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DESIGNING MANAGEMENT OPTIONS TO REDUCE SURFACE RUNOFF AND SEDIMENT YIELD WITH FARMERS: AN EXPERIMENT IN SOUTH-WESTERN FRANCE.

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ABSTRACT

To preserve the quality of surface water, official French regulations require farmers to keep a minimum acreage of grassland, especially bordering rivers. These agro-environmental measures do not account for the circulation of water within the catchment. This paper examines whether it is possible to design with the farmers agri-environmental measures at field and catchment scale to prevent soil erosion and surface water pollution. To support this participatory approach, the hydrology and erosion model STREAM was used for assessing the impact of a spring stormy event on surface runoff and sediment yield with various management scenarios.

The study was carried out in collaboration with an agricultural committee in an area of south-western France where erosive runoff has a major impact on the quality of surface water. Two sites (A and B) were chosen with farmers to discuss ways of reducing total surface runoff and sediment yield at each site. The STREAM model was used to assess surface runoff and sediment yield under current cropping pattern at each site and to evaluate management scenarios including grass strips implementation or changes in cropping patterns within the catchment. The results of STREAM simulations were analysed jointly by farmers and researchers. Morever, the farmers discussed each scenario in terms of its technical and economical feasibility.

STREAM simulations showed that a 40 mm spring rainfall with current cropping patterns led to 3116 m^3 total water runoff and 335 metric tons of sediment yield at site A, and 3249 m3 and 241 metric tons at site B. Grass strips implementation could reduce runoff for about 40% and sediment yield for about 50% at site A. At site B, grass strips could reduce runoff and sediment yield for more than 50%, but changes in cropping pattern could reduce it almost totally.

The simulations led to three main results: (i) grass strips along rivers and ditches prevented soil sediments from entering the surface water but did not reduce soil losses, (ii) crop redistribution within the catchment was as efficient as planting grass strips, and (iii) efficient management of erosive runoff required coordination between all the farmers using the same watershed. This study shown that STREAM model was a useful support for farmers' discussions about how to manage runoff and sediment yield in their fields.

Keywords: erosion; runoff; agriculture; land management options; participatory approach; modelling.

1. INTRODUCTION

Conflicts between agricultural production and environmental quality have grown steadily in recent decades due to the negative impacts of agriculture on the environment and particularly on water quality. Currently there is concern about the sustainability of conventional land-use practices on arable land throughout the world (Stoate *et al.*, 2009). From the 1960s on, policies in most European countries aimed at developing intensive agriculture. Increasing yields required mechanisation and the use of fertilizers and pesticides. At the same time, reducing costs was encouraged by the creation of big farms and land consolidation (Robert, 2000). As a result, environmental problems such as runoff, erosion and water pollutions began to occur (Nearing *et al.*, 2005; Toy *et al.*, 2005). The consequences are of concern to the local authorities which have to face property damages induced by soil-laden water, road clearance and watercourse pollution both by sediments and agricultural chemicals (Papy and Douyer, 1991; Boardman *et al.*, 1994).

Over the past 20 years, monitoring of surface water and groundwater in Europe revealed significant nitrate and pesticide contamination, mainly in France, where samples of surface water often exceeded the drinking water limits of 0.1 µg pesticides per litre (Water Framework Directive, European Community decree 2000/60/EC). For example, the *Comité de Bassin Adour-Garonne* (2004) pointed out that 96% of surface water in the Department *Tarn and Garonne* (south-western France) was contaminated by nitrates, phosphorus and pesticides, partially because erosive runoff in cultivated fields. Moreover, Probst (1985) reported total phosphorus concentration at 0.5 mg.L^{-1} in surface waters, and nitrate concentration from 60 to 130 mg.L^{-1} in subsurface waters according to the season.

In 2000, the European Community (EC) introduced the Water Framework Directive (WFD) as a way of restoring and preserving the quality of all water resources. The WFD, which is based on catchment areas, set targets of water quality to be achieved by 2015. Member States must implement management plans for every river basin to restore and to preserve the quality of surface, coastal and ground waters, and to ensure the protection of existing water stocks. In addition, Member States have to encourage all the stakeholders (e.g. local and regional authorities, farmers, water users and environmental organisations) to draw up, discuss and update their management plans (WFD, EC decree 2000/60/EC).

Since 1992, the Common Agricultural Policy (CAP) introduced instruments that are relevant to achieving better water management: set-aside land (lying fallow a part of arable land) to mitigate agricultural over-production, and agri-environmental measures (AEM) to control agricultural impacts on soil, water, air, biodiversity, habitats and land-use patterns. AEM implementation by farmers is initially only based on voluntary service and EC financial aid. In 1999, the new EC Rural Development Regulation reinforced environmental considerations with expansion of AEM. The CAP reform of 2003 introduced the cross-compliance principle that linked the full payment of CAP aids to farms and compliance with agri-environmental standards called “good agricultural and environmental condition” (GAEC). GAEC obligations constitute AEM baseline; they include in particular a part of the annual cropped area with permanent plant cover (PPC) to prevent soil erosion, and buffer strips (non-cultivated or grass planted) along water courses to prevent surface water pollution.

The first way to prevent water pollution by agricultural practices is to reduce the source of pollution, by choosing the right pesticide type, reducing application rates and improving spraying efficiency. The second way is to reduce the transport of pollutants in runoff, in solution or attached to sediments caused by erosion (Aubertot et al., 2007). This involves changing land use to reduce runoff or planting grass strips downstream the agricultural fields to filter runoff before it reaches the water system. Many authors have shown how grass strips can prevent pollution of surface water. Grass vegetation planted at the downstream edge of sloping field reduce runoff volume and velocity, by increasing hydraulic roughness of the soil surface, and subsequently by improving the infiltration rate (Le Bissonnais *et al*., 2004; Borin *et al*., 2005; Deletic and Fletcher, 2006). Decreasing flow volume and velocity lead to sediment deposition as a result of decreased transport capacity (Wu *et al*., 1999; Järvelä, 2002; Wilson *et al*., 2005). Barfield *et al*. (1979) and Dillaha *et al*. (1989) mentioned that sediment trapping can be substantial as long as the flow is shallow and uniform and the filter is not submerged. Gumiere *et al*. (2011) reported that grass strips remove sediments and pollutants from runoff by filtration, deposition, infiltration, adsorption, absorption, decomposition, and volatilization.

