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Sediment delivery processes and chemical transport in a small forested basin

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Abstract Because the properties of eroded soil affect the deposition phenomena and transport capacity of chemical materials by eroded particles, recent research is trying to link the grain-size distribution of the eroded sediment to that of the original soil in order to explain the enrichment of chemical content of the sediment with the respect to the parent soil. In this study, the spatial distribution of nitrogen, phosphorus and total organic carbon was firstly deduced using the measurements carried out in 47 soil samples distributed over a forested basin together with a kriging interpolation method. Then the load of each chemical was calculated at morphological unit and basin scales using the above-mentioned spatial distributions and sediment yield values calculated by the SEDD (SEdiment Delivery Distributed) model, which couples the universal soil loss equation with a spatial disaggregation criterion of sediment delivery processes. Finally, at basin scale, a new expression of the enrichment ratio of a given chemical was applied.

Key words chemical enrichment ratio; chemical transport; experimental basin; forested basin; geographical information systems; sediment yield; soil erosion; universal soil loss equation

Processus de production sédimentaire et transport chimique dans un petit bassin versant forestier

Résumé Puisque les propriétés d'un sol érodé conditionnent les processus de dépôt et la capacité de transport d'éléments chimiques par les particules érodées, une recherche récente essaye de mettre en relation la distribution granulométrique du sédiment érodé avec celle du sol originaire pour expliquer l'enrichissement du contenu chimique du sédiment par rapport au sol originaire. Dans cette étude, la distribution spatiale de l'azote, du phosphore et du carbone organique total a été initialement déduite de mesures effectuées sur 47 échantillons de sol répartis sur un bassin versant forestier et grâce à une méthode d'interpolation par krigeage. Ensuite, la charge de chaque élément chimique a été calculée aux échelles de l'unité morphologique et du bassin versant en utilisant les distributions spatiales préalablement mentionnées ainsi que les valeurs d'apports solides calculées par le modèle SEDD (Sediment Deliery Distributed) qui couple l'équation universelle de perte de sol et un critère de désagrégation spatiale des processus de production sédimentaire. Finalement, à l'échelle du bassin versant, une nouvelle expression du rapport d'enrichissement en un élément chimique donné a été appliquée.

Mots clefs rapport d'enrichissement chimique; transport chimique; bassin versant expérimental; bassins versant forestier; systèmes d'information géographique; apports solides; érosion du sol; équation universelle de perte de sol

INTRODUCTION

Soil erosion causes loss of soil fertility by a direct loss of the topsoil and of plant nutrients (Palis *et al*., 1990a). In soils most chemicals are adsorbed by clay and organic matter because of their high surface area, leading to the formation of strong adsorption bonds (Novotny & Chesters, 1989). When rainfall reaches the surface horizon of the soil, some chemicals are desorbed and go into solution while others remain adsorbed and move with the soil particles. The clay fraction of the eroded sediment is the site for

most nutrient and chemical adsorption (Young & Onstad, 1976; Frere *et al*., 1977). The capacity of transported particles to carry chemicals is closely related to their specific surface area, which is in turn largely dependent on the clay content of the transported particles and aggregates.

The relationship between the grain-size distribution of the eroded sediment and the original soil helps to explain the increase, or *enrichment*, in a chemical content of the sediment with respect to the parent soil. Clay soils are dominated by aggregates, whereas non-cohesive soils are usually constituted by primary particles (Cogo *et al*., 1983). Soil structure strongly influences sediment yield and the loss of chemicals that are transported in eroded sediments (Palis *et al*., 1990b); aggregational characteristics of soil particles also affect hillslope sediment transport and delivery processes.

The *enrichment concept* is currently applied to clay, organic matter, and all chemicals adsorbed by soil particles, such as nitrogen and phosphorus (Young *et al*.,1986). This concept is expressed using the *enrichment ratio* defined as the content of a given soil or chemical fraction in sediment divided by the content of that fraction in an equal mass of soil (Novotny & Chesters, 1989; Di Stefano & Ferro, 2002; Lemunyon & Daniel, 2002).

