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Sediment Transfer Variation Approach at Large Rural Watersheds Scale of Northern France

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Authors' contributions

This work was carried out in collaboration with all the authors. Authors FXM, HBL and CB wrote the first draft of the manuscript while manipulating the literature review. Author HN first examined the final manuscript carefully before finally approving it.

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ABSTRACT

In the French "Nord-Pas-de-Calais" region, sediments suspended in runoff waters coming from rural watersheds play a major part in the turbidity of surface waters, silting up of streams, and silting of permanent structures such as canals and ports.

One of the main factors in processes limiting sediment transfers is the vegetation cover. Quantitative assessment and comparative analysis of the impacts of vegetation cover performed in various scales (fields, smaller watersheds, and larger watersheds) allow showing effects' analogy in these cases. As a result, it is possible to estimate and quantify, at little cost, the risks induced by erosion and runoff in the larger rural watersheds, and the need to change land use. Thereby, watersheds where the situation is more favorable can serve as a model.

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1. INTRODUCTION

The silting of streams and larger structures such as canals and ports require huge curing operations (50 million m3/yr of sediment extracted from ports and 6 million m3/yr from streams and rivers (in France) to ensure both safe navigation and the water runoff in the event of heavy rainfalls [1].

In lowlands of the North France, silting is the most widespread since low slopes increase the deposit of particles eroded from the upstream side of watersheds. With 680 km of navigable waterway the “Nord-Pas-de-Calais” region represents 10% of the French network and the fourth region in terms of extracted sediments quantities [1].

Suspension and transfer of particles in superficial waters of watersheds can be handled via the following tools, namely 1) the observation of processes leading to erosion and soil protection, 2) the quantitative assessment of factors impacting the quantities of materials transported, and 3) a comparative analyse of territories at different scales (field, small watershed, large watershed) with various protection.

Thanks to these tools, prediction and protection methods can be set up so as to limit transfers to the downstream watersheds, and therefore prevent their silting.

The work presented herein deals, at different scales, with quantitative assessment of transfers of suspended matter (SM) towards surface waters as a function of the soil protecting vegetal cover.

The topic of SM volumes reduction is major but difficult to address due to the variation of sediment origin and the immensity of concerned territories.

Regarding the soil erosion, which the main source of sediments in rural watersheds of Northern France, the protective role of the vegetal cover is well known. However, it remains difficult to associate a protective surface with a quantity of retained sediments unless the watershed area is equipped with measuring instruments. Moreover, the implementation of these tools depends on a long observation period.

To provide readily answers from the comparative analysis of sediments quantities measured at the plot scale, small and large watersheds, we aim to show that the mechanism of decrease in the quantity of sediments observed in plots and small watersheds, according to plant protection, remains significant at large watersheds area level.

2. CHARACTERISTICS OF THE REGION

The relief of the Northern France region is not high, seldom reaching 200 m above the sea level. The north east named “le Bas Pays” (low lands) is lower than the south west named “le Haut Pays” (high lands), which is above 80 m. The soils are made up of aeolian silt covers dating back from the Pleistocene era and resting on ante quaternary deposits [2].

Rural spaces are devoted to intensive agricultural activities (wheat, sugar beet, potatoes, rapeseed, vegetables, etc.). It should be specified that meadows and forests are a minority in this space. The use of heavy and powerful agricultural machineries tends to thin and level soils, thereby provoking some relative imperviousness. Lacks of calcic and of organic matters supply may also render the soil less permeable.

The needs for mechanization have often favoured bigger fields and the suppression of the tertiary hydraulic network, i.e. ditches.

It should be noted that this situation leads to uncontrollable flows and runoffs, often carrying SM [3].