In France, CORPEN (a collaborative organization gathering specialists from public authorities and private organisations involved in agriculture and water protection) published guidelines on how to identify the best locations for grass strips within catchments (CORPEN, 1997, 2003). Based on these guidelines, official French regulations were drawn up to encourage farmers to establish PPC, including grass strips. According to French decree 2009-499 April 30, 2009, which took effect in 2010, the total surface area of PPC in each farm must be at least 3% of the annual cropped area. PPC or grass strips must be planted within fields, most importantly those bordering rivers, the strips must be between 5 to 10 m wide and must cover at least 500 m^2. These regulations apply at farm or field scale but do not account for the hydrological processes at catchment scale. For example, the regulation concerning the width of the grass strip does not take into account the size of the upper runoff area that induces the quantity of runoff flow which have to be filtered (CORPEN, 1997). Moreover, ditches that collect runoff water and flow into rivers will not be protected unless they are considered by authorities as “water courses”.

The design of AEM at catchment scale can be improved by modelling the processes involved in runoff generation (flow concentration and soil erosion). Modelling the interactions between physical characteristics and agricultural practices could help design adequate protective measures (Ludwig et al., 2004). Gumiere et al. (2011) showed that only spatially distributed models account for the effects of the spatial organisation of land management practices on runoff and sediment transport. In such a context, distributed expert-based models are a possible solution (Evrard et al., 2009). The STREAM model (Sealing and Transfer by Runoff and Erosion related to Agricultural Management; Cerdan et al., 2002a & b) developed by INRA (the French National Agronomic Research Institute) belongs to this family of expert-based models.

Getting stakeholders actively involved in AEM implementation can be an efficient way to proceed to design relevant, applicable and acceptable agri-environmental policy (Prager and Freese, 2009; Roe García and Brown, 2009). In this way, the use of hydrologic models can then help farmers collectively evaluate the impacts of their agricultural practices at the catchment scale, and see which practices or protective measures are the most effective. To support a participatory approach, Souchère *et al.* (2010) developed a role-playing game based on STREAM to raise the awareness of the different stakeholders (the mayor, farmers, rural and urban residents) about erosive runoff and the possibility of collective action.

The aim of this study is to verify that farmers can collectively discuss at the catchment scale about the impacts of their individual practices on erosive runoff and subsequently on surface water quality, and design appropriate AEM to reduce these impacts. In this way, we tested the STREAM model as a support for participatory approach: it was used to evaluate by comparisons the impacts of various management scenarios build with the farmers who cultivate the site and have to implement AEM. Farmers were actively involved in validating the model, building alternative scenarios, and analysing the model's response to the scenarios tested. Our study was carried out in the French Department *Tarn et Garonne* in collaboration with Lomagne district agricultural committee. Soil erosion is frequently observed in these catchments and sediment loads in streams and rivers have a direct negative impact on water quality (Lecomte, 1999; Riglos, 2005).

2. MATERIAL AND METHODS

2.1 Study sites

This study was conducted near the town *Lavit de Lomagne* in the Department *Tarn et Garonne* (south-western France) with the active participation of the Lomagne district agricultural committee ("*Communauté de Communes de Lomagne Tarn et Garonnaise*").

The Lomagne region, which spans the Departments of *Tarn et Garonne* and *Gers*, has a humid temperate climate: annual rainfall varies between 700 and 760 mm and average daily temperatures range from -10 to 35 °C. Rainfall is low to moderate in winter, and the most intense rainfall events occur in spring. Most soils at the two sites are silty loam, 'neoluvisol' according to the French classification, and 'excessively drained' according to the USDA soil drainage classification (USDA, 2003). Such soils are very susceptible to surface sealing (CACG, 1965) because of their low clay (8-16%) and organic matter (0.5- 1%) contents. These soil characteristics are similar to those used to calibrate and validate the STREAM model. The water table is very deep (more than 10 metres) and is therefore unlikely to generate saturation excess flow. The risk of erosive events is very high in April-May, when intense rainfall events (20-40 mm in only 2 or 3 hours) occur and many fields have just being cultivated or sown with spring crops and surface soil is bare or almost bare (less than 20% of vegetation cover) during this time period. These pedoclimatic conditions are common in Southern Europa.

In collaboration with the local farmers, we selected two sites to (Fig. 1). The first site (site A; 43° 58’ N, 0° 58’ E) is a 41-ha hillside with slopes ranging from 0 to 15% comprising five large fields cultivated by two farmers. In 2009, 36 ha were used for spring crops (maize and sunflower) and 5 ha for winter wheat crop (Fig. 2a). The farmers suggested this site to study how to reduce erosion because spring storm on just planted spring crops causes mud flows that cover the downhill road nearly every year. The second site (site B; 43° 57’ N, 0° 56’ E) is a small 107-ha catchment that supplies the Serre River and comprises 40 fields cultivated by five farmers. This site is characterised by a steep-sided upstream valley with strong slopes (more than 15%) followed by a relatively flat valley (slope between 0 and 5%). In 2009, five main crops were cultivated (Fig. 2b): winter crops (wheat, barley and rape) on 43% of the area, spring crops (maize, sunflower and sorghum) on 41%, grasslands account for 12% of the area mainly in the upper basin, while forest and set-aside land account for less than 4% of the area.

2.2 STREAM: hydrological model to simulate runoff and erosion

STREAM is an expert-based model of runoff and erosion at the field/small catchment scale and at the rainfall event scale (Cerdan *et al*., 2002a & b). It is spatially distributed and was developed under the ArcGis platform in the ArcObject language. This model is based on the basic hypothesis that soil surface properties are the major controlling factors for water runoff and soil erosion/redistribution processes in agricultural landscapes. Surface characteristics include soil roughness, surface crusting and vegetation cover evaluated at the field scale. It takes into account (i) the effects of soil surface characteristics (surface roughness and crusting) and vegetation cover to compute infiltration rates and soil surface erosion using expert rules, and (ii) tillage direction and landscape features (e.g. ditches, hedges, roads, developed sites) to build the runoff circulation network (Le Bissonnais *et al*., 1998). Input data are topography, field pattern and landscape features, soil surface state (roughness, crusting), vegetation cover (% and type), and tillage direction determined at field scale, and, characteristics of the rainfall event (amount, duration and maximum intensity) and previous rainfall amount. In addition, STREAM model uses expert rules for determining runoff and erosion parameters. Moreover, STREAM has been developed to simulate the influence of changes in land-use (modifying cropping pattern) or in soil tillage (tillage direction, no tillage), and of introducing agri-environmental devices like grass strips (Cerdan *et al.*, 2002a & b; Souchere *et al.*, 2003b). Introduction of such devices is made adding new spatial objects with given infiltration capacities that replace the original ones in the fields. For instance, grass strips are spatial objects that enable an infiltration rate of 50 mm.h^{-1}, as estimated by Cerdan *et al.* (2002b).

