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

4
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12

13 ABSTRACT

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

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

31 STREAM simulations showed that a 40 mm spring rainfall with current cropping patterns led
32 to 3116 m³ total water runoff and 335 metric tons of sediment yield at site A, and 3249 m³
33 and 241 metric tons at site B. Grass strips implementation could reduce runoff for about 40%
34 and sediment yield for about 50% at site A. At site B, grass strips could reduce runoff and

35 sediment yield for more than 50%, but changes in cropping pattern could reduce it almost
36 totally.

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

43

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

46

47 1. INTRODUCTION

48

49 Conflicts between agricultural production and environmental quality have grown steadily in
50 recent decades due to the negative impacts of agriculture on the environment and particularly
51 on water quality. Currently there is concern about the sustainability of conventional land-use
52 practices on arable land throughout the world (Stoate *et al.*, 2009). From the 1960s on,
53 policies in most European countries aimed at developing intensive agriculture. Increasing
54 yields required mechanisation and the use of fertilizers and pesticides. At the same time,
55 reducing costs was encouraged by the creation of big farms and land consolidation (Robert,
56 2000). As a result, environmental problems such as runoff, erosion and water pollutions began
57 to occur (Nearing *et al.*, 2005; Toy *et al.*, 2005). The consequences are of concern to the local
58 authorities which have to face property damages induced by soil-laden water, road clearance
59 and watercourse pollution both by sediments and agricultural chemicals (Papy and Douyer,
60 1991; Boardman *et al.*, 1994).

61 Over the past 20 years, monitoring of surface water and groundwater in Europe revealed
62 significant nitrate and pesticide contamination, mainly in France, where samples of surface
63 water often exceeded the drinking water limits of 0.1 µg pesticides per litre (Water
64 Framework Directive, European Community decree 2000/60/EC). For example, the *Comité*
65 *de Bassin Adour-Garonne* (2004) pointed out that 96% of surface water in the Department
66 *Tarn and Garonne* (south-western France) was contaminated by nitrates, phosphorus and
67 pesticides, partially because erosive runoff in cultivated fields. Moreover, Probst (1985)

68 reported total phosphorus concentration at 0.5 mg.L^{-1} in surface waters, and nitrate
69 concentration from 60 to 130 mg.L^{-1} in subsurface waters according to the season.

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

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

90 The first way to prevent water pollution by agricultural practices is to reduce the source of
91 pollution, by choosing the right pesticide type, reducing application rates and improving
92 spraying efficiency. The second way is to reduce the transport of pollutants in runoff, in
93 solution or attached to sediments caused by erosion (Aubertot et al., 2007). This involves
94 changing land use to reduce runoff or planting grass strips downstream the agricultural fields
95 to filter runoff before it reaches the water system. Many authors have shown how grass strips
96 can prevent pollution of surface water. Grass vegetation planted at the downstream edge of
97 sloping field reduce runoff volume and velocity, by increasing hydraulic roughness of the soil
98 surface, and subsequently by improving the infiltration rate (Le Bissonnais *et al.*, 2004; Borin
99 *et al.*, 2005; Deletic and Fletcher, 2006). Decreasing flow volume and velocity lead to
100 sediment deposition as a result of decreased transport capacity (Wu *et al.*, 1999; Järvelä,
101 2002; Wilson *et al.*, 2005). Barfield *et al.* (1979) and Dillaha *et al.* (1989) mentioned that

102 sediment trapping can be substantial as long as the flow is shallow and uniform and the filter
103 is not submerged. Gumiere *et al.* (2011) reported that grass strips remove sediments and
104 pollutants from runoff by filtration, deposition, infiltration, adsorption, absorption,
105 decomposition, and volatilization.