3. ORIGINS OF SUSPENSION AND SEDIMENT TRANSFERS

Various factors can cause the motion of soil particles such as:

- Impact of raindrops on dislodging soils;
- Rainfalls' intensity and strength;
- Runoff transport;
- Relief accelerating or slowing down their speed;
- Absence of soil cohesion through lack of colloids (clay and organic matter) and/or flocculent agents (calcium);

- Lack of soil protection from vegetation (mainly in runoff zones thus creating gullies);
- Excessive tilling and ploughing causing tearing;

Indeed, the excessive soil work increases runoff by thinning and levelling the soil [4].

Runoff depends on two key elements: rain and the receiving medium. Rainfalls will, indeed, be either stored in the ground or run off on the surface carrying some particles during the process. According to Masson et al. [3], such a process can be described as follows (Fig. 1).

From this schematic representation, it appears that limitation of transfers can be achieved through the following actions:

- Improvement of water storage in the soil to reduce runoff;
- Reduction of the runoff velocity to avoid flooding and retain part of the sediments carried away;
- Enhancement of soil protection and water filtration of vegetation.

These actions prevent an excess of SM in rivers and their transfer to canals and ports [3].

Mostly, the transferred matters budget is estimated from mathematical models [5-7]. These models are either empirical models like USLE-based models [8-10], either process-based models [11], or expert-based models [12, 13].

Another approach is to measure sediment yield with hydro meteorological and turbidity monitoring equipment, which are maintained during several years in catchments [14,15].

Note that as one of the dominant factors of transfers' regulation is the vegetal cover [16 - 20]. For the Northern French Region, we propose herein an approach to set a relationship between soil cover and yield in SM. To achieve this, we have carried out three tests at different scales to define an indicator whose implementation is straightforward.

4. TESTS AT VARIOUS SCALES OF STUDY

To perform these tests, we have studied the influence of vegetal cover on the overall weight of SM in runoff waters. The studies have been achieved at three different scales: the first is that of a field, the second concerns smaller watersheds, while the third involves large watersheds.

It is very useful to recall that, in those tests, our objective is twofold: 1) quantify the importance of vegetal cover on the concentration of SM in runoff waters, and 2) compare the three situations involved.

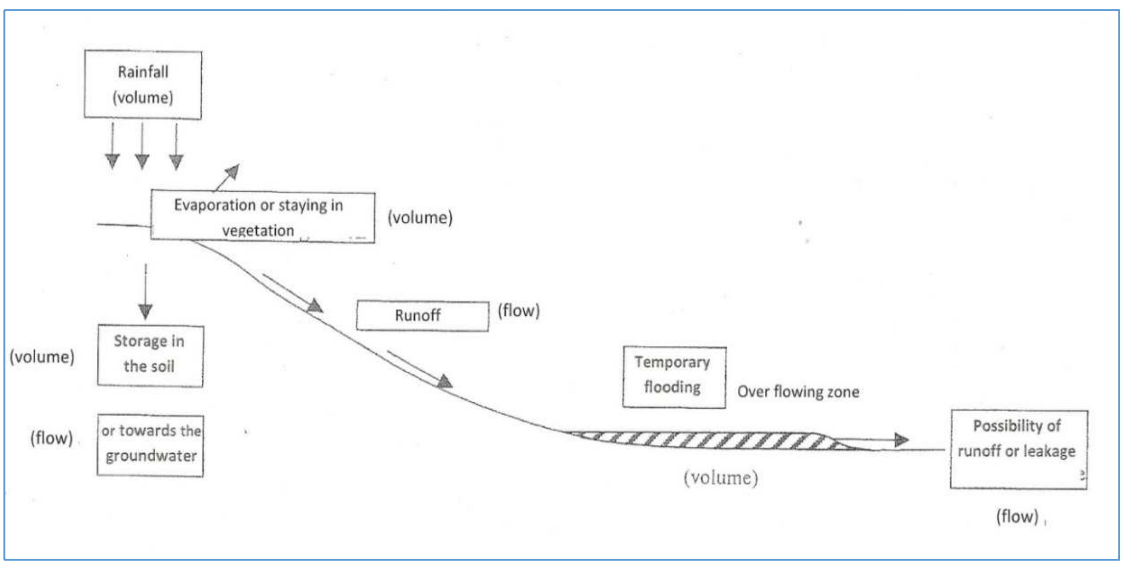

Fig. 1. Rain quantities distribution according Ref. [3]