The model considers an infiltration/runoff balance for a single rainfall event characterised by the total amount of rainfall, its maximum intensity and rainfall duration. Water storage and runoff is computed for each pixel and accounts for soil infiltration as follows (Eq. 1):

$$Bir = R - IR - (I_{\alpha} \, . \, \Delta t) \qquad (1)$$

where *Bir* is the infiltration/runoff balance (mm), *R* is the total rainfall event amount (mm), *IR* is residual water soil storage capacity after the previous rainfall (mm), I_{α} is the steady state soil infiltration rate (mm.h^{-1}) and *t* is the runoff event duration (h). Soil infiltration and water soil storage capacity are estimated from soil surface properties using a decision table that take into account the soil roughness (qualified in four classes according to the size of soil aggregates), the soil surface crusting (qualified in four classes, since fragmentary structure till sedimentary crust), and the vegetation cover (qualified in three classes according to the percentage of soil surface covered). Moreover, the water soil storage capacity decreases with an increase in the amount of previous rainfall. Consequently, the lower the residual water soil storage capacity, the quicker the soil becomes saturated; and once the soil is saturated, runoff occurs. Decision table for determining infiltration capacity in silty loam soils of Normandy with low clay and organic matter contents was established by Cerdan *et al.* (2002a & b). Soils in site A and B having similar characteristics, we applied the same rules without modification. According to this decision table (Table 1), infiltration rate after previous rainfall of 10 mm varies between 5 and 10 mm.h^{-1} in site A and B according to the vegetation cover and soil surface properties (soil roughness in all fields was fixed to 1-2 cm). The resulting runoff is routed at the catchment scale using a classical topographic runoff model (Jenson and Domingue, 1988) calculated at each pixel with a tool implemented in the ArcObject structure code. The flow direction is also modified by an algorithm (Souchère *et al.*, 1998) so that runoff can follow the main linear direction in the landscape, such as the ditch and tillage directions in the fields. Flow accumulation at the catchment scale is calculated taking into account the runoff flow network and the balance infiltration-runoff of each cell (Cerdan *et al.*, 2002a).

The considered erosion processes are water erosion, including both rill and interrill erosion. Interrill erosion includes hillslope processes referred to as mass translocation by runoff, in which water flow is responsible for the remobilisation of soil particles detached by splash erosion. In the model, this evaluation comes from an empirical analysis of the soil surface properties based on rainfall and runoff field observations (Cerdan *et al*., 2002a). A decision table based on soil surface properties (vegetation cover, soil roughness and soil crusting) and maximum rainfall intensity is used to estimate the sediment concentration (S_c) in runoff. We used expert rules established by Le Bissonnais *et al*. (2005) for determining sediment concentration in silty loam soils with low clay and organic matter contents (see Table 1). Sediment delivery for each pixel is then calculated integrating sediment concentration with the runoff volume.

Rill erosion module is based on an empirical relationship between soil surface properties, slope, simulated flow accumulation and observed rill sections as developed by Souchère *et al*. (2003a). The sensitivity to rill erosion (S_{re}) is calculated as follow (Eq. 2):

$$S_{re} = F \,.\, C \,.\, A \,.\, S \qquad (2)$$

where F and C represent the class factors "*friction*" and "*cohesion*" relying to land cover and soil surface roughness, A is the effective cumulated runoff in the pixel (m^3), and S ($m.m^{-1}$) is the local slope. The original rill identification procedure considers also some flow thresholds (i.e. minimum drainage area, 0.6 ha; minimum flow segment length, 80 m) able to generate incipient gully conditions as hypothesized for some small agricultural catchments in France (Ludwig *et al*., 1996). Finally, rill erosion (R_s, kg) is linked to the sensitivity factor by an empirical relationship (Ludwig *et al*., 2005) as follow (Eq. 3):

$$R_s = \rho \,.\, \lambda \,.\, k_s \,.\, S_{re} \qquad (3)$$

where ρ is the soil bulk density ($kg.m^{-3}$) , λ is the pixel dimension (m), and k_s represents a calibration coefficient to estimate the rill section (m^2) on each pixel along the runoff network. The resulting rill section is converted in soil loss volume on the base of the pixel dimension.

Both rill and interrill erosion modules are sediment transport limited, with the maximum sediment concentration controlled by several threshold functions with respect to the local topography and soil cover, including vertical curvature (concavity > 0.055 m^{-1}), slope gradient (< 0.02 $m.m^{-1}$), soil use type and soil cover (> 60%), after applying concentration limits ranging from 2.5 to 10 g l^{-1} (Cerdan *et al*., 2002a).

To simulate the accumulation of runoff flow and erosion, we used a reference rainfall of a one-year return period based on the Montana formula which gives the rainfall intensity as a function of time (Eq. 4):

$$q_r = a \cdot t^{-b} \qquad (4)$$

where q_r is the rainfall intensity (mm.h-1), t is the duration of event (h), and a and b are specific site parameters corresponding to the intensity–duration curve for the one-year return period. Basing on this equation, we computed a reference rainfall event following the method used by Taky et al. (2009). The resulting hyetograph corresponded to a daily spring rainfall event of 25 mm, with a maximum intensity of 40 mm.h^{-1} and a duration of 2 hours. The previous rainfall amount (cumulated rainfall during the preceding 48 hours) was set at 10 mm. According to the farmers, this type of storm event occurred almost every year. For example in 2009 on site A, eroded soil filled the ditches, a mudslide blocked the downhill road and a bulldozer was needed to clear it, the mayor was threatening to make the farmers pay for clearing the road. The sediments deposited downslope destroyed spring crop seedlings, and the affected areas had to be replanted. The sediments (with adsorbed pesticides) flowed to the river via a network of ditches thereby polluting surface water.

