SCALES: An Original Model to Diagnose Soil Erosion Hazard and Assess the Impact of Climate Change on Its Evolution

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1. Introduction

In that they regulate the water supply, determine air quality, are an essential component of the biodiversity of environments, support biomass production, and are a factor in maintaining and developing populations, soils perform environmental, productive and societal functions which take part in maintaining the fragile balance of territories (EEA, 2008). Therefore, soils constitute a natural heritage which has to be sustainably managed at a local as well as global level. There is now an international consensus on this statement, as human-caused soil degradation has accelerated and taken on more diversified manifestations across the world over the past fifty years.

In Europe, water erosion of soils is seen as one of the main forms of degradation of arable land. The surface of European soil affected by erosion is estimated to be around 12%. From continental to local levels, territorial agencies need to avail of geo-referenced information to Fig.ht against or prevent soil erosion. The aim in particular is to map the areas most affected or likely to be affected, in order to formulate restorative or preventative measures (*Gobin* et al., 2004). Besides, in the current context dominated by a global warming which will in the mid and long term disrupt the natural components of habitats, it seems necessary to provide the representatives of civil society with new elements which facilitate rationalized anticipation of future evolutions and of consequences in terms of land management.

To that end, erosion risk maps are essential documents. They are the result in particular of the production of semi-quantitative erosion models such as PSIAC (PSIAC, 1968; Hadley et al., 1985), FSM (Verstraeten et al., 2003; de Vente et al., 2005), EHU (Stocking and Elwell, 1973), CORINE (EEA, 1992) or even INRA (Le Bissonnais and Daroussin, 2001) and PESERA (Kirkby et al., 2003).

Whereas all the semi-quantitative models can be characterized by their simplicity and their high application potential to global spatial and temporal scales, their degree of accuracy does not allow the mapping of erosion problems at local level. To overcome this difficulty, we have developed the SCALES model (Le Gouée et al., 2010). SCALES is a model which offers similarities with semi-quantitative models as regards structure of model, holistic positioning, and strong reproducibility potential, but also with physical and empirical models because of the great accuracy of the data used and of their spatial representation.

After having shown the operational capability of SCALES at the scale of the Calvados department (Le Gouée et al., 2008) which represents 5,500 km² (Fig. 1), we then focused our efforts on adapting this model to produce a diagnosis of the erosion hazard at seasonal and monthly scales (Stepkow, 2008). That approach enabled us most recently to offer a prospective insight into the effects of climate change in the distant future (scenario A1B of the IPCC for 2100) on the evolution of soil erosion hazard in Normandy (Goulet, 2010).

Fig. 1. The regional council of Basse-Normandie. A: Catchment of the Branche. B: Catchment of the Lingèvres.

2. The SCALES model

2.1 Background

SCALES provides a mapping of soil erosion hazard which offer local land managers spatialized data at regional scale while having high accuracy on the local scale. As a result, hazard assessment is carried out on erosion source areas identified by elementary spatial units such as agricultural parcels.

In many European regions, agricultural land is structured visually and physically by the juxtaposition of these parcels. Each of these units is an erosion system whose activation depends less on near environment than on the distinct features of each parcel. By mapping the hazard at the scale parcel, the aim is to provide land management organizations with data so as to rationalize the Fig.ht against erosion hazard not at catchment area scale, but directly at source area level.

Taking into account anthropic activity in assessing hazard means resorting to the concept of agricultural practices as opposed to that of land cover, unlike all others erosion models at regional scale. The idea here is to re-contextualize hazard by looking at agricultural practices strongly structured along annual cycles (duration and management of intercrop) and multiannual cycles (crop rotation).

Initial, intermediate and final data from the model needs to be implemented as numeric geo-referred informations, usable with GIS and presented at different spatial resolutions showing the main agricultural, administrative and hydrological divisions of the area.

Since diagnostic of erosion hazard is based on data susceptible to change on a short or medium time, the model needs to be designed in order to easily generate data and hazard level updates. This perspective will then offer the possibility to develop an exploratory approach aiming to measure the positive or negative effects of a climatic tendency or a planned change in agricultural practices.

The SCALES approach can be reproduced where such agricultural practices as descrubed above occur and where the climate is a mild maritime one. In Europe, the application of the model can be carried out all along the Oceanic façade from the N-W of Spain until the South of England.

2.2 The SCALES model characteristics

SCALES is displayed as a regional scale applicable model keeping high precision and high quality of information at local scale. This tool allows us to produce in a short time a diagnostic of erosion hazard using high resolution data coming from accurate data. This diagnostic is specific to arable lands. It cannot be proposed in context of "natural" vegetation such as woods or forests or for urbanized areas. SCALES is also designed to be accessible to a wide range of companies dealing with questions of environmental relevance. Furthermore, this model also displays the possibility to aggregate hazard data with administrative or hydrological units like municipality and elementary catchment, in order to adapt the diagnostic to intervention scales of local land managers.

2.2.1 Basic statements

SCALES is a tree form model based on the use of GIS in order to map the potential sensibility of areas and soil erosion hazard. Potential sensibility of areas represents the first fundamental concept of the model. This concept aims to precise if the studied area is able to generate erosive runoff when we integrate both erodibility of soils, land-use and topography. The computational model is therefore a global indicator.
Erosion hazard defines the probability of appearance of soil erosion by water when potential sensibility and rainfall erosivity are put together. The rainfall erosivity depends on meteoric conditions. The latter will be higher during wet years and lower during dry years. We thus estimate a mean of rainfall erosivity based on rainfall data originating from pluri-annual period. Therefore, the erosion hazard has to be considered as a mean hazard.
The factors of evaluation of soil erosion hazard (soil erosion, agricultural practices, topography and rainfall erosivity) are displayed by the input data which can be of quantitative or qualitative relevance. Each factor is defined by one or several types of input data. All data types are converted in measurable data which in turn will express levels of pressure on the erosive runoff trigger. Some input data are combined in order to obtain combined data which generate also level pressure. Levels of pressure from combined data will lead to the estimation of level of hazard.

2.2.2 Parameters and input data

The choice of input data (Fig. 2) in the view of characterizing factors of evaluation of erosion hazard result from well-established scientific concepts in the literature, expert opinions and by conclusions originating from numerous personal observations for two years in the Department of Calvados (Le Gouée et al., 2008).
In order to estimate the soil erodibility, we selected and considered the structual instability as input data. This characteristic corresponds to the soils sensibility to degradation of its superficial structure by rainfalls. The degradation by water can be explained by the different physical and physico-chemical mechanisms among which we can cite: bursting, mechanical disaggregation, disaggregation by differential blow, and the chemical spread. Mechanical disaggregation due to the impact of rain drops constitute, in the temperate regions influenced by the ocean, the main mechanism acting on the soil crusting.

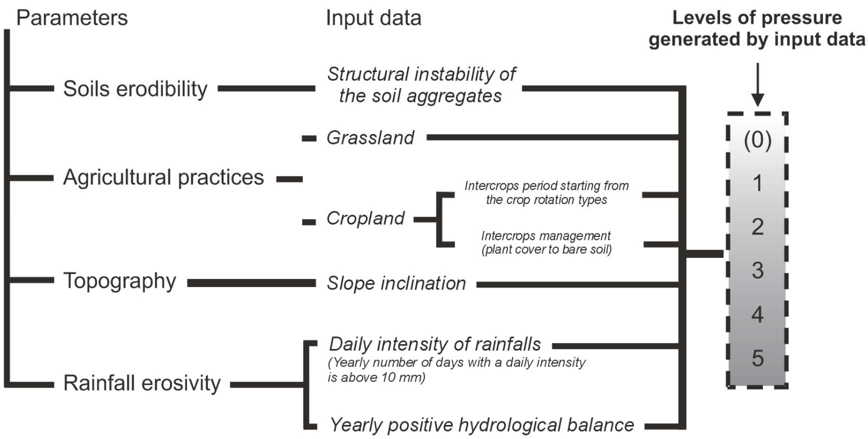

Fig. 2. Types of parameters and input data and levels of pressure concerning soil erosion

Soil erodibility

However, one must be aware that the sensibility of the soil to erosion is not always correlated with the soil crusting notion and a fortiori to the soil characteristics which lead to this phenomenon. In case of heavy rainfalls combined with water-saturated soils we will observe the establishment of a runoff on soils with stable structure able to transport heavy aggregates or stony load. This case will be integrated to the model when we will show input data relative to rainfall erosivity factors.