106 In France, CORPEN (a collaborative organization gathering specialists from public
107 authorities and private organisations involved in agriculture and water protection) published
108 guidelines on how to identify the best locations for grass strips within catchments (CORPEN,
109 1997, 2003). Based on these guidelines, official French regulations were drawn up to
110 encourage farmers to establish PPC, including grass strips. According to French decree 2009-
111 499 April 30, 2009, which took effect in 2010, the total surface area of PPC in each farm must
112 be at least 3% of the annual cropped area. PPC or grass strips must be planted within fields,
113 most importantly those bordering rivers, the strips must be between 5 to 10 m wide and must
114 cover at least 500 m². These regulations apply at farm or field scale but do not account for the
115 hydrological processes at catchment scale. For example, the regulation concerning the width
116 of the grass strip does not take into account the size of the upper runoff area that induces the
117 quantity of runoff flow which have to be filtered (CORPEN, 1997). Moreover, ditches that
118 collect runoff water and flow into rivers will not be protected unless they are considered by
119 authorities as “water courses”.

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

130 Getting stakeholders actively involved in AEM implementation can be an efficient way to
131 proceed to design relevant, applicable and acceptable agri-environmental policy (Prager and
132 Freese, 2009; Roe García and Brown, 2009). In this way, the use of hydrologic models can
133 then help farmers collectively evaluate the impacts of their agricultural practices at the
134 catchment scale, and see which practices or protective measures are the most effective. To
135 support a participatory approach, Souchère *et al.* (2010) developed a role-playing game based

136 on STREAM to raise the awareness of the different stakeholders (the mayor, farmers, rural
137 and urban residents) about erosive runoff and the possibility of collective action.

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

149

150 2. MATERIAL AND METHODS

151

152 2.1 Study sites

153

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

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

169 vegetation cover) during this time period. These pedoclimatic conditions are common in
170 Southern Europa.

171 In collaboration with the local farmers, we selected two sites to (Fig. 1). The first site (site A;
172 43° 58' N, 0° 58' E) is a 41-ha hillside with slopes ranging from 0 to 15% comprising five
173 large fields cultivated by two farmers. In 2009, 36 ha were used for spring crops (maize and
174 sunflower) and 5 ha for winter wheat crop (Fig. 2a). The farmers suggested this site to study
175 how to reduce erosion because spring storm on just planted spring crops causes mud flows
176 that cover the downhill road nearly every year. The second site (site B; 43° 57' N, 0° 56' E) is
177 a small 107-ha catchment that supplies the Serre River and comprises 40 fields cultivated by
178 five farmers. This site is characterised by a steep-sided upstream valley with strong slopes
179 (more than 15%) followed by a relatively flat valley (slope between 0 and 5%). In 2009, five
180 main crops were cultivated (Fig. 2b): winter crops (wheat, barley and rape) on 43% of the
181 area, spring crops (maize, sunflower and sorghum) on 41%, grasslands account for 12% of the
182 area mainly in the upper basin, while forest and set-aside land account for less than 4% of the
183 area.

184

185 2.2 STREAM: hydrological model to simulate runoff and erosion

186

187 STREAM is an expert-based model of runoff and erosion at the field/small catchment scale
188 and at the rainfall event scale (Cerdan *et al.*, 2002a & b). It is spatially distributed and was
189 developed under the ArcGis platform in the ArcObject language. This model is based on the
190 basic hypothesis that soil surface properties are the major controlling factors for water runoff
191 and soil erosion/redistribution processes in agricultural landscapes. Surface characteristics
192 include soil roughness, surface crusting and vegetation cover evaluated at the field scale. It
193 takes into account (i) the effects of soil surface characteristics (surface roughness and
194 crusting) and vegetation cover to compute infiltration rates and soil surface erosion using
195 expert rules, and (ii) tillage direction and landscape features (e.g. ditches, hedges, roads,
196 developed sites) to build the runoff circulation network (Le Bissonnais *et al.*, 1998). Input
197 data are topography, field pattern and landscape features, soil surface state (roughness,
198 crusting), vegetation cover (% and type), and tillage direction determined at field scale, and,
199 characteristics of the rainfall event (amount, duration and maximum intensity) and previous
200 rainfall amount. In addition, STREAM model uses expert rules for determining runoff and
201 erosion parameters. Moreover, STREAM has been developed to simulate the influence of
202 changes in land-use (modifying cropping pattern) or in soil tillage (tillage direction, no

203 tillage), and of introducing agri-environmental devices like grass strips (Cerdan *et al.*, 2002a
204 & b; Souchere *et al.*, 2003b). Introduction of such devices is made adding new spatial objects
205 with given infiltration capacities that replace the original ones in the fields. For instance, grass
206 strips are spatial objects that enable an infiltration rate of 50 mm.h⁻¹, as estimated by Cerdan
207 *et al.* (2002b).

