results showed that only the January image was really pertinent. In our study, the year 1991/92 was characterized by a strong concentration of autumn rains: of the average rainfall of 380mm between October and March, 78% fell in autumn with an additional peak of 54% for the month of November. This means that most rain fell before 22 January, the date of our first image and may explain the low relationship between the cumulative SCRs developed in january–march and soil loss. It seems that winter rains have contributed to increase the crusted areas but were not sufficient to induce an active runoff able to cause new incisions or to enlarge the existing one. Only the sown plots became encrusted after the first autumn rains and generated strong runoff. As rills were only observed in the plots that were sown first, it can be assumed that an image taken earlier would have led to a more exact definition of SCR. This underlines the difficulties of such a multi-temporal approach, when the optimum observation date(s) may vary according to the climatic conditions of a particular winter. To compensate for this difficulty, it is essential to have the capacity to modify the observation date(s) during the winter according to a program of image acquisition. This program should consider in semi-real time the evolution of rains in comparison with a reference winter previously defined as well as the evolution of crusted surfaces observed in the field. In that way the SPOT programming capacity is a valuable tool to multiply image acquisition attempts and then increase the probability to obtain an image close to the period of interest. In addition that approach will open new possibilities to elaborate different maps of soil erosion risk function of the climatic conditions. Nevertheless in winter conditions another technical difficulty arises, i.e. that of cloud cover may render it impossible to obtain any image in the required wavelengths. We should thus look to radar techniques (Solberg, 1992) to develop a reliable technique of early detection of SCRs, a possibility that presently occupies the efforts of several research teams.

5. Conclusions

The first interest of our method is that it provides a reliable means of estimating surfaces affected by runoff on a given date, and that it can be used for the mapping of large areas. Another original point lies in the logistics of this study: it remains quantitative notwithstanding the use of data based on real conditions, not only as far as the size of the site is concerned, but also regarding the time needed for data acquisition and processing. The limitations of our work lay in the conditions of less-than-average erosion during the particular winter of observations. This made it impossible to extrapolate the estimates made for elementary watersheds into predictive indicators of erosion. However, the principle of correlating between effective erosion and data from satellite images remains inescapable for devising methods that should predict erosion on a regional scale.

Acknowledgements

This paper, BRGM scientific contribution 93029, is the result of a research project funded by the French National Program for Spatial Remote Sensing (PNTS), the BRGM and INRA. The authors thank Silsoe College (Cranfield Institute of Technology, U.K.) and Professor J.C. Taylor, Head of the Remote Sensing Department, for their contribution to this study. The paper was translated from French by H.M. Kluyver.

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