Agricultural practices

In temperate regions, soil erosion is linked to agricultural land. We can observe this erosion when soils are not protected by a permanent or well-developed plant cover. At this stage, a first distinction must be established between areas entirely and durably covered by agricultural vegetation i.e., permanent grassland and orchard, and the ones dedicated to crops. In the first case, water erosion remains absente or very anecdotic. In the second case, the risk to soil erosion is closely linked to the agricultural practices and their temporality.

The choice between crops or grassland and the technical management of cultivated parcels is integrated within the framework of logics of management of the farms fixed over several years. The assessment of the pressure generated by the agriculture on erosion hazard fulfills these logics. This is the reason why we prefer talking about agricultural practices more than land cover: the first term refers to the impact of agriculture at a multiannual scale when the second refers to plant covers (grassland, cereal crops, fodder crops) at a given moment. As we explained about rainfall erosivity, the role of agricultural practices on erosion is finally estimated by a mean pressure level characterizing the global erosive impact of technical practices during agricultural cycles. Therefore, the soil erosion hazard is an indicator of the soil degradation at multiannual scale.

The impact of agricultural practices in the modeling is established out of 3 types of input data. The first type of input data is related with the presence or absence of plant cover. A distinction is made between the areas characterized by permanent plant cover (grassland or orchards) and cultivated areas.

For the latter, another type of data aims to precise the profile of crop rotation. It allows us to gather information about the duration of the crop rotations and of the duration of the intercrop periods. This intercrop period data is essential for the application of SCALES because it specifies the amount of time during which the soil is directly subjected to the erosive action by the rainfalls. When the intercrop period is persisting, the risk of soil erosion increases. The mean duration of intercrop period has been chosen to estimate erosive pressure levels due to agricultural practices.
For cultivated lands, a third type of input data is used. It is related to intercrop management. This management is indeed leading to very different soil erosion responses whether keeping a bare soil or establishing temporary plant cover such as temporary crops or ray-grass. The duration and terms of intercrop management are linked to the types of crop rotations. The diversity of observed situations during the rotation cycle is integrated in the form of erosive pressure levels calculated for "intercrop period" and "intercrop management" input data.

Topography

The role of topography in the assessment of erosion hazard is expressed through the selection of only one type of input data which is slope inclination. Possibilities of runoff of the non-infiltrated water are depending on the slope at every point of space. These possibilities increase rapidly as soon as the slopes are strong.

Rainfall erosivity

Rain is the main factor of soil erosion by water. Its capacity to damage the soils depends on rainfall intensity, on volume of precipitations and on the hydrological response of the soil to rainfalls. This led us to propose two types of input data.
The first type defines the rainfalls ability to erode the soil based on its intensity. Among the indicators usually employed, we chose to considerate the yearly number of days with a Daily Intensity is above 10 mm (Fig. 2). Data comes from records of local meteorological stations of Météo France network.
The second type of data results from the response of the soils to the rainfalls. It refers to the concept of yearly positive hydrological balance and is given by applying the methods of hydrous budget. The positive hydrological balance is regarded as available water either for drainage or runoff. Data are resulting from the combination of potential evapotranspiration, rainfalls and available water content. If it is difficult to estimate the part of drainage and runoff, we can recognize that the risk of runoff increases with an increase of positive hydrological balance. These data are calculated at monthly scale and then cumulated to obtain results at yearly scale. The data used are means of climatic period. The main problem encountered to get this type of data comes from the methods implemented to gather accurate and reliable data about available water content. This problem is solved since it has been decided to start a wide program of soil mapping over the Calvados.

2.2.3 Steps of the modeling

The first step aims to convert all input data into erosive pressure levels (Fig. 3). 6 levels of pressure had been specified, from 0 to 5. Level 0 indicates absence of pressure and level 5 refers to a very high pressure level.
Some types of input data have only 5 levels. In this case, there is no level 0. This applies to "intercrop period", "daily intensity of rainfalls", "intercrop management" and, "yearly

positive hydrological balance" types. Regardless of their characteristics, these four types of data generate favorable conditions for triggering soil erosion. Therefore, even with very short intercrop periods, soils will always be exposed to the erosive effect of the rain. Also, in spite of protecting practices during intercrop period such as implantation of plant cover, the time required by the plants to grow gives a period during which the bare soil stays unprotected from erosion agents. Concerning rainfall erosivity, the weather conditions of a mild maritime climate rule out the absence of rainy events during the intercrop period, that is to say between September and April.

Level 0 has been affected to "grassland" and "slopes" input data. The presence of a permanent plant cover such as grassland always protects soil from erosion, even if it is common to observe some runoff on permanent grassland. Parcels dedicated to orchard culture are also included in this category. For slopes, the level 0 refers to topography with surface gradient lower than 1%. In that case, the slope does not cause the surface water to flow, preventing all possibilities of soil erosion by water.

The second step consists of combining the pressure levels of input data following an additive approach (Fig. 3). Between two types of input data, every combination is conceivable. Summations are included in an interval from 0 to 10. These values are subsequently classed in the following categories: ≤ 2, 3-4, 5-6, 7-8 and 9-10. Each category is then reclassified into simple value equivalent to a combined level of erosive pressure. Combined levels can later be combined again with other input data or other combined levels. In any case, the combination and simplification process remains the same.

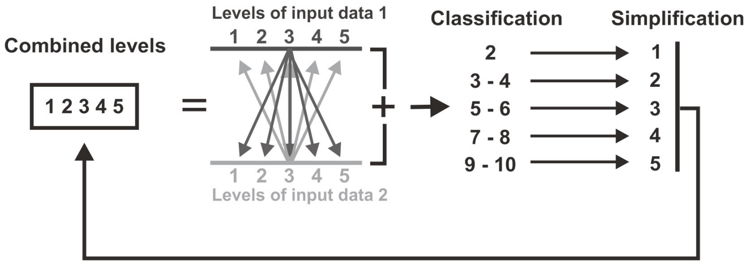

Fig. 3. Levels of erosive pressure and combination procedure in the SCALES model

The third step leads to the estimation of hazard levels. It implies to know the structure of the model (Fig. 4). SCALES is a tree form model, which means that input data are organized in a hierarchy according to their influence on the genesis of erosive runoff. Arguments in favor of this organization are the same as those previously exposed about the choice of input data. Therefore we can notice that the "intercrop period" type for example has a lower impact on triggering erosive runoff than the "slope" type, which has itself a lower impact than "structural instability".

Even if this organization differs from a weighting using coefficients, the classification of input data associated with additive approach make good case for this idea. The weighting occurs at every combination until the final hazard level. The weight of input data is always divided by two during the first combination, and then divided by two again with the next combination. According to this way of operating, we notice that the impact of pressure level of input data on final hazard is decreasing significantly when input data are lowered in the proposed hierarchy.

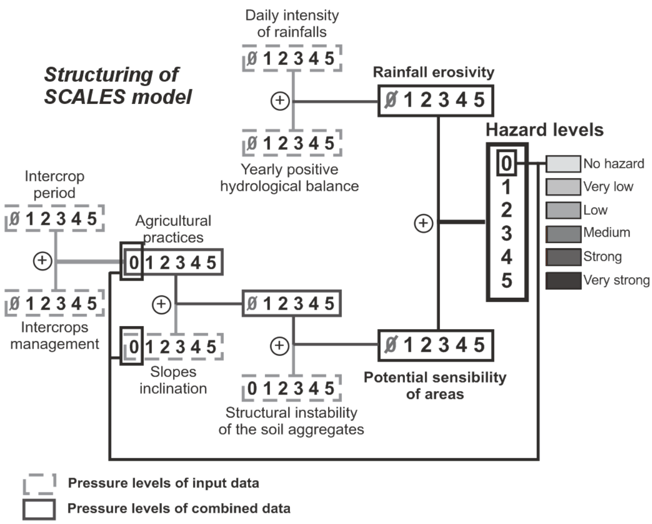

Fig. 4. Defining hazard levels using SCALES model

The SCALES model incorporates specific cases that don't follow the general rule. The level 0 of combined data, referring to agricultural practices for permanent grassland and orchards and the level 0 of "slope" type when gradient is lower than 1 %, are automatically excluded from the treatments. These levels are directly converted into level 0 of erosion hazard. This conversion does not require the agricultural areas to fulfill these two conditions.