4.1 Measurement at the Field Site

Thirty-one tests were carried out using an ORSTOM rain simulator [21] corresponding to 21 fields located in the “Pays du Val de Canche” region. The agricultural parcels have an area ranging from 5 to 20 hectares. The tests consisted of sprinkling 1 m² of the test field with an intensity of 33 mm/h, corresponding to a heavy downpour of this region. Note that soils were mostly silt-based (pure silt and sandy silt) and had similar hydrodynamic properties.

The agricultural parcels had different covers (meadows, crops, fodder plants, cereals at various growth stages, hoed plants or tilled land with no vegetal cover). The portion of soil protection represented by each type of these vegetal covers, has been assessed by counting per square meter watered.

The Fig. 2 depicts concentrations of SM in the running water as a function of the percentage of the vegetal cover of the field. The suspended solids are collected during rainfall, which also corresponds to the flow period.

The results can be classified into four percentage groups of vegetation cover as follows:

- Bare soils (0%)
- Cultivated soils (1 to 42%)
- Meadows and forests (90 to 100%)
- Not encountered soils (42 to 90%)

The first group corresponds to bare soils, for which the concentrations are very diverse, ranging from 1.6 to 16 g/l depending on characteristics of soil aggregates (stable or unstable).

This instability can be caused by excessive soil work, yet also by other parameters such as physicochemical properties, organic matter content and clay content.

The second group reflects cultivated soils. SM concentrations are mainly within the 0.5 and 3 g/l range and never exceed 5g/l. This is a partly protected medium.

SM concentrations observed on meadow and forest soils in the third group, are always less than 0.5 g/l. This medium appears to be the most protective in the transport of SM concentrations.

As for the four group, the percentage of cover between 42 and 90% have never been encountered, due to the partial covering of soils by crops over the measurement periods (autumn, winter and spring).

In addition, these observations show that meadow and forest soils generate nearly sixty times less SM (0.13 g/l) than bare soils (7.53 g/l).

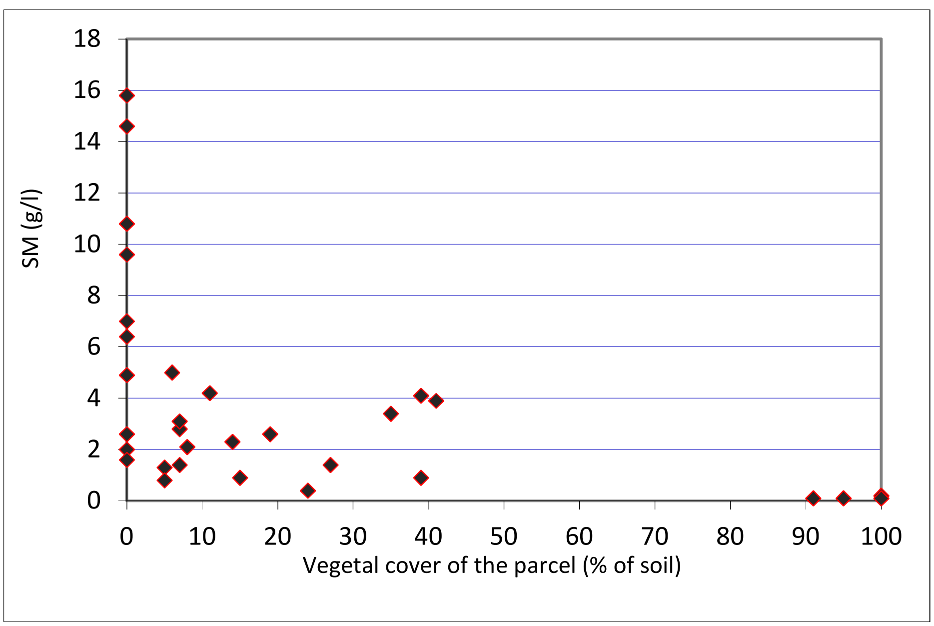

Fig. 2. Suspended matter as a function of vegetal cover [3]