208

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

$$212 \quad Bir = R - IR - (I_{\alpha} \cdot t) \quad (1)$$

213 where *Bir* is the infiltration/runoff balance (mm), *R* is the total rainfall event amount (mm), *IR*
214 is residual water soil storage capacity after the previous rainfall (mm), *I_α* is the steady state
215 soil infiltration rate (mm.h⁻¹) and *t* is the runoff event duration (h). Soil infiltration and water
216 soil storage capacity are estimated from soil surface properties using a decision table that take
217 into account the soil roughness (qualified in four classes according to the size of soil
218 aggregates), the soil surface crusting (qualified in four classes, since fragmentary structure till
219 sedimentary crust), and the vegetation cover (qualified in three classes according to the
220 percentage of soil surface covered). Moreover, the water soil storage capacity decreases with
221 an increase in the amount of previous rainfall. Consequently, the lower the residual water soil
222 storage capacity, the quicker the soil becomes saturated; and once the soil is saturated, runoff
223 occurs. Decision table for determining infiltration capacity in silty loam soils of Normandy
224 with low clay and organic matter contents was established by Cerdan *et al.* (2002a & b). Soils
225 in site A and B having similar characteristics, we applied the same rules without modification.
226 According to this decision table (Table 1), infiltration rate after previous rainfall of 10 mm
227 varies between 5 and 10 mm.h⁻¹ in site A and B according to the vegetation cover and soil
228 surface properties (soil roughness in all fields was fixed to 1-2 cm). The resulting runoff is
229 routed at the catchment scale using a classical topographic runoff model (Jenson and
230 Domingue, 1988) calculated at each pixel with a tool implemented in the ArcObject structure
231 code. The flow direction is also modified by an algorithm (Souchère *et al.*, 1998) so that
232 runoff can follow the main linear direction in the landscape, such as the ditch and tillage
233 directions in the fields. Flow accumulation at the catchment scale is calculated taking into
234 account the runoff flow network and the balance infiltration-runoff of each cell (Cerdan *et al.*,
235 2002a).

236

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

248

249 Rill erosion module is based on an empirical relationship between soil surface properties,
250 slope, simulated flow accumulation and observed rill sections as developed by Souchère *et al.*
251 (2003a). The sensitivity to rill erosion (S_{re}) is calculated as follow (Eq. 2):

$$252 \quad S_{re} = F \cdot C \cdot A \cdot S \quad (2)$$

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

$$260 \quad R_s = \rho \cdot \lambda \cdot k_s \cdot S_{re} \quad (3)$$

261 where ρ is the soil bulk density ($kg \cdot m^{-3}$), λ is the pixel dimension (m), and k_s represents a
262 calibration coefficient to estimate the rill section (m^2) on each pixel along the runoff network.

263 The resulting rill section is converted in soil loss volume on the base of the pixel dimension.

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

269

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

$$273 \quad q_r = a \cdot t^b \quad (4)$$

274 where q_r is the rainfall intensity (mm.h⁻¹), t is the duration of event (h), and a and b are
275 specific site parameters corresponding to the intensity–duration curve for the one-year return
276 period. Basing on this equation, we computed a reference rainfall event following the method
277 used by Taky et al. (2009). The resulting hyetograph corresponded to a daily spring rainfall
278 event of 25 mm, with a maximum intensity of 40 mm.h⁻¹ and a duration of 2 hours. The
279 previous rainfall amount (cumulated rainfall during the preceding 48 hours) was set at 10 mm.
280 According to the farmers, this type of storm event occurred almost every year. For example in
281 2009 on site A, eroded soil filled the ditches, a mudslide blocked the downhill road and a
282 bulldozer was needed to clear it, the mayor was threatening to make the farmers pay for
283 clearing the road. The sediments deposited downslope destroyed spring crop seedlings, and
284 the affected areas had to be replanted. The sediments (with adsorbed pesticides) flowed to the
285 river via a network of ditches thereby polluting surface water.