Validating a STREAM model requires measures of runoff and sediment yield amounts. Such measures on both sites did not exist, and we used decision tables which were built and validated for same soils and same crops. Moreover our aim with the models was not to obtain an accurate estimation of runoff and sediment yield amounts on both sites, but to support discussion between farmers about options to manage it. Following other participative modelling and simulating approaches (Bellon, 2001; Antunes *et al.*, 2006; Bécu *et al.*, 2008; Jankowski, 2009), qualitative model validation was devoted to the farmers who are used to observe runoff and erosion in their fields. Moreover, we analysed the impacts of scenarios by comparison in the simulated results and considering only big differences.

2.3 Participative approach supported by simulations with STREAM

Participatory approaches concern many situations in decision making, notably natural resources management (Wondolleck and Yaffe, 2000) or integrated water resource management (Pahl-Wostl et al., 2007), from local (e.g. Bécu et al., 2008) to large (e.g. De Stefano, 2010) scales, and involve stakeholders with various forms: from information, to consultation, to designing policy, to shared decision making (Hare *et al.*, 2003). Participative approaches frequently involve the use of simulation models that provide evaluation of management options (Bots and van Daalen, 2008). Here, we used the simulation STREAM model as a support for a participatory approach with farmers to discuss possible ways to prevent erosive runoff (and hence to avoid the risk of river pollution) at both sites. This approach combined 3 steps: (i) assessing the risk of erosive runoff due to current agricultural practices, (ii) testing the impact of possible changes to mitigate erosive runoff risks, and (ii) discussing their feasibility. The farmers were encouraged to play an active role in the decisions affecting their catchment, to interactively explore alternative practices, and to discuss economic and technical constraints/assets that winder or encourage their adoption.

Five meetings with farmers took place between January and June 2009. The two first meetings were with the Lomagne district agricultural committee to choose the sites. Site A (the hillside) was chosen because erosive runoff is severe and occurs almost every year in spring. Site B (the catchment) was chosen because it is small and different crops are grown there. Another important aspect was that most of the farmers (5 of 6) at the two sites agreed to spend time with us working on erosive runoff and surface water pollution. The third meeting in early May 2009, was spent visiting the sites with most of the farmers to record cropping practices and the state of the surface soil. The fourth and fifth meetings (2 successive evenings in June 2009), which all the 5 farmers attended, were spent (i) qualitatively validating the simulated runoff network, (ii) building scenarios for the two sites including alternative locations of grass strips and/or changes in cropping patterns, and (iii) analysing the simulated impacts of changes.

The STREAM model was first run using the crops and soil surface states recorded at each site during the first visit. These “original scenarios” (A0 and B0) were used to validate qualitatively the simulation models: the farmers compared simulated and observed (in the past) runoff pathways and erosion-accumulation rates. The model scenarios were then used as support for discussions among farmers about the system to be managed and to explore possible changes to prevent erosive runoff. Scenarios A0 and B0 (see fig. 2) were used at each site as benchmark and the simulated results of changes were evaluated by comparing them with this scenario.

Analysis of scenarios A0 and B0 led to suggestions for several changes to prevent erosive runoff: two scenarios (A1 and A2) for site A and three scenarios (B1, B2 and B3) for site B. Two kinds of management options were discussed: (i) grass strips inside or on border of fields, or grassland fields to slow down runoff and enable it to infiltrate; (ii) changes in the cropping pattern knowing runoff and erosion on spring crops are higher than on winter crops.

For the hillside at site A, proposals concerned only the location and dimensions of grass strips to prevent erosion: standard 5-m wide strips bordering ditches (scenario A1; Fig. 3a); 10-m wide strips located mid-slope in the fields where slopes are steepest (scenario A2; Fig.3b). None cropping option (replacing spring by winter crops) were tested at site A because farmers did not choose to test it and we prefer to keep it for site B. Four ideas were discussed for the catchment at site B. The first was to cultivate grassland (or create set-aside land) in the form of one long narrow field bordering the river to collect runoff from upstream fields; the second was to plant standard grass strips bordering rivers and ditches. These two proposals were combined with existing cropping patterns in scenario B1 (Fig. 4a). The third and fourth proposals concerned changes in the cropping pattern. In scenario B2 (Fig. 4b), a cropping pattern with redistribution of spring and winter crops within the watershed was combined with the first proposal. In scenario B3, all cropped fields were changed to winter crops (Fig. 4c).

Other cropping options, such as changing tillage direction or installing spring crops without tillage for instance, have not been tested by simulation for several reasons: (i) options to test were chosen by the farmers, and (ii) qualitative validation of our models required being careful with the quantitative simulated results. Those cropping options were too “hot topics” to be tested by simulation; nevertheless, they were discussed during analysis of scenarios.

3. RESULTS

Three kinds of results were obtained: (i) quantitative results concerning the simulated runoff volume and the amount of eroded soil exported; (ii) qualitative results, in which farmers analysed the location of waterways and of areas that contributed to erosive runoff, and compared with their past observations in their fields; and (iii) discussion among farmers about the simulated results and the easiness/constrains in implementing the tested option. The qualitative results were used with the farmers (i) to validate the hydrological models (one model per site) and (ii) to help locate areas where preventive measures would be appropriate. The model was validated by checking the surface runoff and soil erosion pathways within the hillside or catchment.

3.1. Reducing erosive runoff on the hillside at site A

With the existing cropping pattern and soil surface state (scenario A0), simulated total runoff for one rainfall event reached 3116 m^3, and 335 metric tons of soil were lost (Table 2). Taking into account the area of site A (41 ha), these total amounts corresponded to 76 m3 of water and 8 tons of soil per hectare. A simulated map of spatial runoff and which soil was lost. Farmers confirmed that patterns matched well their observations made in the past in their fields, notably with great runoff paths and erosion scratches. Soil losses and erosion (Fig. 5) showed the water pathway and the main locations at sediment transport deriving from runoff flow, erosion pathway is therefore very similar to runoff pathway as shown in figure 5.