2.2.4 Integration and aggregation of SCALES data

SCALES is a large-scale assessment model intended for mapping soil erosion hazard at the finest level of organization of the agricultural area. It supposes an integration of input data at parcel unit scale. Their area can exceed a few hectares but are generally lower than this unit of reference. This scale seems to be the better scale to determine the spatial context of soil erosion in Basse-Normandie. The layer of parcel units exists in the form of a vectorized and geo-referred database and such data came from the Inventory of Common Agricultural Politics given by the agricultural administration. Data inform on the land cover types in 2006 (source: Rpg_anonyme_014_AUP_2006). The parcels are classified in the three following: Grassland and arboriculture parcels (26,500 parcels, 111,000 ha) Temporary grassland parcels (13,200 parcels, 99,600 ha) and Crop parcels (25,800 parcels, 154,400 ha).

The integration of data in the parcel units requires beforehand a mapping of input data under raster format. We used the principle of allocating for each parcel unit and for each input data type, only one mode. When parcel unit holds several modes, we chose using a decision rule, to select the spatially most dominant mode. The application of the dominance rule has been carried out using the module *Spatial Analyst* in ESRI ® ArcView Gis 9.2. Obtained maps concerning the rainfall erosivity, the potential sensibility of areas and the soil erosion hazard are vector maps. Those are transformed to raster format for incorporating the output data in larger vector units as administrative units (approximately 800 ha) or as hydrologic units (approximately 2,000 ha).

2.3 Data processing
2.3.1 Topography

To calculate slopes inclination, we used Digital elevation Model of Calvados with a grid resolution of 20 X 20 m. The high resolution of DEM is essential because it allows us to carry out a topographical analysis of a very high degree of accuracy. Claessens et al. (2005) shows that DEM resolutions influence the slope inclination distribution: the coarser resolutions underline a larger contribution of lower slope angles (smoothing the effect on the landscape topographical representation). This report is in particular validated while comparing 50 m and 25 m DEMs. For Calvados, slope values result from the local cell-to-cell slope, rather than using a smoothing multiple cell windows, as done in major GIS procedures. Slopes were classified into six classes. Their limits were defined starting from values determined by statistics treatments of the cell slopes (classification according to the geometric progression method) and values coming from the literature (Le Bissonnais et al., 2002). In contrast to the latter, the slopes larger than 15% have been regrouped in one class because of the absence of major dissected relief.
The classes selected are as follows: [0-1%[; [1-2%[; [2-5%[; [5-10%[; [10-15%[; >=15%.
Those are respectively corresponding to the levels of pressure 0, 1, 2, 3, 4, 5.

2.3.2 Climate

Rainfalls are regarded as the average factor of water erosion. It is allowed that the amount and the intensity of rains characterize the rainfall erosivity. Climate data comes from records of local meteorological stations of Météo France network. Insofar as the number of stations decreases with the lengthening of rains recording period, we decided to limit the reference period to 15 years (1991-2004) to be able to profit from a solid network of meteorological stations. This is composed of 22 stations located inside the Calvados and 19 stations located in periphery of this one. The main climatic data used are daily rainfalls.
Variables selected to appreciate the erosivity are (1) the yearly number of days with a Daily Intensity is above 10 mm (DI10) according to De Bruyn et al. (2001) and (2) the Yearly Positive Hydrological Balance (YPHB). This last variable at the same time allows us to take into account the amount of rains and the available water content (AWC) of soils. Let us recall that one of the major causes of erosion in Basse-Normandie is due to the saturation of soil. Also, we have to calculate beforehand the AWCs starting from the soil database presented further. Concerning the first variable, data of stations were interpolated by kriging method. In order to avoid interpolation errors related to the edge effect, we integrated data of the stations located just at outside of Calvados.
Classes are the following.
For DI10: < 20; [20-25[; [25-32[; [32-40[; >=40
For YPHB: <150 mm; [150-250 mm[; [250-350 mm[; [350-450 mm[; >=450 mm
Those are respectively comparable with the levels of pressure 1, 2, 3, 4, 5.

2.3.3 Agricultural practices

In order to define the agricultural practices (Fig. 5), we had recourse to the data of the Agricultural census for 2000 realized at holding scale (source: Agricultural administration). 21 variables have been retained to evaluate the agricultural specialties of the 4844 holdings of the Calvados. They relate to socio-demographic characteristics of agricultural households, to juridical statute and economic dimension of the farms and to production systems (Dobremez and Bousset, 1996).

Adapted statistical treatments allowed us to draw up a typology of dairy farm (9 types) and non-dairy farm (13 types). A statistic aggregation (by summation) has been realized in order to assign them to the small administrative units (municipality scale). That led to the characterization of repartition profiles of different farm types for each municipality of Calvados which counts 706 of them. The following stage consisted in operating an Ascending Hierarchical Cluster followed by K-means method in order to reach a typology of farms (12 types) according to type repartition profiles (Bermond, 2004). Each type refers to modes of farm management, and to specific agricultural practices. A local farmer practice survey has been carried out in this direction, which enable us to produce our own data.

After selecting a sample of municipalities for each farm type, we interviewed the farmers about soil work methods used, plot localization and farm characteristics. This investigation showed that types of farm had notably evolved between 2000 and 2007. Thus, interviews have been used to update the 12 types of farm and to specify the current agricultural practices. This procedure has been applied to the sampled administrative units and, by extrapolation, generalized with all municipalities. Knowledge of crop rotations and management of intercrops allowed us to determine various modes concerning these agricultural input data of the SCALES model.

For crop rotations, the types are: winter crops, dominance of winter crop, balance winter crops/ spring crops, dominance of spring crops, spring crops. The passage of the first to the last type represents insofar the lengthening of the period during which soil is not protected. The duration of this period is in this way lower than 4 months for rotations based on winter crops and reaches a duration of 7 months in case of a succession of spring crops.

Those are respectively comparable with the levels of pressure 1, 2, 3, 4, 5.

Regarding the management of intercrops numerous publications underline the influence of different practices on soil erosion risks (Auzet, 1987; Martin, 1997; Martin 1999; Baumhardt and Jones, 2002; Le Bissonnais et al., 2002; Lipiec et al., 2006; Strudley et al., 2008). Therefore the creation of a temporal plant cover like oilseedrape or mustard, in the period between two crops, will effectively protect the soil against run-off erosion. This measure will be less effective in case the crop partially covers the soil like for example rye (concept of scarce plant cover). One also considers that the wheat stubble correspond to this concept. With the absence of a temporal crop, soil tillage will permit to temporally reduce the erosion risk because of a better infiltration and a higher soil roughness. More the tillage operations are deeper, more effective are infiltration and soil roughness against soil erosion. The most unfavorable condition occurs when there is no tillage during the intercrop period remaining the soil bare. These different practices between crops or their absence (plant cover, scarce plant cover, deep ploughing, superficial ploughing, bare soil) are respectively comparable with the levels of pressure 1, 2, 3, 4, 5. The level 0 corresponds at the grassland and arboriculture areas.

2.3.4 Soils

To achieve the aim of a fine diagnosis of soil erosion hazard, it was necessary to have a sufficiently precise soil database. It was not conceivable to exploit the Soil Geographical Database of France at scale 1 : 1 000 000. The regional BDSol-250 on a 1 : 250 000 scale (source INRA) does not exist. So we decided to create our own data.