286

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

296

297 2.3 Participative approach supported by simulations with STREAM

298

299 Participatory approaches concern many situations in decision making, notably natural
300 resources management (Wondolleck and Yaffe, 2000) or integrated water resource
301 management (Pahl-Wostl et al., 2007), from local (e.g. Bécu et al., 2008) to large (e.g. De
302 Stefano, 2010) scales, and involve stakeholders with various forms: from information, to
303 consultation, to designing policy, to shared decision making (Hare *et al.*, 2003). Participative

304 approaches frequently involve the use of simulation models that provide evaluation of
305 management options (Bots and van Daalen, 2008). Here, we used the simulation STREAM
306 model as a support for a participatory approach with farmers to discuss possible ways to
307 prevent erosive runoff (and hence to avoid the risk of river pollution) at both sites. This
308 approach combined 3 steps: (i) assessing the risk of erosive runoff due to current agricultural
309 practices, (ii) testing the impact of possible changes to mitigate erosive runoff risks, and (ii)
310 discussing their feasibility. The farmers were encouraged to play an active role in the
311 decisions affecting their catchment, to interactively explore alternative practices, and to
312 discuss economic and technical constraints/assets that hinder or encourage their adoption.
313 Five meetings with farmers took place between January and June 2009. The two first
314 meetings were with the Lomagne district agricultural committee to choose the sites. Site A
315 (the hillside) was chosen because erosive runoff is severe and occurs almost every year in
316 spring. Site B (the catchment) was chosen because it is small and different crops are grown
317 there. Another important aspect was that most of the farmers (5 of 6) at the two sites agreed to
318 spend time with us working on erosive runoff and surface water pollution. The third meeting
319 in early May 2009, was spent visiting the sites with most of the farmers to record cropping
320 practices and the state of the surface soil. The fourth and fifth meetings (2 successive
321 evenings in June 2009), which all the 5 farmers attended, were spent (i) qualitatively
322 validating the simulated runoff network, (ii) building scenarios for the two sites including
323 alternative locations of grass strips and/or changes in cropping patterns, and (iii) analysing the
324 simulated impacts of changes.

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

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

338 For the hillside at site A, proposals concerned only the location and dimensions of grass strips
339 to prevent erosion: standard 5-m wide strips bordering ditches (scenario A1; Fig. 3a); 10-m
340 wide strips located mid-slope in the fields where slopes are steepest (scenario A2; Fig.3b).
341 None cropping option (replacing spring by winter crops) were tested at site A because farmers
342 did not choose to test it and we prefer to keep it for site B. Four ideas were discussed for the
343 catchment at site B. The first was to cultivate grassland (or create set-aside land) in the form
344 of one long narrow field bordering the river to collect runoff from upstream fields; the second
345 was to plant standard grass strips bordering rivers and ditches. These two proposals were
346 combined with existing cropping patterns in scenario B1 (Fig. 4a). The third and fourth
347 proposals concerned changes in the cropping pattern. In scenario B2 (Fig. 4b), a cropping
348 pattern with redistribution of spring and winter crops within the watershed was combined
349 with the first proposal. In scenario B3, all cropped fields were changed to winter crops (Fig.
350 4c).

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

356

357 3. RESULTS

358

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

368

369 3.1. Reducing erosive runoff on the hillside at site A

370

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

379
380 Planting 5m width grass strips bordering ditches and roads (scenario A1) reduced runoff by
381 about 46% and sediment yield by 26% (Table 2). Runoff and erosion were not prevented in
382 the fields, but grass strips partially retained the flows of water and sediments before they
383 reached the ditches. When 10-m wide grass strips were planted where the slope was steepest
384 or at mid-slope in the fields (scenario A2), runoff was reduced by 43%, and sediment yield by
385 39%. Scenario A2 was thus more efficient than scenario A1 for preventing to mud flows on
386 the road, and soil losses in the fields were also reduced. Efficiency of grass strips depend
387 therefore on its location: (i) grass strip has better efficiency when it is located on runoff flow
388 pathway; (ii) it enable soil sedimentation when it is located downstream (by filtering the
389 runoff water highly concentrated with soil sediment); (iii) it prevent from soil wrenching
390 when it is located upstream (by reducing/slowing down the runoff flow).