Planting 5m width grass strips bordering ditches and roads (scenario A1) reduced runoff by about 46% and sediment yield by 26% (Table 2). Runoff and erosion were not prevented in the fields, but grass strips partially retained the flows of water and sediments before they reached the ditches. When 10-m wide grass strips were planted where the slope was steepest or at mid-slope in the fields (scenario A2), runoff was reduced by 43%, and sediment yield by 39%. Scenario A2 was thus more efficient than scenario A1 for preventing to mud flows on the road, and soil losses in the fields were also reduced. Efficiency of grass strips depend therefore on its location: (i) grass strip has better efficiency when it is located on runoff flow pathway; (ii) it enable soil sedimentation when it is located downstream (by filtering the runoff water highly concentrated with soil sediment); (iii) it prevent from soil wrenching when it is located upstream (by reducing/slowing down the runoff flow).

Farmers are already used to planting grass strips as shown in scenario A1. They agreed that grass strips had a beneficial impact on runoff and on the simulated results of scenario A1, but said that sediments accumulated in the grass strip and did not want to install wider ones. Planting a grass strip means reducing the size of field and, in addition, creates a problem because tractors are not allowed on the strip to prevent soil compaction, which decreases infiltration rate. Most of the farmers (3 of 5) did not like scenario A2. Planting grass strips in the middle of fields is thus more problematic than at the edge. What is more, most farmers initially failed to understand how grass strips planted mid-slope could reduce erosive runoff. One farmer provided the explanation: due to the slope, water flows faster and planting grass strips in the field slows runoff down before it becomes erosive.

3.2. Reducing runoff in the catchment at site B

With the existing cropping pattern and soil surface state (scenario B0), total simulated runoff volume reached 3249 m^3 and 241 metric tons of soil were lost (Table 2). Like for site A, farmers confirmed the pathways of the main simulated runoff flows (Fig. 6) compared well with flows in their fields. Especially, runoff accumulation in fields on the right river bank in the western part of the catchment (see Fig. 6a), explained why two farmers had decided to use them as set aside land or grassland. Nevertheless, one field, cultivated by a third farmer, was still being cultivated with sorghum (a spring crop). Moreover, the upstream basin (western from set aside field long the river) produced about the half of total sediment yield (see Fig. 6b). Taking into account the area of site B (107 ha), these total amounts corresponded to 30 m3 of water and 2 tons of soil per hectare, i.e. 2.5 and 4 times less than in site A. Greater proportion of covered soil and also weaker average slope in site B explained this difference.

A map was created identifying fields that contributed most to runoff along with those that collected runoff. By comparing figure 6a (runoff pathways) and figure 2b (existing cropping pattern and land use), farmers concluded that the main runoff started in fields planted with spring crops and the reasons were discussed collectively. In fields that are cultivated in spring, vegetation covers less than 20% of the soil surface. When intense rainfall strikes unprotected soil with low structural stability, runoff occurs, and when runoff accumulates on bare soil, erosion occurs. Soil sediments transported by runoff then pollute the river. Conversely, grassland and winter crops do not generate runoff and help slow down water flows from uphill fields. Winter crops completely cover the soil surface thus protecting it from the raindrops. Heavy vegetation slows down water flows and improves infiltration.

In scenario B1, except in grassland and set aside fields, grass strips were planted bordering the rivers, in accordance with official regulations. This resulted in a reduction of more than 50% in runoff and sediment yield (Table 2). The sloping upstream basin at site A contributed a lot in the total sediment yield (see sediment yield pathway on fig. 6b). Installation of grass strips on the left bank and grassland on the right bank of the river in the upstream basin resulted in a strong reduction of sediment yield. For the farmers, this result confirmed the usefulness of grass strips in protecting rivers from pollution. However, official regulations do not make it obligatory to plant grass strips in small fields, of which there were many on both river banks.

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The reallocation of winter and spring crops in the catchment (scenario B2) achieved a slightly lower reduction in sediments yield (46%), but runoff was only reduced by 22% (Table 2). In this scenario, winter crops were preferentially planted in fields bordering the rivers. Taking into account the crop rotation over years, this scenario induced to select in these fields only winter crop rotations (e.g. rape with wheat and barley). Winter cropped fields bordering the river retained the soil sediments to the same extent as grass strips and protected the rivers. Spring crops were planted in uphill fields where the slopes were slightly steeper than in downhill fields, thus increasing runoff. However, grass strips reduce the size of the field and consequently the farmers' income. In scenario B2, redistributing spring and winter crops did not affect the farmers' income. Exchanging fields between farmers is possible but not easy because crop rotations need to be taken into account: spring crop like maize, sorghum and sunflower, are often cultivated alternately with winter crops like wheat and barley. In addition, the farmers said that they preferred using downhill fields for spring crops, which produce more income than winter crops. The farmers consider downhill soils to be deeper and more fertile, and to enable higher yields with less irrigation and fertilisation. This is in accordance with soil being eroded in uphill fields and soil sediment accumulating in downhill fields.

In scenario B3, all the fields were well covered by vegetation of winter crops, and runoff and erosion almost completely stopped (Table 2). However, the farmers did not agree with this cropping plan because it would lead to a major reduction in their income: in 2005, the income from maize and sunflower ranged from €541 to €1025 per hectare, while the income from winter wheat and rape ranged from €508 to €618 per hectare (Table 3). But this income depends also on prices of agricultural products that can strongly vary between years (for instance, prices in 2007 was about the double). In addition, farmers confirmed that alternating spring and crops enabled better pest and weed control (Macé *et al*., 2007). In fact they only accepted trying this scenario to evaluate its impact on runoff and erosion. As the results of the simulation demonstrated the major impact spring crops have on erosion, the farmers were willing to discuss this drastic solution in catchments where erosion is a very serious constraint.

IV DISCUSSION

Even though STREAM model requires a lot of input parameters, especially for decision tables, these parameters are quite simple and easy to inform with farmers. Nevertheless, it requires to know soil surface state and vegetation type and cover in each plot, and decision table suppose to have measures on infiltration capacity and potential interrill and rill erosion for each kind of plot according to soil, vegetation cover and topography. Here, in one hand, we could know the parameters for each field because both sites are very small; to obtain a global view of a larger territory, it would be necessary to adapt STREAM to incorporate remote-sensing data instead of field data (Souchère *et al.*, 2005); the feasibility of this upscalling has been demonstrated by King *et al*. (2005). In the other hand, we used decision tables established by Cerdan *et al*. (2002b) and Le Bissonnais *et al*. (2005) for silty soils of Normandy, assuming that runoff and erosion processes are similar because soils and vegetation covers have same characteristics.