4.2 Measurements at Smaller Watersheds

As beforehand, we aim to show the influence of soil cover on SM concentrations at an average scale of study, that of smaller watersheds.

The 12 watersheds studied belong to the same territory as the previous agricultural parcels, and the observations were performed in the same winter season. These are rural watersheds of only a few tens of square kilometres (see Table 1). The part of urbanized surface is limited to access roads to no-concentrated housing (not villages). They are, therefore, not taken into account in land-use types.

With respect to soil cover, field tests have distinguished (for SM concentration) first bare soils from cultivated soils, meadows and forests soils. As a result, we decided to take up this classification by grouping the bare soils with the cultivated soils, and meadows with forests. The latter has been assessed from aerial photographs. As for bare and cultivated soils, they have been evaluated by difference assuming urbanized areas as nonexistent.

It should be noted that SM concentrations were measured downstream watersheds in generally dry streams with only sporadic flow. For each sampling location, several measurements were taken; the numerical values retained are those corresponding to the most important rainfall where SM concentrations are the most numerous.

In the case of smaller watersheds with temporary flow, SM measurements can be very difficult due to nonstandard rain and site selection, which is not always ideal. That is why we have chosen the most important rainfall event for each watershed.

The Fig. 3 shows, respectively, SM concentrations in the runoff waters as a function of the percentage of forest and meadow, and as a function of bare and cultivated soils on the smaller watersheds.

As for the plot tests, the results can fall into three categories of vegetal cover, but with two different values. Thereby, we have three groups:

- Soils of meadows and forest minority (5 to 38 % of the total watershed surface area);
- Soils of meadow and forest majority (75 % of the total watershed surface area);
- Not encountered cases (meadows and forests between 38 and 75% of the watershed surface).

The first group of points having meadow-forest values between 5 and 38% corresponds to partially cultivated areas. The SM concentrations observed are dispersed and vary between 0.3 and 12 g/l. Such a dispersion shows the variability of the cultivated parcels' states: the bare soil, which is more or less thin, and the vegetal cover that is more or less important according to the growth of vegetation and the type of crops.

The second group is represented by one point and corresponds to another system with a dominance of forests and meadows (75% of the territory). SM concentrations are not high (around 0.3 g/l) corresponding to an important protection.

The third group shows an absence of values and reflects the frequent discontinuity in this region between a mixed system (annual crops and perennial occupation of meadows and forests) and a system with a dominance of meadows and forests.

Table 1. Description of watersheds and SM measured

Water sheds	Surface area (km²)	Meadows & forest %	Bare & cultivated soil %	Suspended matter g/l
Chartreux	7.37	5.2	94.8	10.7
Monchaux	4.1	11.5	88.5	8.7
Jumel	2.05	14.6	85.4	7.8
Chene	4.66	15.2	84.8	12.1
Saint-Remy	10.33	15.7	84.3	7.8
Delille	10.91	16.2	83.8	0.6
Ecuires	37.32	16.5	83.5	6.1
Varnette	27.78	19.8	80.2	3.1
Courval	17.25	23.1	76.9	0.3
Plumoison	3.53	30	70	0.45
Vaux	3.47	37.8	62.2	6.4
Surgeon	3.98	74.5	25.5	0.3