During the delivery processes the texture of the eroded sediment changes and can be enriched in the fine fractions (Walling, 1983). Enrichment of sediment by clays can be considered a two-step process: enrichment due to particle entrainment and to re-deposition of coarser particles (Novotny & Chesters, 1989).

Particle selectivity within the erosion process can occur because inter-rill flows do not have sufficient energy to transport many of the larger particles and because aggregates are preferentially deposited on the hillslopes. However, particle selectivity is unlikely when rill erosion dominates because of the efficient removal of sediments from rills (Meyer *et al*., 1975). Stability of aggregates during sediment transport (Meyer *et al*., 1992) and basic mechanisms of aggregate breakdown (Le Bissonais, 1990) have to be considered to account for the particle size selectivity of sediment transport. Generally aggregates progressively break down into smaller aggregates of greater stability. The aggregate breakdown mechanisms associated with erosion processes result in detached particles generally being easily-transportable elementary particles and small aggregates, so that the subsequent sediment transport across the hillslopes will be primarily controlled by the overland flow transport capacity (Di Stefano & Ferro, 2002). The clay-sized particles, carried by flow as elementary particles and microaggregates, can be expected to move through the conveyance system (hillslopes and channel network) without deposition (Di Stefano *et al*., 2000).

However, there have been few attempts to assess the grain-size distribution of the sediment moving through the delivery system of an active drainage basin. Recently, Slattery & Burt (1997) compared the effective and the ultimate particle size distribution of sediment collected during 11 rainfall–runoff events. They concluded that for increasing discharges the sediment load generally becomes finer and less well aggregated, probably due to increased turbulence of hillslope flow which in turn influences aggregate breakdown. Slattery & Burt (1997) established that most of the clay seemed to move as primary particles, or at least clay-sized aggregates, both as suspended sediment in the stream and in the sediment transported by hillslope runoff.

At the basin scale, the relationship between the grain-size distribution of the eroded sediment and the source soil is also affected by the potential for selective losses

of the coarser fractions in a wide range of depositional environments associated with the transport of eroded sediment from its source to the basin outlet (Walling, 1983). Size selective deposition of the eroded sediment occurring throughout the channel network and during the transport from the hillslopes to the stream can result in sediment having a particle size distribution finer (enriched in clay) than the original soil.

The increased clay content of eroded sediment, due to particle selectivity during erosion (small particles eroded from inter-rill areas) and transport (easily-transportable clay particles and small aggregates) processes, is counteracted by the clay deposited within large aggregates during the conveyance process.

In the past, chemical enrichment of eroded sediments was often attributed to the selectivity of the erosion process for the finer fractions of the soil without taking into account that the hillslope flow could be unable to carry large and small soil aggregates including a high percentage of soil clay. Alberts & Moldenhauer (1981), carrying out measurements applying simulated rainfall on six plots, showed that nutrient enrichment occurs for all investigated size classes of eroded aggregates (2–1, 1–0.5, 0.5–0.21 and 0.21–0.05 mm), with different enrichment levels depending on the runoff transport capacity.

Since sediments and adsorbed chemicals are produced from different sources distributed throughout a drainage basin, Di Stefano *et al*. (2000) suggested that improvements in modelling chemical soil transport phenomena can be obtained by employing a spatially-distributed approach of sediment delivery processes (Richards, 1993).

The difficulties of physically-based modelling (numerous input parameters, differences between the scale of measurement of the input parameters and the scale of basin discretization, uncertainties of the selected model equations, etc.) have increased the attractiveness of a simple parametric soil erosion model, like the universal soil loss equation, USLE (Wischmeier & Smith, 1965) or its revised version, RUSLE (Renard *et al*., 1994) coupled with a Sediment Delivery Distributed (SEDD) approach (Ferro & Porto, 2000). Furthermore, at present, the physically-based models give sediment yield estimates with a reliability comparable to those obtained by the RUSLE (Bingner, 1990; Risse *et al*., 1993; Renard *et al*., 1994) coupled with a spatial disaggregation criterion of sediment delivery processes (Ferro & Minacapilli, 1995; Ferro, 1997; Ferro *et al*., 1998c; Ferro & Porto, 2000).