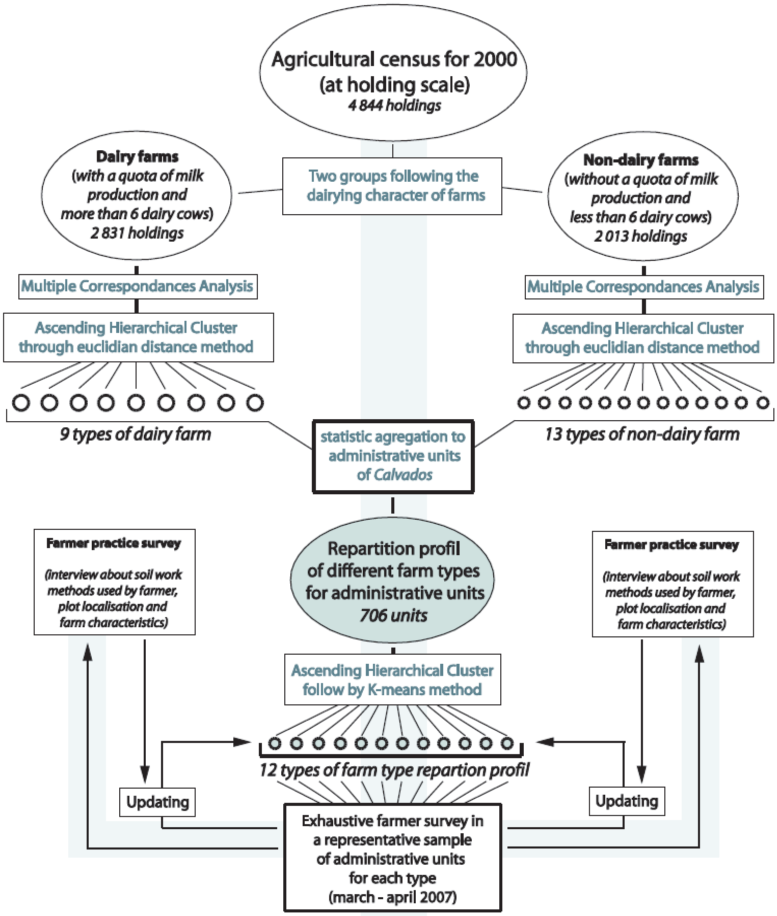

Fig. 5. Procedure for characterizing the agricultural practices in Calvados

During two years, we carried out nearly 8000 soil boreholes, which represent one borehole per 40 ha of agricultural land. Pedogenesis, soil thickness, coarse fragments, texture and hydromorphy have been registered. Data and Progressive knowledge of the soil landscape allowed us to produce a first soil map on which we selected 150 representative soil boreholes. Physical (granulometry, structural instability of surface horizon), hydrologic (AWC taking into account per cent of coarse fragments) and chemical properties have been determined. Structural instability has been evaluated starting from the INRA test of structural stability carried out on aggregates (Le Bissonnais and Le Souder, 1995).

Consequently, the soil features do not come from the application of the pedotransfer rules. This analytical step has been led us to finalize a global soil map on a 1 : 50 000 scale, to suggest at the same scale a map of soil structural instability, to propose another map in connection with spatial distribution of available water content of the soil, and, finally, combining the latter with interpolated rainfall data, to define the yearly positive hydrological balance. Classes of structural instability of the soil aggregates come from a small adaptation of MWD (medium weight diameter of aggregates) classes found by Le Bissonnais and Le Souder (1995). This adaptation is based on the formation of two classes instead of one, which was initially provided for aggregates with a size larger than 2mm. For MWD of aggregate: > 3.5 mm; [3.5-2 mm[; [2-1.3 mm[; [1.3-0.8 mm[0.8-0.4 mm[; =<0.4 mm. Those are respectively comparable with the structural instability levels 0, 1, 2, 3, 4, 5.

2.4 Results

Combination of potential sensitivity of areas to erosion and rainfall erosivity in a "normal" climatic context leads to evaluation and mapping of mean erosion hazard (Fig. 6a). This document highlights of the existence of all levels of hazard. Level 0 shows parcels promoted with permanent grassland or orchards and/or with a slope lower than 1%. These parcels represent 1600 km² of agricultural surface (42 %). They are localized by the form of coherent spatial units in the north-west and center-east of the territory.

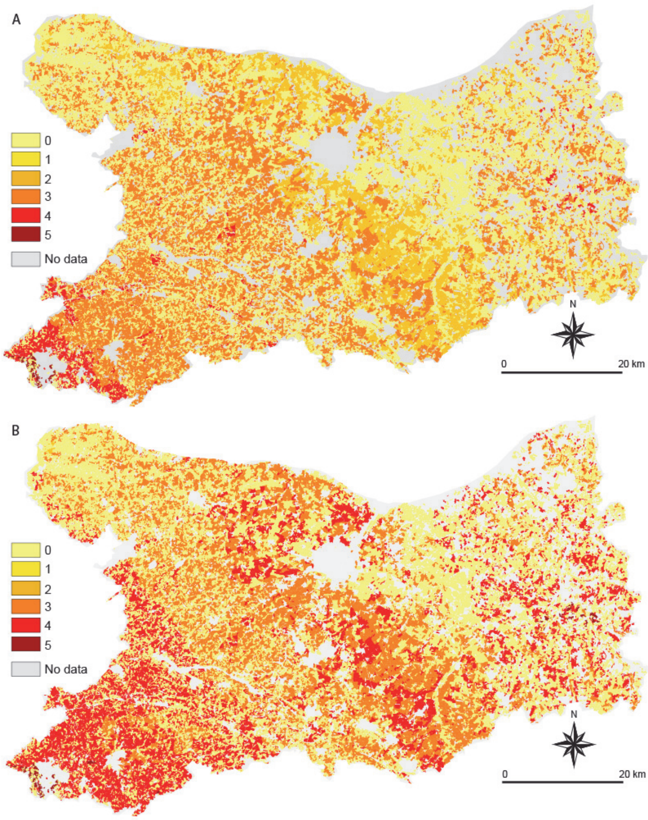

Fig. 6. Soil erosion hazard in Calvados at parcel scale (A) for a normal climatic contex, (B) for a rainy year

Levels 1 and 2 of soil erosion hazard cover more than 500 km² of agricultural surface (13 %). It is located in majority in the central part of the Calvados along a North/South axis. Level 3 is

the most represented since it covers 1400 km² (37%) of agricultural surface. It is located south-west of the department and locally in the East. The fourth level is the only one representing important hazard since the level 5 is absent. The affected parcels cover a surface of 100 km² (2,6%). They are essentially gathered at the extreme south-west of Calvados.
The assessment of the soil erosion hazard for a rainy year (2001, + 15% compared to the "normal" 1970-2000) has been achieved in order to study the potential impact of the rainfall conditions supporting high erosivity (Fig. 6b). Results are particularly interesting because they show that agricultural surfaces affected by a level 4 (strong hazard) extended more than 800 km² compared to a year with "normal" climatic conditions. The most affected areas are South-West, the central North/South axis and secondarly the eastern part of the territory. This brings us to considerate that Calvados is a department presenting a strong predisposition for the genesis of soil erosion by water, erosion which express itself as soon as climatic conditions induce strong erosivity.
Finer representation with zoom effect of levels of hazard at the scale of parcel unit reveals the occurrence of a mosaic of colors expressing very frequent spatial disjunction at local scale about erosion hazard (Fig. 7C). The rapid and brutal spatial variations of physic properties of the area associated with the interpenetration of grassland and crops parcels contribute to the strong heterogeneity of the results at local scale. The precision of input data of the model SCALES allows to obtain this type of conclusion. It also comes to the idea that the management of this issue assumes in priority an approach at the scale of a parcel or a group of parcels.
The aggregation of soil erosion hazard data at administrative and hydrologic scales (Fig. 7A-B) shows a significant loss of information when the basic scale is given up (Fig. 7C). SCALES model loses quickly its interest but can become a communication tool about the question of soil erosion.

3. Adaptation of the SCALES model at seasonal and monthly scales

The SCALES model leads to the production of soil erosion hazard levels on a very precise spatial scale and for region-size territories. However, the results enable at best to compare median annual situations in a normal climatic context and during years with rainfalls higher than the normal climatic context. Yet, these are tendencies that hide an intra-annual variability of the erosion hazard, which shall be necessary to evaluate in order to take into account the quick change of climate conditions and of the surface state of cultivated soils. The next step is hence about an adaptation of the initial model in order to be able to evaluate the erosion hazard on seasonal and monthly scales.

3.1 Data with intra-annual variability

The data of the initial model characterized by an intra-annual variability correspond to agricultural practices and to climatic and pedoclimatic parameters (rainfalls and yearly positive hydrological balance). The modalities of the yearly repartition of the daily high intensity rainfalls and precipitations' volumes will affect the variability of the rain erosivity during months and seasons. As well, the agricultural practices associated to climatic conditions will affect the rate of plant covering and its evolution. Yet, the plant covering of a bare soil strongly intervenes on the probability of soil erosion by water. The adaptation of the SCALES model needs to get the monthly and seasonal data about 1° rates of plant covering and their evolution for cultivated parcels and 2° rain erosivity conditions.