391
392 Farmers are already used to planting grass strips as shown in scenario A1. They agreed that
393 grass strips had a beneficial impact on runoff and on the simulated results of scenario A1, but
394 said that sediments accumulated in the grass strip and did not want to install wider ones.
395 Planting a grass strip means reducing the size of field and, in addition, creates a problem
396 because tractors are not allowed on the strip to prevent soil compaction, which decreases
397 infiltration rate. Most of the farmers (3 of 5) did not like scenario A2. Planting grass strips in
398 the middle of fields is thus more problematic than at the edge. What is more, most farmers
399 initially failed to understand how grass strips planted mid-slope could reduce erosive runoff.
400 One farmer provided the explanation: due to the slope, water flows faster and planting grass
401 strips in the field slows runoff down before it becomes erosive.

402

403 3.2. Reducing runoff in the catchment at site B

404

405 With the existing cropping pattern and soil surface state (scenario B0), total simulated runoff
406 volume reached 3249 m³ and 241 metric tons of soil were lost (Table 2). Like for site A,
407 farmers confirmed the pathways of the main simulated runoff flows (Fig. 6) compared well
408 with flows in their fields. Especially, runoff accumulation in fields on the right river bank in
409 the western part of the catchment (see Fig. 6a), explained why two farmers had decided to use
410 them as set aside land or grassland. Nevertheless, one field, cultivated by a third farmer, was
411 still being cultivated with sorghum (a spring crop). Moreover, the upstream basin (western
412 from set aside field long the river) produced about the half of total sediment yield (see Fig.
413 6b). Taking into account the area of site B (107 ha), these total amounts corresponded to 30
414 m³ of water and 2 tons of soil per hectare, i.e. 2.5 and 4 times less than in site A. Greater
415 proportion of covered soil and also weaker average slope in site B explained this difference.

416
417 A map was created identifying fields that contributed most to runoff along with those that
418 collected runoff. By comparing figure 6a (runoff pathways) and figure 2b (existing cropping
419 pattern and land use), farmers concluded that the main runoff started in fields planted with
420 spring crops and the reasons were discussed collectively. In fields that are cultivated in spring,
421 vegetation covers less than 20% of the soil surface. When intense rainfall strikes unprotected
422 soil with low structural stability, runoff occurs, and when runoff accumulates on bare soil,
423 erosion occurs. Soil sediments transported by runoff then pollute the river. Conversely,
424 grassland and winter crops do not generate runoff and help slow down water flows from
425 uphill fields. Winter crops completely cover the soil surface thus protecting it from the
426 raindrops. Heavy vegetation slows down water flows and improves infiltration.

427
428 In scenario B1, except in grassland and set aside fields, grass strips were planted bordering
429 the rivers, in accordance with official regulations. This resulted in a reduction of more than
430 50% in runoff and sediment yield (Table 2). The sloping upstream basin at site A contributed
431 a lot in the total sediment yield (see sediment yield pathway on fig. 6b). Installation of grass
432 strips on the left bank and grassland on the right bank of the river in the upstream basin
433 resulted in a strong reduction of sediment yield. For the farmers, this result confirmed the
434 usefulness of grass strips in protecting rivers from pollution. However, official regulations do
435 not make it obligatory to plant grass strips in small fields, of which there were many on both
436 river banks.

437

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

455
456 In scenario B3, all the fields were well covered by vegetation of winter crops, and runoff and
457 erosion almost completely stopped (Table 2). However, the farmers did not agree with this
458 cropping plan because it would lead to a major reduction in their income: in 2005, the income
459 from maize and sunflower ranged from €541 to €1025 per hectare, while the income from
460 winter wheat and rape ranged from €508 to €618 per hectare (Table 3). But this income
461 depends also on prices of agricultural products that can strongly vary between years (for
462 instance, prices in 2007 was about the double). In addition, farmers confirmed that alternating
463 spring and crops enabled better pest and weed control (Macé *et al.*, 2007). In fact they only
464 accepted trying this scenario to evaluate its impact on runoff and erosion. As the results of the
465 simulation demonstrated the major impact spring crops have on erosion, the farmers were
466 willing to discuss this drastic solution in catchments where erosion is a very serious
467 constraint.