At the basin scale, the links between on-site erosion, soil loss from hillslopes and sediment yield at the basin outlet are still not fully understood. Since the clay fraction of the sediment arriving at the basin outlet seems to be less sensitive to aggregation processes (Slattery & Burt, 1997), the sediment delivery processes could be explained using the clay enrichment ratio *CER*, defined as the ratio between clay in sediment C_{sed} as a percentage and in the original soil C_{soil} as a percentage.

In this paper, the spatial distribution of the load of nitrogen, phosphorus and total organic carbon is deduced using the measurements carried out in soil samples taken from a small Calabrian basin, forested with a *Eucalyptus occidentalis* high forest, and following the above-mentioned procedure for estimating sediment yield.

For each chemical the analysis has been developed at morphological unit and basin scales and a new definition of the enrichment ratio of a given chemical is proposed.

EXPERIMENTAL BASIN AND MEASUREMENT TECHNIQUE

The studied area is located near Crotone (35 m a.s.l.; 39°09′02″N, 17°18′10″E) in the basin of the ephemeral Crepacuore stream, which drains to the Ionian Sea (Fig. 1). The basin, named W3, has a relief range of 13 m and a mean altitude of 114 m a.s.l. The basin area is 1.654 ha, with slopes ranging from 11 to 35%.

The basin was equipped in 1978, by a grant of the "Soil Conservation Project" of the Italian National Research Council (CNR), for studying the relevant soil erosion phenomena in the mountainous Calabrian region (Aronica & Ferro, 1997) and to monitor the effects of afforestation on hydrological response and sediment yield (Avolio *et al*., 1980; Iovino & Puglisi, 1991). The basin is presently managed by the Istituto di Ecologia and Idrologia Forestale of the National Research Council, Cosenza, Italy (Ferro *et al*., 1998d).

The basin W3 was covered with a *Eucalyptus occidentalis* high forest in the period 1968–1986; in 1986 the forest cover was coppiced. The forest cover is uniform, and the percentage of bare area is equal to 3% of the total basin area (Cantore *et al*., 1994). The basin is monitored by an H-flume weir (Brakensiek *et al*., 1979) and measurement of flow depth is carried out at the end of a rectangular channel by a mechanical