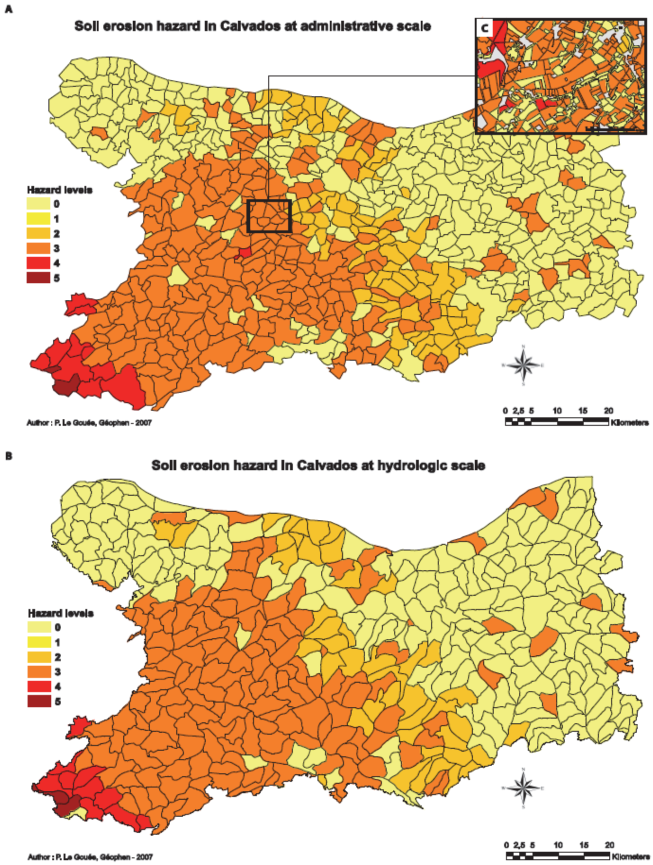

Fig. 7. Aggregation of the soil erosion hazard data: (A) at the administrative scale (municipality); (B) at the hydrologic scale; (C) significant deterioration of results from the parcel scale to the administrative scale due to aggregation procedure

3.1.1 Plant covering

The plant covering on cultivated areas can be estimated by the foliar surface of plants. In French regions with temperate climate, it is very difficult to get reliable data about monthly rates of plant covering and their intra-annual evolution. The data that we show (Fig. 8) have been sent by the Technical Institute for Plants specialized in the agronomic research (ARVALIS – Institut Technique du Végétal), a Calvados-based and nationally recognized organism. These data concern the principal plants cultivated annually or in intercrop periods, in Normandy.

Fig. 8 enables to show on a monthly scale three types of evolution for the plant covering by plants in crop areas. A first type gathers the plants characterized by a poor rate of plant covering at the end of the first month of growth and then by a very quick and totally covering rate at the end of the second month. This type concerns maize silage and ray grass. The following type refers to rapeseed and mustard. The rate of plant covering is very important at the end of the first month of growth and reaches 100% at the end of the second month. Finally, the third type is slightly different from the two others as it needs 4 months of growth to get a rate of plant covering of 50% and then 6 months for a complete rate. Cereals correspond to this type.

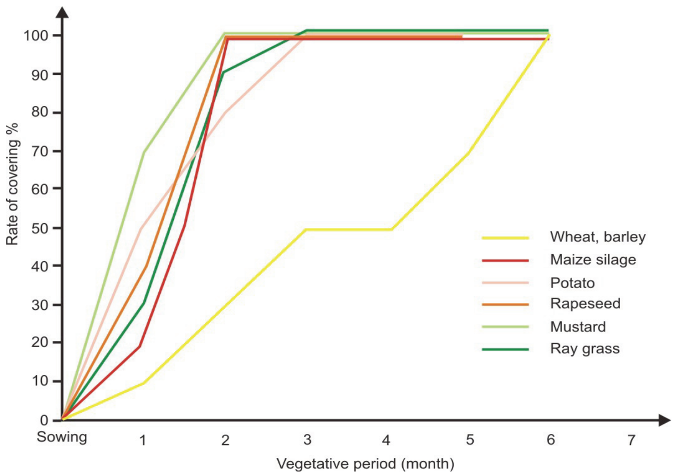

Fig. 8. rate of covering according to the vegetative period of various cultures (Arvalis)

A first adaptation of the SCALES model consisted then in replacing the initial data "intercrop period" and "intercrops management" by the data "rate of plant covering".
The monthly classes selected are as follows: >90%; [90-70%[; [70-50%[; [50-30%[; [30-10%[; <=10%. Those are respectively corresponding to the levels of pressure 0, 1, 2, 3, 4, 5.

3.1.2 Climate

The data of the initial model that characterized the rainfall erosivity have been conserved. Concerning the number of days when the rainfall intensity is above 10 mm, we made an average monthly counting for the 1991-2004 period starting from the network of meteorological stations presented previously. For the average monthly positive hydrological balance, we used the monthly data of hydrous budget reports used in the initial version of the SCALES model.
Monthly classes are the following.
For DI10: =1; =2;=3;=4; >=5
For YPHB: <30 mm; [30-60 mm[; [60-90 mm[; [90-120 mm[; >=120 mm
Those are respectively comparable with the levels of pressure 1, 2, 3, 4, 5.

3.1.3 From monthly data to seasonal data

In order to estimate the soil erosion hazard at seasonal scale, we calculated, for the initial data rate of plant covering, DI10 and YPHB, the average of values of the months that characterized each season. Thus, the value relative to the spring results from the average of values obtained for March, April and May. The values of June, July and August provide the summer value ; the ones from September, October and November give the autumnal value and the ones from December, January and February are the winter value. Thus, the monthly classes presented previously are reused to estimate the seasonal levels of pressure for the initial data that showed an intra-annual variability.

3.2 Application to the Branche catchment

The monthly and seasonal approach of the SCALES model has been tested in Basse-Normandie, on a catchment scale (Fig. 1A).

3.2.1 Study area

Localized in the French department of the Manche, the Branche catchment covers 1100 hectares and is a part of the Vire catchment, a larger hydrological area of 1270 km². The uphill of the test zone shows an undulating relief resulting of many small valleys. The slopes are between 1% and 5%. The downhill is marked by deeper steeply sided settings of the rivers. The slopes are more abrupt, between 5 and 15%. The study area is situated in the Armorican block, formed by Precambrian schist and sandstones. Umbric leptosols and cambisols cover the major parts of the slopes and gleysols can be found in the valleys bottoms. Their thickness varies from 40 cm to 120 cm. The local climate is characterized by abundant annual rainfalls, around 950 and 1000 mm.
The average size of the farms is 100 ha. The local agriculture shows a system of intensive pastures with a high proportion of ploughings dominated by spring crops. The grass surfaces represent 60% of the agricultural land. Crop and wheat respectively occupy 53% and 36% of the cultivated areas.

3.2.2 Acquisition of input data

To calculate slopes inclination, we used Digital elevation Model of Manche with a grid resolution of 50 X 50 m. The climate data start from the Torteval-Quesnay station, based 15 km East from our site. As for the general model, we collected the daily data for the 1991-2004 period. These data were used for mapping the soil erosion hazard on monthly, seasonal and annual scales within the framework of an average climatic year. The data related to the agricultural practices result from a survey carried out among farmers who exploited catchment lands between 2005 and 2008. Those were used to map the annual hazard. For the other temporal scales, the hazard was estimated from agricultural data from the 2007-august 2008 period. Finally, the soil data (structural stability, available water content) were obtained from soil boreholes according to a density of 1 hole for 10 ha about agricultural area and from laboratory analysis concerning the structural instability of the superficial horizons. The spatial units of integration of the SCALES data correspond to the agricultural parcels.

3.2.3 Results

The monthly maps obtained for the September 2007-august 2008 period primarily reveal a significant intra-annual variability of the soil erosion hazard (Fig. 9).
One note a first sequence, between September and October, characterized by quite a low hazard on the majority of the cultivated parcels (approximately 300 hectares). The surfaces with medium level represent 2% of the catchment area. During this period, the erosivity is low because of nonexistent or very low hydrological surplus and insofar as the plant covering is relatively important because of the presence of fast-growing temporary crop (mustard) and wheat stubble.

A second sequence goes from November to January, which is different because of the levels of soil erosion hazard increase, with maximum levels in December. During this month, the parcels associated to a high soil erosion hazard represent 7% of the agricultural surfaces. December combines bare soils after the maize silage with abundant hydrological surplus and more numerous daily rainfalls exceeding 10 mm.
The third sequence goes from February to Match. Its marks a fall of the hazard levels on all the cultivated parcels because of an increase of the rate of plant covering and an important decrease of hydrological surplus.
The fourth period corresponds to April and May. We can notice higher hazard levels than in the previous period. The razing of temporary crops comes with the soil baring of the parcels used for maize production. In addition, this culture has a slow plant covering during the beginning of its growth, which leads to a prolonged exposition to intense rainfalls for the soil. Nevertheless, in spite of a large increase of bare soils, the erosivity is low because the hydrological surplus are nil and the repetition of daily rainfalls that exceed 10 mm are very low.
The last period, from June to August, is characterized by the lowest hazard levels that don't change during those three months. This can be explained by a nonexistent or low erosivity and a complete plant covering for the cultivated parcels.
At seasonal scale, the temporal variability of levels of soil erosion hazard, observed at monthly scale, is significantly smoothed (Fig. 10). However, the evolution in time of the soil erosion hazard intensity remains sensible. Winter appears as the period in which hazard levels are the highest. Yet they don't exceed the average level. This level concerns 32% of the agricultural area in the test zone.