468

469 IV DISCUSSION

470

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

483 Mapping land use, cropping patterns, and simulation results were the key points to engage
484 with farmers. All discussions among the farmers were based on the maps that were created to
485 validate runoff pathways and to locate grass strips and crops. This confirms that geographical
486 information systems (GIS) are a good support for participatory approaches in many sectors, as
487 reported by many authors (e.g. Repetti and Prélaz-Droux, 2003; De Freitas and Tagliani,
488 2009; Jankowski, 2009; Lagabriele *et al.*, 2010).

489
490 Most farmers are aware that their practices have an impact on the environment, especially on
491 water quality and quantity, but not all of them are ready to change (Michel-Guillou and
492 Moser, 2006). In our case, the farmers knew that bare soil and along-slope tillage increase the
493 risk of erosion. We did not try to test the effect of changing the direction of tillage because (i)
494 our model had not been validated for it, and (ii) because farmers did not want to change
495 tillage direction in sloping fields as across-slope tillage is impossible and even dangerous
496 (risk of overturn) when slope exceeds 10%. Nevertheless, it is a fact that in downslope and
497 less steep fields, across-slope tillage slows downhill runoff (Basic *et al.*, 2001). Despite this
498 knowledge, farmers base their choice on the geometry of the field and aim to minimize turns,
499 which not only increase work time but also soil compaction. Choosing tillage direction is thus
500 an economic choice like choosing between winter and spring crops. Spring crops imply bare
501 soils in winter and at the beginning of spring. The European Common Agricultural Policy
502 encourages the cultivation of a catch crop in the intercropping period to prevent nitrate
503 leaching and erosive runoff during winter. The catch crop then has to be ploughed under at
504 the beginning of spring just before the spring crop is planted. In our case, farmers balked at

505 cultivating catch crops in plots with silty loam soil because ploughing this soil in the wet
506 conditions typical of the beginning of spring generated big clods that make it impossible to
507 obtain a suitable seedbed for the following spring crop.

508 Direct seeding spring crops into mulch (crop residues or cover crop) could also be an option
509 to prevent the risk of erosion (Holland, 2004; Lobb *et al.*, 2007). Farmers did not choose to
510 test this option because this topic was burning and divided the farmers in the Tarn and
511 Garonne department. Nevertheless, they accepted to discuss this option after the simulation of
512 scenarios. Impacts of direct seeding in mulch system on runoff and yield sediment could
513 indeed be compared with scenarios B2 or B3, because mulch covers soil for more than 60%
514 as in winter cropped fields. Farmers agreed with this comparison and the beneficial impacts of
515 direct seeding, but they claimed this option presents two major constrains: (i) it is devoted to
516 large cropping area because it needs high cost drilling machine, and (ii) it is risky in this type
517 of soil because results (yield and cultivation cost) are very variable/unpredictable, as observed
518 by Ball *et al.* (1994) on imperfectly drained loamy soils.

519

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

530

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

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

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

559

560 CONCLUSION

561

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

568 Using a hydrological model, based on spatial input data and simulated results, with farmers
569 could be a useful way to discuss ways of preventing the impact of agriculture on the
570 environment and to design management options of erosive runoff at the field and catchment
571 scales. But this approach is costly and time consuming and consequently cannot be used in all
572 catchments in a given region. However, models on selected catchments where the risk of