Mapping land use, cropping patterns, and simulation results were the key points to engage with farmers. All discussions among the farmers were based on the maps that were created to validate runoff pathways and to locate grass strips and crops. This confirms that geographical information systems (GIS) are a good support for participatory approaches in many sectors, as reported by many authors (e.g. Repetti and Prélaz-Droux, 2003; De Freitas and Tagliani, 2009; Jankowski, 2009; Lagabrielle *et al*., 2010).

Most farmers are aware that their practices have an impact on the environment, especially on water quality and quantity, but not all of them are ready to change (Michel-Guillou and Moser, 2006). In our case, the farmers knew that bare soil and along-slope tillage increase the risk of erosion. We did not try to test the effect of changing the direction of tillage because (i) our model had not been validated for it, and (ii) because farmers did not want to change tillage direction in sloping fields as across-slope tillage is impossible and even dangerous (risk of overturn) when slope exceeds 10%. Nevertheless, it is a fact that in downslope and less steep fields, across-slope tillage slows downhill runoff (Basic *et al*., 2001). Despite this knowledge, farmers base their choice on the geometry of the field and aim to minimize turns, which not only increase work time but also soil compaction. Choosing tillage direction is thus an economic choice like choosing between winter and spring crops. Spring crops imply bare soils in winter and at the beginning of spring. The European Common Agricultural Policy encourages the cultivation of a catch crop in the intercropping period to prevent nitrate leaching and erosive runoff during winter. The catch crop then has to be ploughed under at the beginning of spring just before the spring crop is planted. In our case, farmers balked at

cultivating catch crops in plots with silty loam soil because ploughing this soil in the wet conditions typical of the beginning of spring generated big clods that make it impossible to obtain a suitable seedbed for the following spring crop.
Direct seeding spring crops into mulch (crop residues or cover crop) could also be an option to prevent the risk of erosion (Holland, 2004; Lobb *et al*., 2007). Farmers did not choose to test this option because this topic was burning and divided the farmers in the Tarn and Garonne department. Nevertheless, they accepted to discuss this option after the simulation of scenarios. Impacts of direct seeding in mulch system on runoff and yield sediment could indeed be compared with scenarios B2 or B3, because mulch covers soil for more than 60% as in winter cropped fields. Farmers agreed with this comparison and the beneficial impacts of direct seeding, but they claimed this option presents two major constrains: (i) it is devoted to large cropping area because it needs high cost drilling machine, and (ii) it is risky in this type of soil because results (yield and cultivation cost) are very variable/unpredictable, as observed by Ball *et al*. (1994) on imperfectly drained loamy soils.

Fields cultivate with spring crops are the main source of erosive runoff. This observation has led some mayors in France (e.g. Ettendorf in Alsace) to issue an order limiting spring crop acreage in their municipality and obliging farmers to come up with a collective cropping plan. The farmers in our study were not firmly opposed to the limitation of spring crop acreage: they were prepared to accept the resulting drop in income as a way of preventing erosive runoff. But they pointed out that a collective cropping plan was not easy to set up for several reasons. Crop history has to be taken into account in the choice of the crop, and soil fertility is not homogenous within the catchment and thus has an impact on inputs and yield. Designing a collective cropping plan thus requires discussion between neighbours. Coordination is even more difficult when farmers rent fields.

In our study, all the farmers were aware of the effect of erosion on soil fertility. Several decades after land consolidation, they see top soil has been lost from sloping fields (Bruno and Fox, 2004). However, the farmers said that they could easily (and cheaply) compensate for the annual effect of soil erosion on crop yield though fertilisation, and that they preferred to cultivate crops with high potential (i.e. maize) in downhill fields because these fields were more fertile. By the end of the study, farmers had not changed their practices or done anything to stop the process of erosion in their own fields. By using the hydrological model, the farmers learned how grass strips function. Standard grass strips bordering rivers and ditches

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preserve water quality by preventing pollution by soil sediments resulting from erosive runoff, but do not stop soil losses within fields. Stopping erosion requires reducing runoff accumulation especially in large sloping fields. In this kind of field, planting grass strips inside the field rather than on the border can prevent both erosion and water pollution by soil sediments.

Farmers' practices are based on economic choices that take into account many different issues (Greiner *et al.*, 2009). As is true for other economic agents, farmers consider short-term income before long-term income and are more likely to consider impacts that are easy to evaluate in monetary terms. Changing their practices to reduce the impact of their activities on the environment is not a priority for farmers (Marsh, 1977). CAP regulations base payment of EC subsidies upon compliance of environmental practices. Non-compliance of environmental rules is penalised by a reduction of direct subsidies to farm income. Reduction rate is fixed generally between 1 and 5%, very occasionally 20%, according to the level of fault and its intentional character (Ministère de l'Agriculture et de la Pêche, 2009). The proportion of EC subsidies into farm income varies considerably with the farming system (Blogowski and Chatellier, 2004): EC aids to farm comprise subsidy “coupled” to the production depending on its current cropping pattern (see Table 3), and decoupled income support depending its production activity in the past. Penalties are therefore different according to the part of EC subsidies in farm income. Moreover, penalties need to be compared with the economic gain resulting from the non-respect of environmental regulation.

CONCLUSION

STREAM was successfully used to simulate the impact of different agri-environmental scenarios on runoff and yield sediment in both studied sites. It could then serve as a decision support tool to design options for controlling runoff and erosion. The model framework is hence applicable in others sites, but decision rules that determine infiltration rate, and rill and interrill erosion need to be adapted to the local context by combining plot, field and catchment measurements and observations.

Using a hydrological model, based on spatial input data and simulated results, with farmers could be a useful way to discuss ways of preventing the impact of agriculture on the environment and to design management options of erosive runoff at the field and catchment scales. But this approach is costly and time consuming and consequently cannot be used in all catchments in a given region. However, models on selected catchments where the risk of erosive runoff is high could provide useful information for farmers, advisors, managers about designing water and soil conservation issues at the catchment scale. The selection of catchments should be based on several criteria, especially land use, slopes, plot size and soil type (IFEN, 1998; Riglos, 2005), and could be based also on the experience of local stakeholders (farmers, watershed and river managers, mayors…). Case studies at these selected sites would generate different proposals on how to control erosive runoff. These proposals, adapted to local and regional contexts, could be useful to policy makers in drawing up relevant agro-environmental measures. In this way, local district committees like in Lomagne, and chambers of agriculture, from department to region, could have major roles.