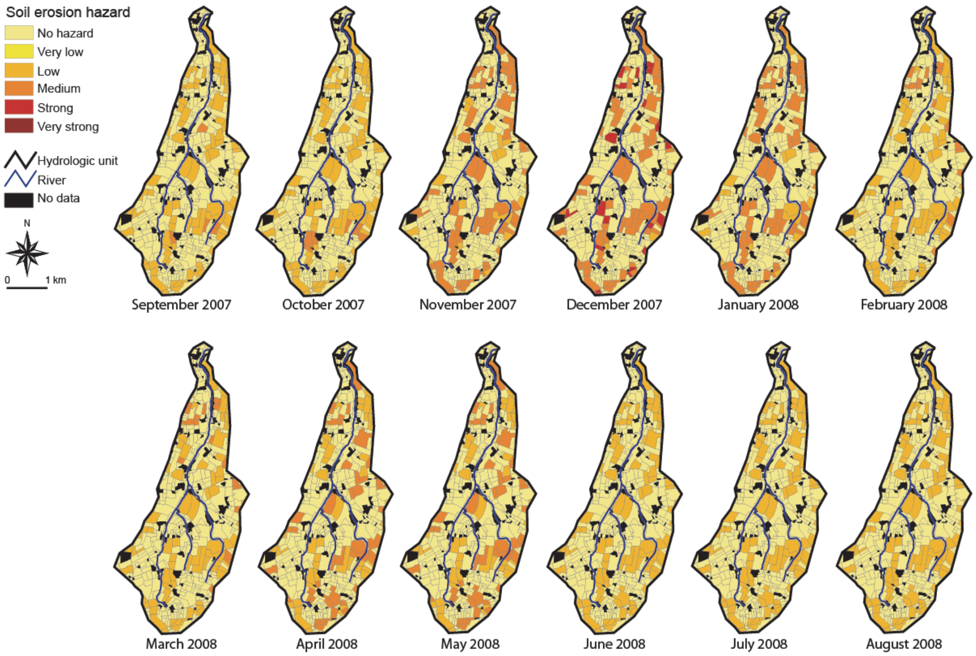

Fig. 9. Maps of soil erosion hazard at monthly scale.

Autumn comes at the second rank for the soil erosion's most favorable seasons, before spring. The low hazard level is observed in the main parts of the cultivated parcels. But the medium hazard is still highly represented as it concerns 12% of the agricultural surfaces. During summer, no cultivated parcel exceeds a low hazard level.

3.3 Discussions

The initial conception of SCALES enables us to consider an adaptation of the model to succeed in the mapping the soil erosion hazard at intra-annual time scales. The evolutionary character of the model proves that we can go from a static temporal vision of the soil erosion hazard within the framework of an annual approach to a dynamic point of view starting from monthly and seasonal representation of the hazard.

When we compare the monthly and seasonal data of the soil erosion hazard with the annual data (Fig. 11), we first notice that the initial version of the SCALES model doesn't enable to perceive the intra-annual variability of the hazard. In addition, the reading of the seasonal and annual hazards shows that the annual values are overestimated. Insofar as the input data of the initial model have changed, the results' comparison therefore appears to be delicate. However, we notice that the modularity of the SCALES model enables us to display the erosion hazard at different temporal scales and to get highly complementary results.

The adaptation of SCALES allows us to take into account the temporal as well as spatial variability of input data concerning climate and agricultural practices. Hence, for instance, the monthly erosive pressure of agricultural practices will move spatially from year to year according to the crop rotations decided by the farmer. Hazard levels will act in like manner. Thus, SCALES can be considered as a model which is spatially and temporally dynamic.

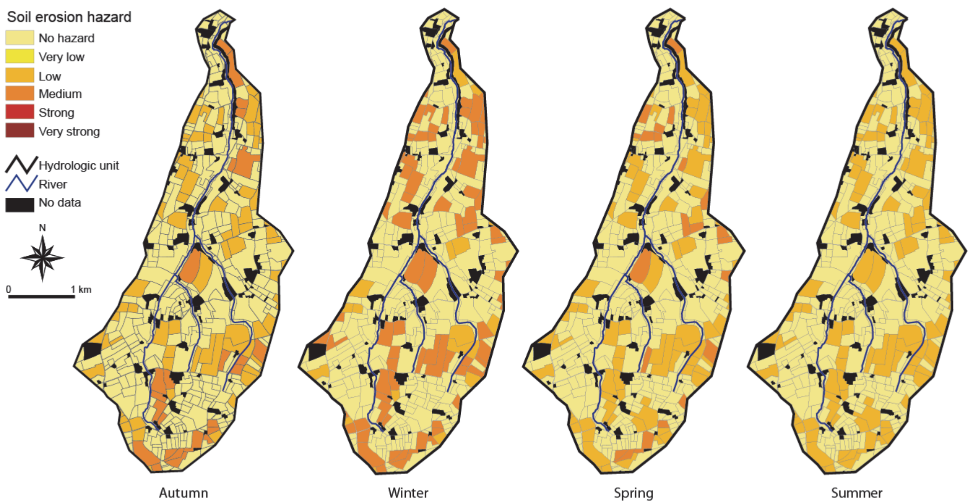

Fig. 10. Maps of soil erosion hazard at seasonal scale.

The monthly and seasonal approach of the soil erosion hazard needs to have local and precise information about agricultural practices. In addition, the characterization of the soil proprieties has to be based on field and laboratory data in a high spatial resolution. In these conditions, it is not possible to carry out a monthly mapping of the hazard erosion for territories that exceed several hundred or thousand of km². This work must be limited to areas recognized as sensitive through the initial model's representation of the hazard or by the intermediary of the land managers' knowledge.

4. SCALES, a model to consider the climate change impact on soil erosion by water

The structure and modularity of SCALES allows us to plan its use at long-term scale. This approach has been set as part of study of the impact of the climate change on the soil erosion hazard. We tried to compare at a monthly scale the present levels of hazard with those forecasted for the year 2100 based on a case study carried out in Normandy (Fig. 1B).

4.1 Study area

The study area is located in the north-west of Calvados. The catchment called the Lingèvre covers an area of 15 km². It is part of the Seulles, a larger catchment covering an area of 450 km² in the western part of the French department. The Lingèvres is located on a transition zone between the Armorican block upstream and the Paris basin downstream. At the periphery of the catchment, more particularly upstream, some thick patches of aeolian silt (loess) over clay and limestone formations from Secondary and Tertiary.

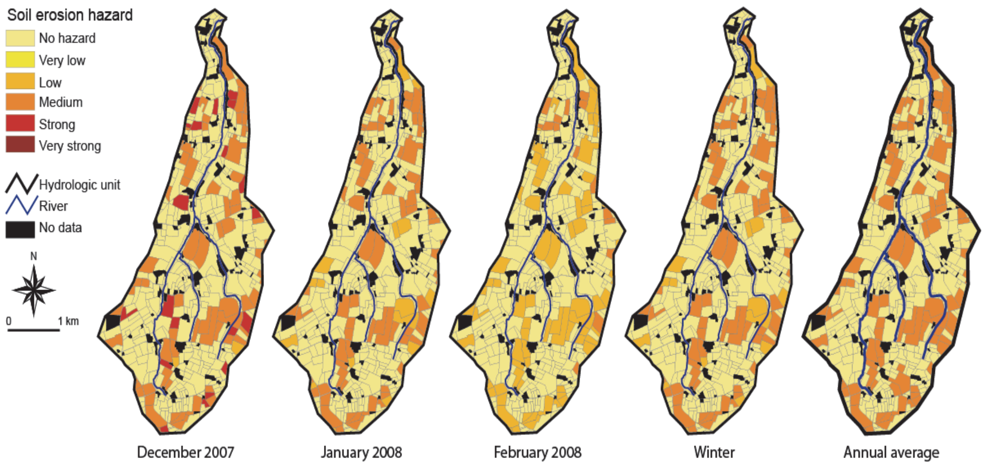

Fig. 11. Maps of soil erosion hazard at various temporal scales.