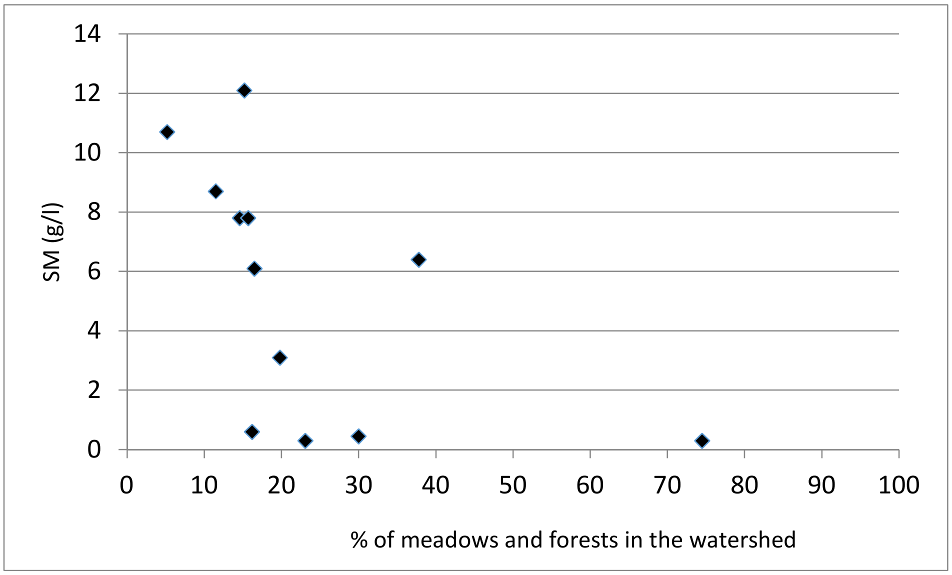

Fig. 3. Suspended matter as a function of the portion of meadow and forest in the smaller watershed [3]

In these conditions, the suspended matter observed quantities for bare and cultivated soils are, in average, twenty times greater than for the meadow and forest nearly that cover 75% of the watershed.

4.3 Results of Larger Watersheds

Recall that the objective remains to couple the land-use with the SM concentration observed downstream for a watershed of several hundreds of square kilometres.

While small rural watersheds are territories with specific knowledge of coverage and SM, this is not the case for large watersheds, not only for runoff measurements, but also for kinds of cover [22].

Fifteen watersheds have been selected from all of "Nord-Pas-de-Calais" region corresponding to different land-use situations ranging from areas favouring crops to areas with a predominance of forest and meadow (see Fig. 4).