Our case study also showed that changing the cropping pattern currently used in the catchment would be at least as efficient as planting grass strips in reducing mud flows and surface water pollution. Such changes require coordination between farmers and imply that the farmers (i) are aware of the impact of their practices on the environment, (ii) are willing to change their practices, and (iii) consult their neighbours. A role-playing game developed by Souchère *et al*. (2010) pointed to the need for coordination between the different agents living in the same area: farmers, rural and urban residents, and the mayor of the commune concerned. This kind of game could also be used with farmers in a typical catchment to simulate current runoff situations and to test different solutions to prevent erosion and surface water pollution. According to Prager and Freese (2009), results of simulations with stakeholders directly concerned by agro-environmental policy could then be used to draw up official regulations at regional scale.

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Table 1: Decision table for evaluating infiltration rate and sediment concentrations in runoff from silty loam soils with low clay and organic matter contents, with soil surface roughness set at 1-2 cm, for a typical 25 mm spring rainfall event with a previous rainfall of 10 mm and a maximum rainfall intensity of 40 mm.h^{-1}.

Table 2: Simulated runoff and sediment yields for each scenario at site A (A0, A1, A2; 41 ha) and at site B (B0, B1, B2, B3; 107 ha).

Table 3: Gross income, CAP subsidy, production costs (excluding cost of harvest), and average yield and price of winter (wheat and rape) and spring (maize and sunflower) crops in the Midi-Pyrénées region (*Midi-Pyrénées* Chamber of Agriculture, 2006).

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Table 1

Land use	Vegetation cover	Soil surface crusting	Infiltration rate (mm.h^{-1})	Sediment concentration (g.L^{-1})
Spring crop	< 20%	transitional crust	5	5
Winter crop	> 60%	transitional crust	10	2
Grassland or set-aside	> 60%	structural crust	20	5
Forest	> 60%	fragmentary	50	0

(fragmentary stage: initial fragmentary structure with all fragments clearly distinguishable; structural crust: altered fragmentary state with local structural crust; transitional crust: generalized structural crust with local appearance of depositional crust)

Table 2

Scenario	Runoff volume (m^3)	Sediment yield (tons)
A0	3116	335
A1	1677	248
A2	1761	206
B0	3249	241
B1	1508	112
B2	2524	131
B3	232	9

Table 3

	Yield (tons.ha^{-1})	Price (€.ton^{-1})	Costs (€.ha^{-1})	CAP subsidy (€.ha^{-1})	Gross income (€.ha^{-1})
Irrigated maize	10.57	109.18	619	490	1025
Sunflower	2.17	215.21	226	300	541
Rape	2.99	187.29	352	300	508
Wheat	5.99	104.51	308	300	618

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Figure 1: Location of the two study sites in the *Tarn et Garonne* Department of France.

Figure 2: Landscape features and cropping pattern in 2009 on the hillside at site A (a) and site B catchment (b). The original land use corresponds to scenario 0 for each site (denoted A0 and B0).

Figure 3: Scenarios A1 (a; grass strips along ditches) and A2 (b; grass strips at mid-slope) with the actual cropping pattern of site A.

Figure 4: Scenarios B1 (a; grass strips or grassland along river and ditches and actual cropping pattern of site B), B2 (b; cropping pattern with reorganisation of spring and winter crops), and B3 (c; cropping pattern with winter crops only).

Figure 5: Map of simulated total runoff accumulation (in m^3; a) and total sediment yield accumulation (in metric tons; b) for scenario A0 (each figured "gray" cells of 25 square metres carried more than 8 m^3 water runoff and 40 kg soil sediment).

Figure 6: Map of simulated total runoff accumulation (m^3; a) and total sediment yield accumulation (in metric tons; b) for scenario B0 (each figured "gray" cells of 25 square metres carried more than 8 m^3 water runoff and 40 kg soil sediment).