573 erosive runoff is high could provide useful information for farmers, advisors, managers about
574 designing water and soil conservation issues at the catchment scale. The selection of
575 catchments should be based on several criteria, especially land use, slopes, plot size and soil
576 type (IFEN, 1998; Riglos, 2005), and could be based also on the experience of local
577 stakeholders (farmers, watershed and river managers, mayors...). Case studies at these
578 selected sites would generate different proposals on how to control erosive runoff. These
579 proposals, adapted to local and regional contexts, could be useful to policy makers in drawing
580 up relevant agro-environmental measures. In this way, local district committees like in
581 Lomagne, and chambers of agriculture, from department to region, could have major roles.
582 Our case study also showed that changing the cropping pattern currently used in the
583 catchment would be at least as efficient as planting grass strips in reducing mud flows and
584 surface water pollution. Such changes require coordination between farmers and imply that
585 the farmers (i) are aware of the impact of their practices on the environment, (ii) are willing to
586 change their practices, and (iii) consult their neighbours. A role-playing game developed by
587 Souchère *et al.* (2010) pointed to the need for coordination between the different agents living
588 in the same area: farmers, rural and urban residents, and the mayor of the commune
589 concerned. This kind of game could also be used with farmers in a typical catchment to
590 simulate current runoff situations and to test different solutions to prevent erosion and surface
591 water pollution. According to Prager and Freese (2009), results of simulations with
592 stakeholders directly concerned by agro-environmental policy could then be used to draw up
593 official regulations at regional scale.

594

595

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602

603

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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).

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

Figure 1: Location of the two study sites in the Tarn Valley (Cahors Department of France).

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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).

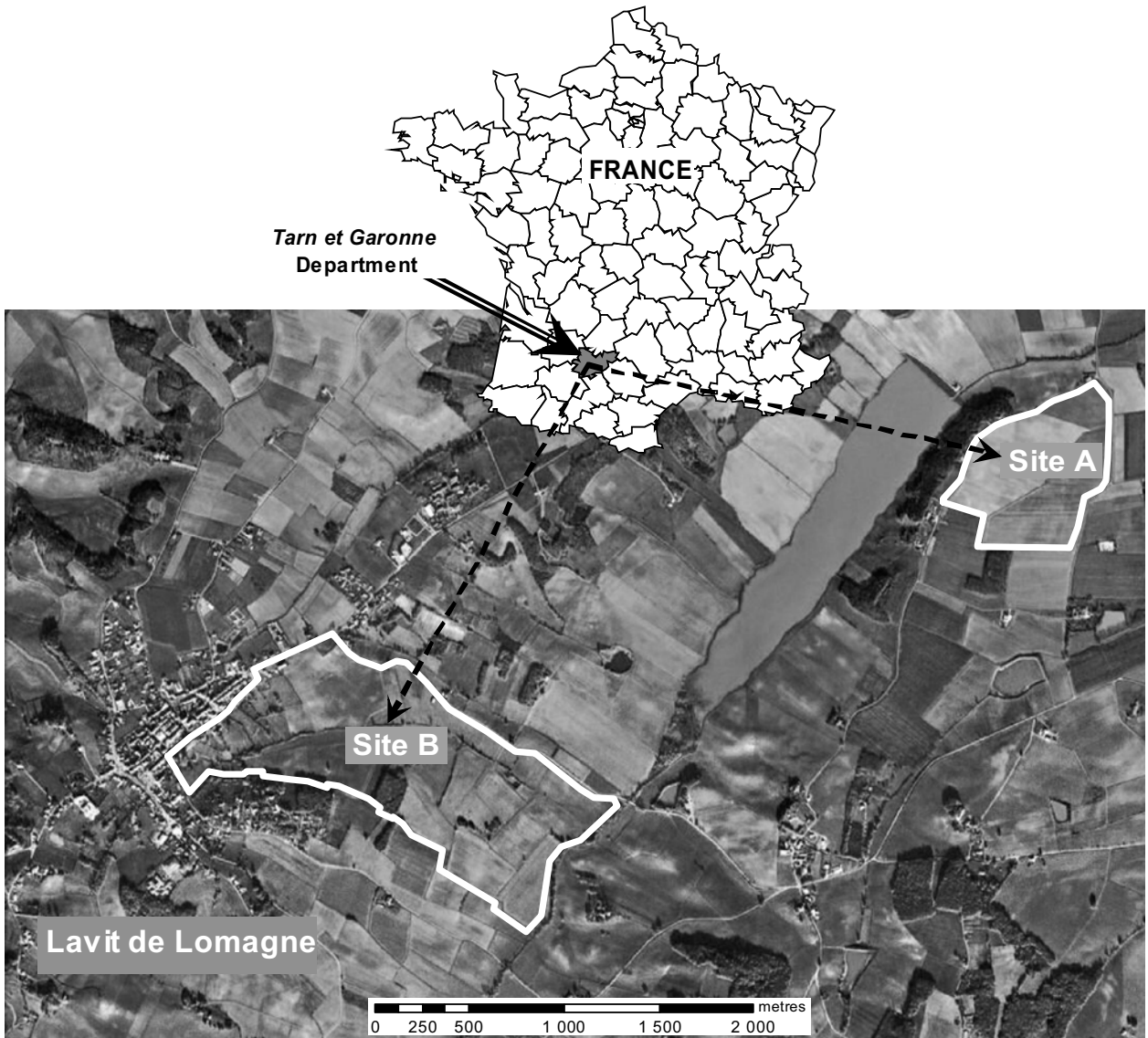
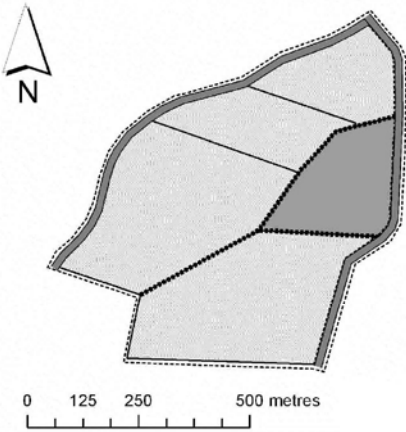