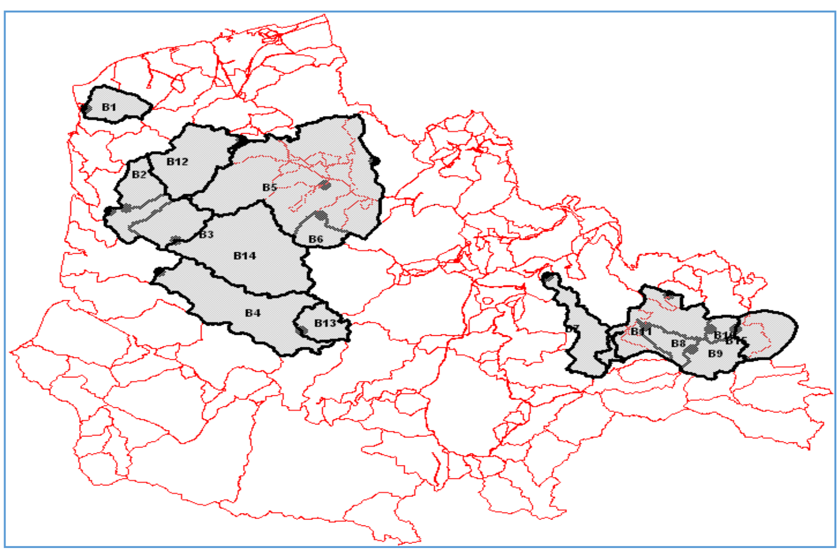

Fig. 4. "Nord-Pas-de-Calais" watershed: localization of 15 watersheds

Table 2. Characteristics of larger watersheds

N° BV	Name of measurement point (Water agency)	Area (km²)	% bare and cultivated soil	% meadow and forest	% urbanised zones	SM max (mg/l)
B1	Slack at Ambleteuse	152	59.51	30.79	9.70	796
B2	Course at Estrées	147	63.50	33.59	2.91	51
B3	Canche at Beutin	1197	66.56	28.46	4.98	859
B4	Authie at Dompeierre/Authie	785	71.04	24.95	4.01	190.8
B5	Lys canalisée at Estaires	1423	67.60	19.38	13.02	342
B6	Lawe at Bruay la buissière	110	66.63	20.81	12.57	346
B7	Selle at Noyelles/Selle	246	64.08	29.74	6.18	1110
B8	Helpe at Maroilles	270	13.42	81.99	4.59	320
B9	Helpe at Etroeungt	167	10.27	83.01	6.72	185
B10	Helpe at Semeries	266	11.18	84.48	4.35	261
B11	Sambre canalisée at Pont/Sambre	904	17.60	76.94	5.45	79
B12	AA at Wizernes	378	60.51	34.49	4.99	378
B13	Authie at Thièvres	135	76.08	20.41	3.51	764
B14	Canche at Aubin st Vast	720	68.70	25.97	5.34	1910
B15	Helpe at Willies	206	10.09	86.55	3.36	36

On the other hand the choice of watersheds was conditioned by the existence of a measurement point for the SMs corresponding to the outlet (point of measurement, which does not correspond to the downstream of an urban area or a discharge station). The parameters studied consider the SM as a function of vegetation cover.

Considering the vegetation cover, we identified three groups, viz., bare and cultivated soils, grasslands and forest soils, and urbanized areas.

On this scale, urbanization-related areas are not negligible. Moreover, in our study, they represent between 3 and 13% of the studied territories (see Table 2 above).

For each of these fifteen watersheds, land use was estimated with the European data base Corine Land Cover 2006[1], coupled with a GIS.

It should be noted that, unlike small watersheds, SM measurement points for large watersheds, which are more complex, are located in the river or canal. The water flow is permanent due to the supply by springs and urban or industrial flows. For SM measurements on the river course, there are zones of sedimentation or of taking up of sediments depending on the suspended quantities of matters that stream can carry. They vary as a function of different episodes of spates as well as longitudinal and transverse section and slope variations.

SM concentrations were collected from the data base Artois/Picardie Water Agency[2]. The SM kept are the maximum concentrations observed on available chronological series (see Table 2).

From Fig. 5, it appears that, at the scale of larger watersheds, the crossing between vegetal cover and SM concentrations leads to still distinguish three categories, namely:

- Soils of a minority of meadows and forests (19 to 35% of the watershed surface area);
- Intermediate situations not encountered (35 to 76% of the watershed surface area);
- Soils of a majority of meadows and forests (76 to 86% of the watershed surface area).

The first group corresponds to soils of meadows and forests that are in a minority (bare and cultivated soils in a majority). It exhibits SM concentrations quite dispersed from 51 to 1910 mg/l for an average of 675 mg/l. The dispersion of the measures encountered is certainly due to the percentage of bare and cultivated soils. To this phenomenon, the presence of urbanization can be added (6.72% of the surface on average with a maximum of 13.02% and a minimum of 2.91%). As for the second group, it corresponds to intermediary

[1] http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-clc2006-100-m-version-12-2009