Slopes are generally gentle, especially on the higher parts reaching 130 meters high. The difference of height with the outlet is about 80 meters at the north of the basin. Slopes are increasing downstream of the Lingèvres.

Soils are predominantly hydromorphic. At the basin's periphery, on the higher slopes, we notice the presence of moderately to strongly redoxic silty luvic cambisols which thickness exceeds 1 meter. 70% of the Lingèvre's slopes are made of thin (40 cm) clayey redoxic soils. Umbric an rendzic leptosols less than 40 cm thick are sporadically localized. Gleysols are located in valley bottoms.

The climatic context is similar to the one described in the previous case study. Rainfall is quite constant all year long with an increase in autumn and winter. The annual accumulation of rain is around 950 mm.

Agriculture combines cereal crops, fodder crops, and bovine breeding gathered in huge farms intensively exploited. Grassland cover half of the agricultural land of the catchment. These are almost always permanent grassland. Crops are covering an area equivalent to the one of the grassland. Arable lands are fairly divided between spring crops (maize silage) and winter crops (wheat).

4.2 SCALES data for the current period and for 2100

4.2.1 Data for the current period

The digital elevation model of Calvados at 20 m scale was used to estimate the slopes of the Lingèvres. The local climatic data comes from the same weather station than the one mentioned in the case study of the Branche catchment. This weather station is located 5 km from the Lingèvres. The identification of the agricultural parcel network and agricultural practices was based on field work. The data collected covers the period from September 2009 to august 2010. The soil data used for calculation of available water content and hydrous budget were extracted from the database related to the 1/50000 map of Calvados soils described in the first part of this document. Additional survey with soil boreholes also allowed refining the spatial resolution of pedological characteristics of the Lingèvres. Therefore the structural instability of the catchment's soils was deducted from already existing administrative data and from 18 additional analysis on representative of the soils and agricultural practices diversity. Input data of the model and their treatment at monthly and seasonal scale for an average climatic year had been integrated in elementary spatial units represented by agricultural parcels.

4.2.2 Input data for a forecast of the soil erosion hazard to 2100

The agricultural and climatic data represent the two types of data that show a temporal variability. Nowadays, works relating to climate change allow us to have pieces of information that make consensus in the scientific community of climatologists for a distant future (GIEC, 2007a). Unfortunately, we cannot say the same for agricultural practices as the agricultural evolution depends at the same time on its interaction with climate, political choices and the socio-economic situation. Yet, it is not possible to precise with certainty what will be local agriculture in a distant future because we know little if nothing about the agricultural consequences of these interactions, political choices and socio-economic characteristics by 2100. So, our projection of the erosion hazard in 2100 leans on data from the GIEC that reproduce by default the current agricultural situation.

To characterize the Norman climatic context by 2100, we used and adapted the GIEC's simulation data (GIEC, 2007a) concerning the A1B scenario (Cantat et al., 2009). These ones reveal a annual increase of temperatures in Normandy on the order of 2.8° C from now to 2100 (Fig. 12A) with a global warming being more intense during summer (+ 3.2° C). With regard to rainfalls, the annual accumulations would remain stable, which would nevertheless hide differentiated seasonal behaviors: +9% during winter and -21% during summer (Fig. 12B). All these data were used to determine the conditions of rainfall erosivity in 2100.

	J	F	M	A	M	J	J	A	S	O	N	D	Year
A. Temperature (°C)	2.5	2.5	2.5	2.6	2.8	3.1	3.3	3.2	3.1	2.8	2.7	2.5	2.8
B. Rainfall (%)	9	9	9	4	-6	-20	-23	-20	-6	4	8	9	-2

Fig. 12. Regional climatic projections at horizon 2100 starting from scenario A1B concerning temperatures (A) and rainfalls (B)

4.3 Results

4.3.1 Soil erosion hazard for the current period

In order to show the most interesting results, our comments will concern more specifically on the period that goes from September to February in which the temporal variability of the erosion hazard is the highest. The monthly mapping of the hazard according to the current climatic data shows that the cultivated parcels are characterized by a susceptibility to the soil erosion by water which is medium or high (Fig. 13).

In September, the hazard levels are quite low or medium. At this time, the available water contents in the soils are not refilled, which postpone the presence of hydrological surplus. In addition, the plan covering is assured by corn and wheat stubbles.

In October and November, the average level of the soil erosion hazard concerns nearly 90% of the cultivated parcels. The increase of the soil susceptibility to erosion results from the bare soil of areas ensilaged and sowed with wheat. This can also be explained by the appearance of the first poor hydrological surplus.

The soil erosion hazard reaches its highest level in December and January. It becomes important for half the cultivated parcels. If the rate of plant covering is not very different from the previous period, the erosivity has increased due to important hydrological surplus and to the increase of days in which rainfalls exceed 10 mm.

In February, the susceptibility to erosion comes back to medium on the catchment's uphill border and quite poor elsewhere. This is explained by a better plan covering and land use and by a significant decrease of the amount of days in which the rainfalls intensity is exceeding 10 mm.

4.3.2 Forecasts for 2100

The projection of the soil erosion hazard for September shows levels that are similar to those found for the current period (Fig. 14). In October, we notice that in 2100 the cultivated areas concerned by the low and very low hazard increase and that parcels characterized by a high hazard vanish. The reduction of the susceptibility of cultivated surfaces to soil erosion could be explained by a huge decrease of summer rainfalls (-21%). This would lead to a delay in the filling of available water contents and thus to differ until November for the beginning of the first hydrological positive balance.

For November, the projection highlights a reinforcement of medium and high levels of the erosion hazard. The tendency would be even more marked in December. The parcels characterized by a high hazard would represent 90% of the cultivated areas. The increase of the susceptibility fo the catchment to soil erosion would be discernable until February. The strong hazard would still be present and the medium hazard would concern more than 80% of the cultivated areas.

Comparing the foreseen climatic data for 2100 with the ones from our period of reference (1991-2004), we noticed that 1994 was a very comparable year to the climatic projection of

2100. Knowing the frequency of occurrence of the 1994 climatic conditions, it leads us to the conclusion that the hazard levels obtained for an average year by 2100 would correspond to a current period's year whose occurrence periodicity is 4 years.

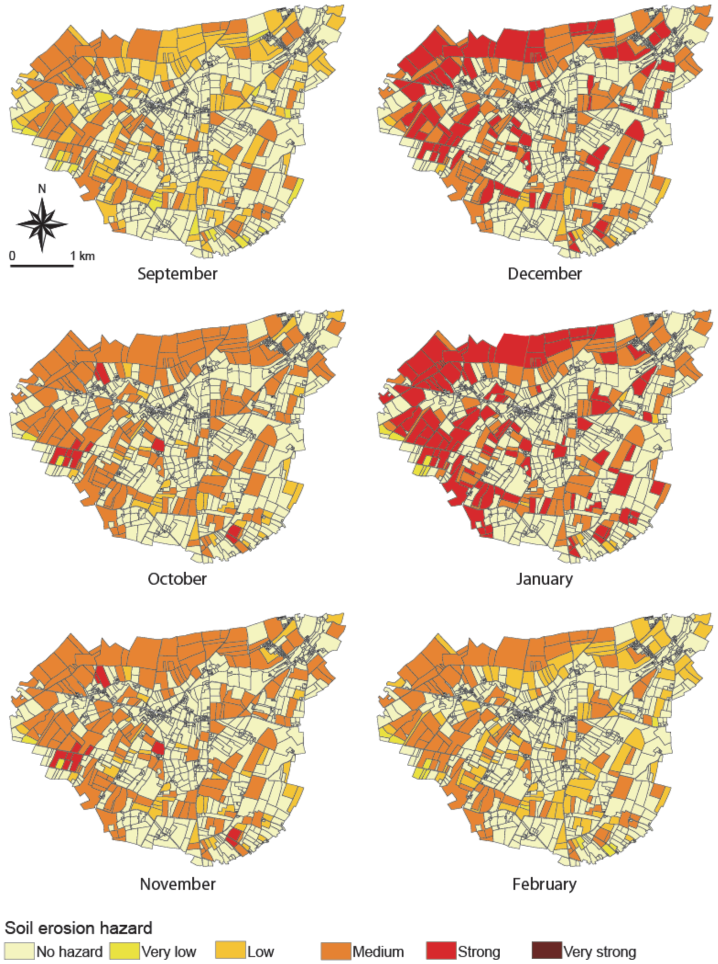

Fig. 13. Maps of soil erosion hazard in current climatic context at monthly scale.