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Figure 1

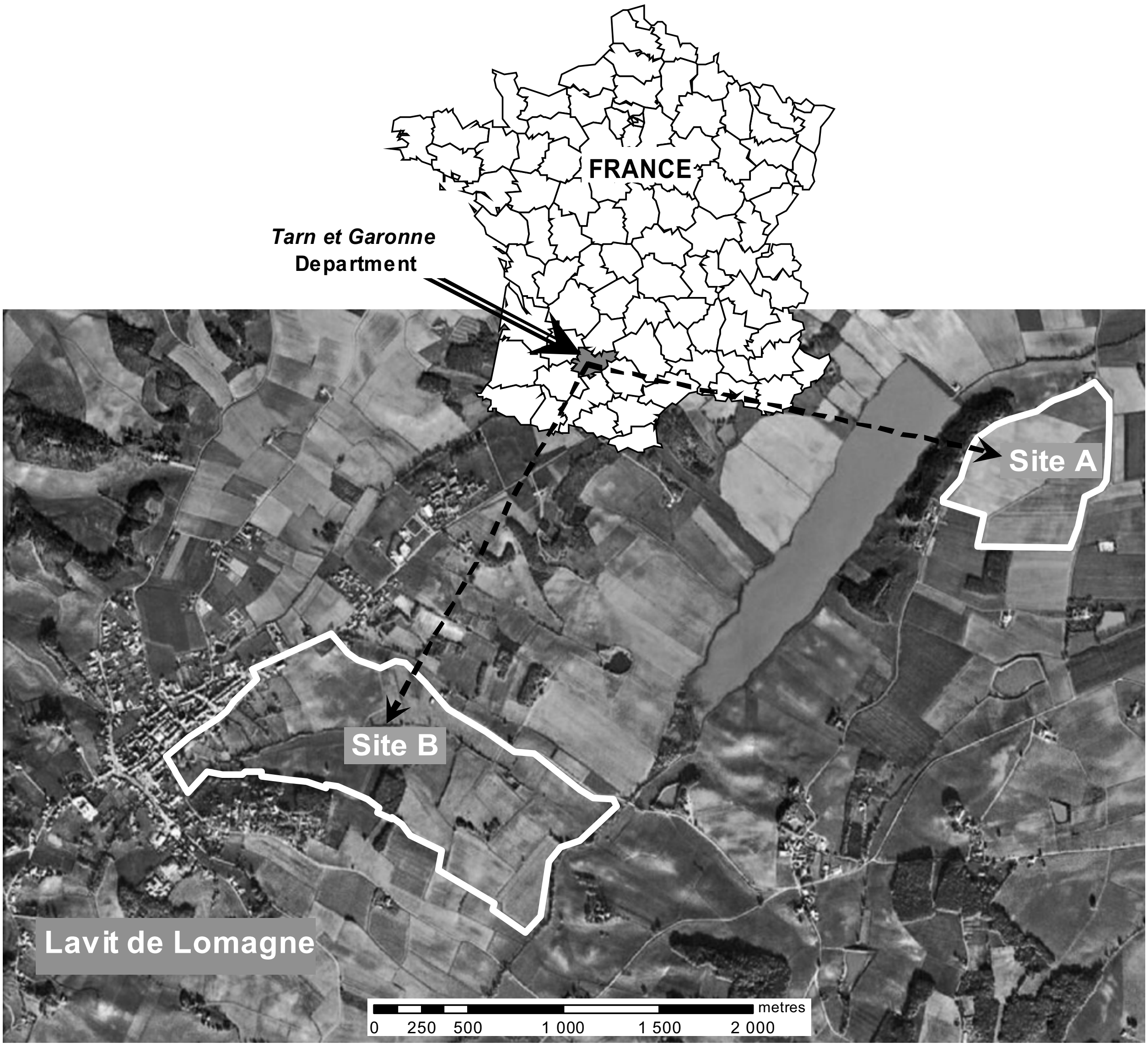
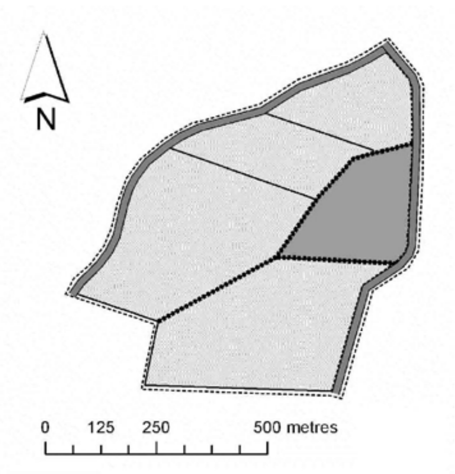


Figure 2

a) site A



b) site B

Author- produced version ot the article published in Journal of Environmental Management, 2011, 96,76-85.
The original publication is available at http://www.sciencedirect.com
doi : 10.1016/j.jenvman.2011.11.001

Figure 3

a) A1

b) A2

Author- produced version ot the article published in Journal of Environmental Management, 2011, 96,76-85.
The original publication is available at http://www.sciencedirect.com
doi : 10.1016/j.jenvman.2011.11.001

Figure 4

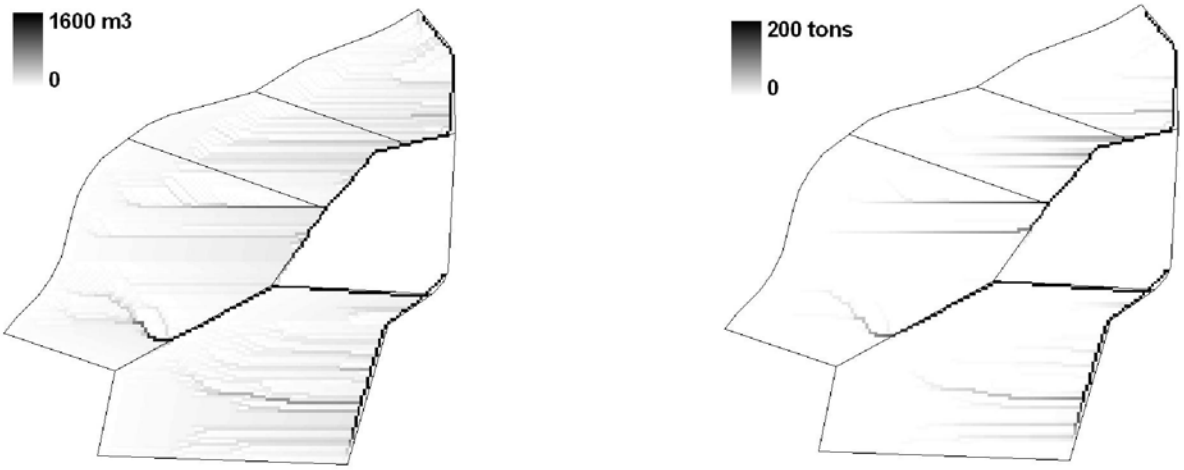
a) B1

b) B2

c) B3

Author- produced version ot the article published in Journal of Environmental Management, 2011, 96,76-85.
The original publication is available at http://www.sciencedirect.com
doi : 10.1016/j.jenvman.2011.11.001

Figure 5

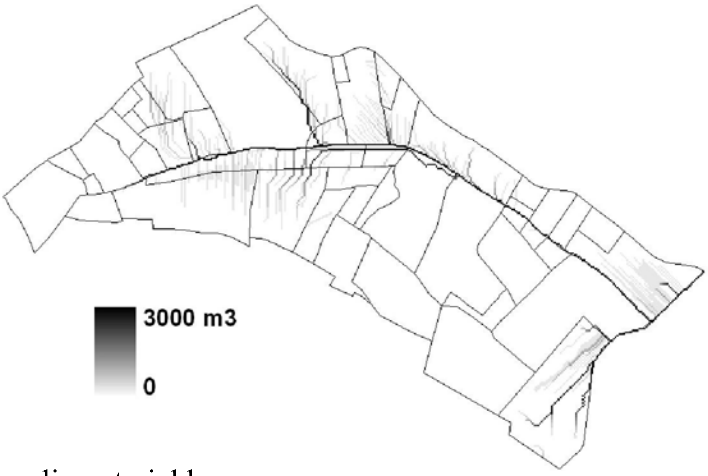


a) runoff

b) sediment yield

Figure 6

a) runoff



b) sediment yield