[2] http://donnees.eau-artois-picardie.fr

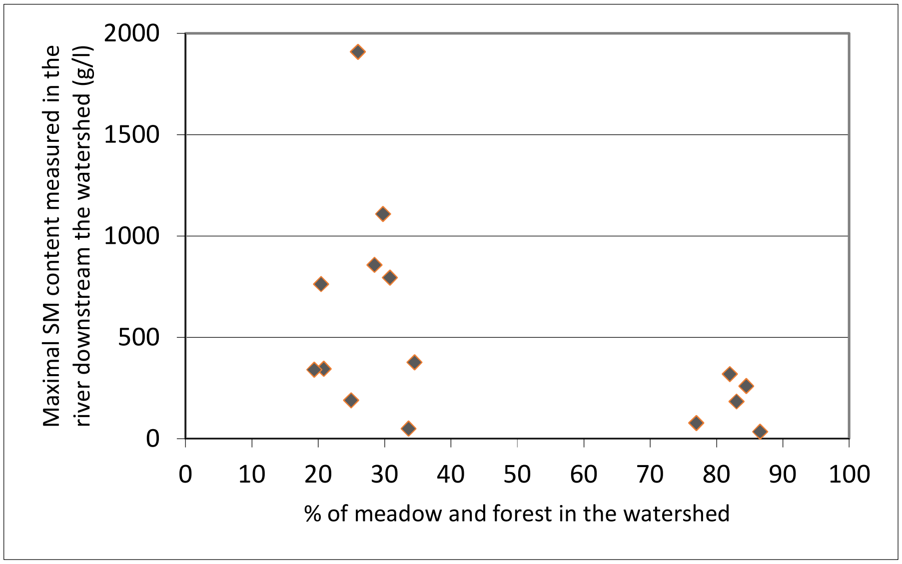

Fig. 5. Suspended matter and portion of meadows and forests in large watersheds

situations not encountered. Such a situation has been already observed in smaller watersheds. Finally, the third group corresponds to meadow and forest soils that are in a majority, and showing few dispersed concentrations: from 36 to 320 mg/l for an average of 176 mg/l. It should be noted that the dispersion of values reflects the influence of other factors such as the local presence of urban or industrial equipment (4.89% of the watershed surface on average with a maximum of 6.72%, and a minimum of 3.36%) thereby generating waste of SM, river canalization, dykes slowing down the velocity of the current and provoking the sedimentation of SM.

5. DISCUSSION AND CONCLUSION

In small watersheds, unlike fields' measurements performed, the three kinds of soil (soils of meadows and forest minority, intermediary situations) present, at least, a fraction of bare and cultivated soils, which determines values superior to 5% (Fig. 3).

We found two groups of results, one corresponding to crop-dominated areas (bare soils and cultivated between 62% and 95%), and the other corresponding to predominantly prairie and forest areas with Lower SM concentration values. These results are comparable to those observed at the plot scale despite the fact that indicators used (field protection percentage and cover type) are different for the watershed.

We find that SM concentrations are lower on the smaller watersheds than those measured in the agricultural plot with simulated rain. Factors that may explain this difference include the intensity of rainfall, which is generally lower in the last measurements, the effect of sedimentation, and new erosion phenomena when water flows.

For the larger watersheds and despite the influence of factors such as urbanization or economic activities, and the loss of precision in terms of percentage of cover (meadow and forest), obtained results remain similar to those obtained at the scales of small watersheds and plots: Concentrations in these territories are about four times lower than those of most croplands. This result, with the support of public information, provides a relatively good overview of the territories in terms of erosion and risk of flow and allows having a first idea in terms of territorial development priorities.

In addition, this comparative investigation of real cases demonstrates that the knowledge of the vegetal covered section ensuring the protection of the large rural Northern France watersheds enables to quickly know the risks of sediment transfer at the scale of these territories at low cost. The quantitative approach of these observations indicates potential gains that plots coverage could bring. These elements are basic since they neither detail the morphology nor the localisation of the covered land; they allow reflecting on watershed management that are partly responsible of down-streaming watercourses and structures silting in terms of priority.

Finally, this analysis makes it easy to estimate the protection level needed to achieve a significant reduction in sediment transfer.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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