4.4 Discussions

The climate change which has been observed in Europe from the pre-industrial to the current period resulted in an increase of temperatures in the order of 1°C and in a modification of rainfall distribution: +10% to +40% in Northern Europe during the 20th century and -20% in the South (EEA, 2008). On a world scale, we may not evade a climate warming in the order of 2 to 3°C by 2100 (Séguin, 2010).

Available data of the climate change effects on soils are very insufficient in European countries (EEA, 2008). However, according to some work, It seems that this leads to an

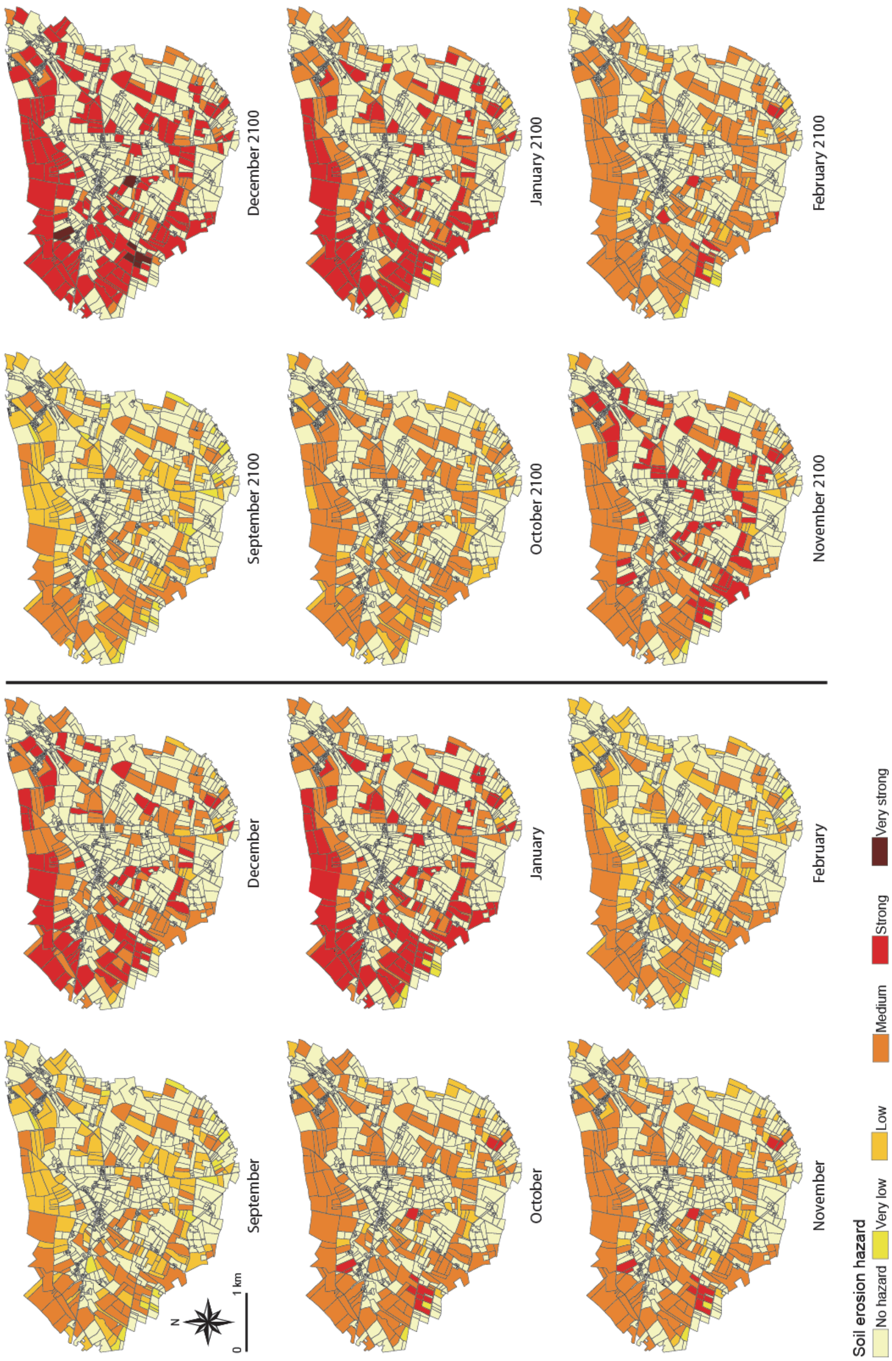

Fig. 14. Soil erosion hazard for current period and for 2100 at monthly scale.

increase of soils sensitiveness to erosion by water in Northern European areas on account of an increase of the rainfall frequency and intensity (Boardman, 1990; Boardman and Favis-Mortlock, 1993).

Nevertheless, this increase could be minimized under the influence of a modification of the vegetative cycles in the natural and cultivated areas (Ellis et al., 1990 ; Wheeler et al., 1993). We thus notice a significant progress of phenology in Europe (Séguin, 2010). In addition, a CO_2 multiplication by 2 at the end of the 21st century may lead to a 20 to 30% increase of photosynthesis (Séguin, 2010). The sensitiveness to erosion may even be lowered by conservative agricultural practices (Hulme et al., 1993; Zhang et al., 2009)

However, it is impossible to foresee the agricultural practices evolution for the 21st century because we know well yet the interactions between climate change and agricultural practices. Besides, agriculture depends on political direction and socio-economic contexts. In these conditions, it is not totally unrealistic to consider the climate change impact on the soils sensitiveness on erosion if we base on the current agricultural practices. This choice may also be justified by the fact that, in Europe, agricultural production systems are characterized by a large geographic stability (Seguin, 2010). In addition, the results we obtained deserve to be well examined.

Our work shows that the increase of erosive pressure on the cultivated soils which is forecast for an average year by 2100 would correspond to a scenario which the current frequency is one out of four. The fragility of cultivated soils may therefore be more important and more continuous over time. Although these results for a normal year are given, we must not forget that the climatic variability in a distant future may have consequences as harmful as the deep-rooted trend. Besides, it should be reminded that two climatically similar years may reach different erosive solutions (Favis-Mortlock and Boardman, 1995).

SCALES model helps to propose high spatial and temporal resolution custom-built scenarios of the climate change impact on the evolution of soils sensibility to erosion by water by 2100. Nevertheless, these data can only be produced on a local scale. However, our work is in the spirit of the European Environment Agency which reminds us the necessity to develop tools to assess the impact of climate change on soils (EEA, 2008).

5. Conclusions

Soil erosion is a major and growing cause of soil deterioration in many European countries. The main issue is that we must no longer consider soil as a renewable natural resource. Whatever the scale of intervention, the territorial structures need to have spatially spread information in order to overcome or prevent soil erosion. In this regard, maps of erosion hazard constitute essential documents.

Our goal was multiple when we developed SCALES model. Firstly, the point was to prove that it was reasonable to foresee a regional scale model and map while we have detailed local scale data. Then, we wanted to limit the model applicability to the European oceanic areas which are marked by a mutual pedoclimatic situation and a territorial dividing into agricultural parcels. Besides, our idea was to consider the soil erosion hazard within these parcels which are area sources: assuming that in this geographic context the erosion is more controlled by agricultural units rather than the environment where they dwell. We eventually had to take into consideration the weight of agricultural practices through their temporality when we assessed this hazard.

After we proved SCALES was operational in Calvados, we contemplated editing the model in order to achieve an assessment of the erosion hazard within intra-annual time scales. SCALES progressive nature allows us to consider this model as spatially and temporally dynamic. However, the required investment for produce the data in order to decline the model at the monthly and seasonal scales does not allow us to establish a mapping of the soil erosion hazard on a regional level. Consequently, this fine temporal approach must be held for sectors with strong environmental stake.

If SCALES can be used in a predictive approach, its structuring and its modularity also give opportunities within a prospective framework. It is what we did, in Basse-Normandie, concerning the topic of the impact of the climate change on the evolution of the cultivated soils susceptibility to erosion by water. In average year at horizon 2100, the results of this new application show that the levels of soil erosion hazard would be comparable with those currently obtained within the one year framework rainy of which the probability of return is once every 4 years. One would thus witness a reinforcement of the soil erosion hazard in average year.

We now wish to look further into the prospective application of SCALES starting from the studies which present, in comparable areas, the scenarios of agricultural practices evolution in a near future and a future distance. Our first results and the aim which we propose are altogether in the spirit of the recommendations of the GIEC (2007b) and the European Environment Agency which reminds us the necessity to develop tools to assess the impact of climate change on soils.

6. Acknowledgements

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