Figure 2

a) site A



b) site B



Figure 3

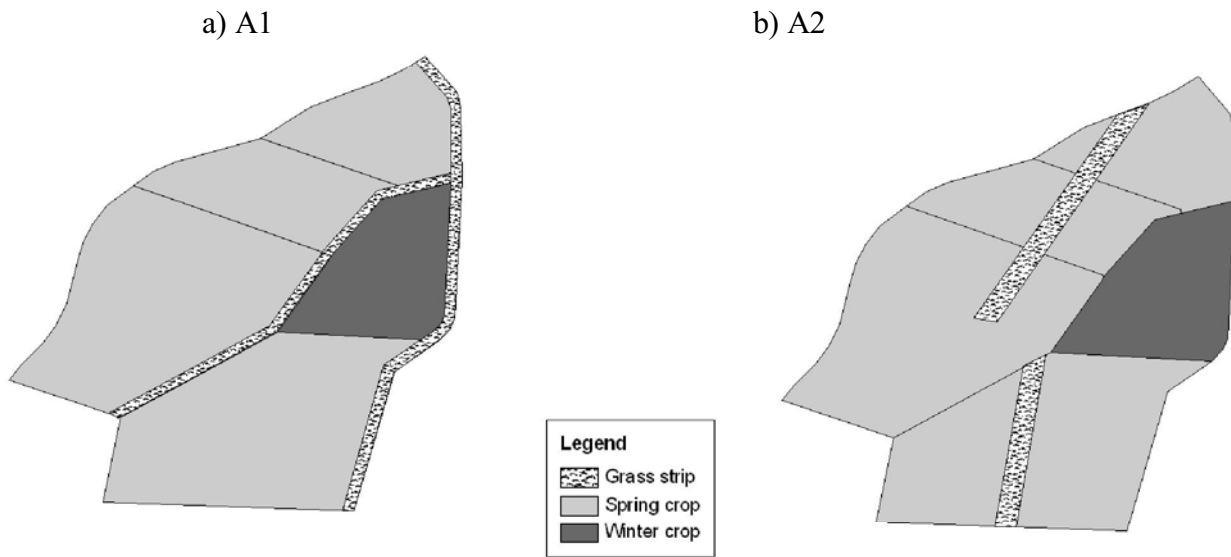


Figure 4

a) B1



b) B2



c) B3



Figure 5

a) runoff



b) sediment yield



Figure 6

a) runoff



b) sediment yield