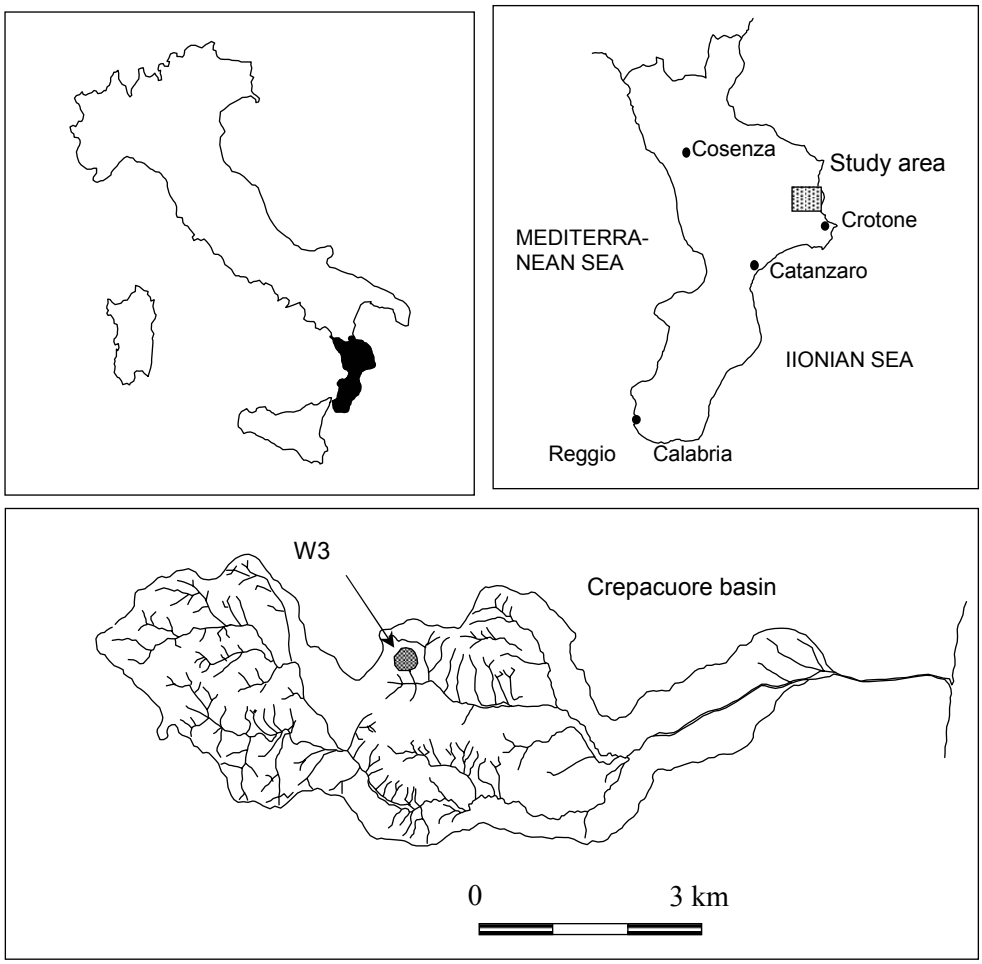

Fig. 1 Location of the experimental W3 basin.

Fig. 2 View of the H-flume weir and the Coshocton wheel.

recording water level gauge (Fig. 2). The sampling device is a Coshocton wheel (Fig. 2) (Parson, 1954; Carter & Parson, 1967) collecting a sample ($\cong 1/200$) of the flow volume. Each collected sample flows into appropriately-sized tanks. At the end of each event, the collected suspension is well mixed. One-litre suspension samples at different heights are collected, and the suspended soil content concentration in the sampled volume is determined by oven-drying at 105°C. The sediment yield of each event is calculated by the product of the mean concentration, calculated by the sediment concentration profile sampled in the tank, and the total runoff volume for the event measured by the H-flume.

The annual sediment yield is in turn calculated as the sum of the sediment loads for all rainfall events occurring during a year.

Rainfall is measured by a recording raingauge (Fig. 3) and the rainfall erosivity factor of Wischmeier & Smith (1965) is calculated for each rainfall event. Forty-two events were measured at basin W3 in the recording period 1978–1994 (Avolio *et al*., 1980; Callegari *et al*., 1994; Cantore *et al*., 1994; Cinnirella *et al*., 1998). The annual values R_a of the rainfall erosivity factor were used to estimate the mean annual value R_b equal to 52.6 t m mm ha^{-1} h^{-1}.

Soil sampling was carried out at 47 sites distributed over the basin area (Fig. 3). For each site, a subsample of 50 g of soil was used to determine the soil grain-size distribution for calculating the percentage, f, of finer particles (particle diameter d ranging from 0.002 to 0.1 mm) and the percentage, g, of coarser particles (0.1 mm < $d \leq$ 2 mm) according to the procedure of Wischmeier & Smith (1965). The percentage organic matter, h, was calculated by the total organic content which was measured by dichromatic-wet combustion (Raveh & Avnimelich, 1972). Total phosphorus was determined by perchloric acid digestion (Walker & Adams, 1958) and total nitrogen was measured by a semi-micro Kjeldahl procedure (Bremner & Mulvaney, 1982).

The soil erodibility factor K (in t ha^{-1} per unit of rainfall erosivity factor of each soil sample) was calculated by the nomograph of Wischmeier *et al*. (1971) using a structure index equal to 4 (massive/blocky) and a permeability index of 5 (slow). The on-site values of K and the kriging interpolation method (De Marsily, 1986) were used

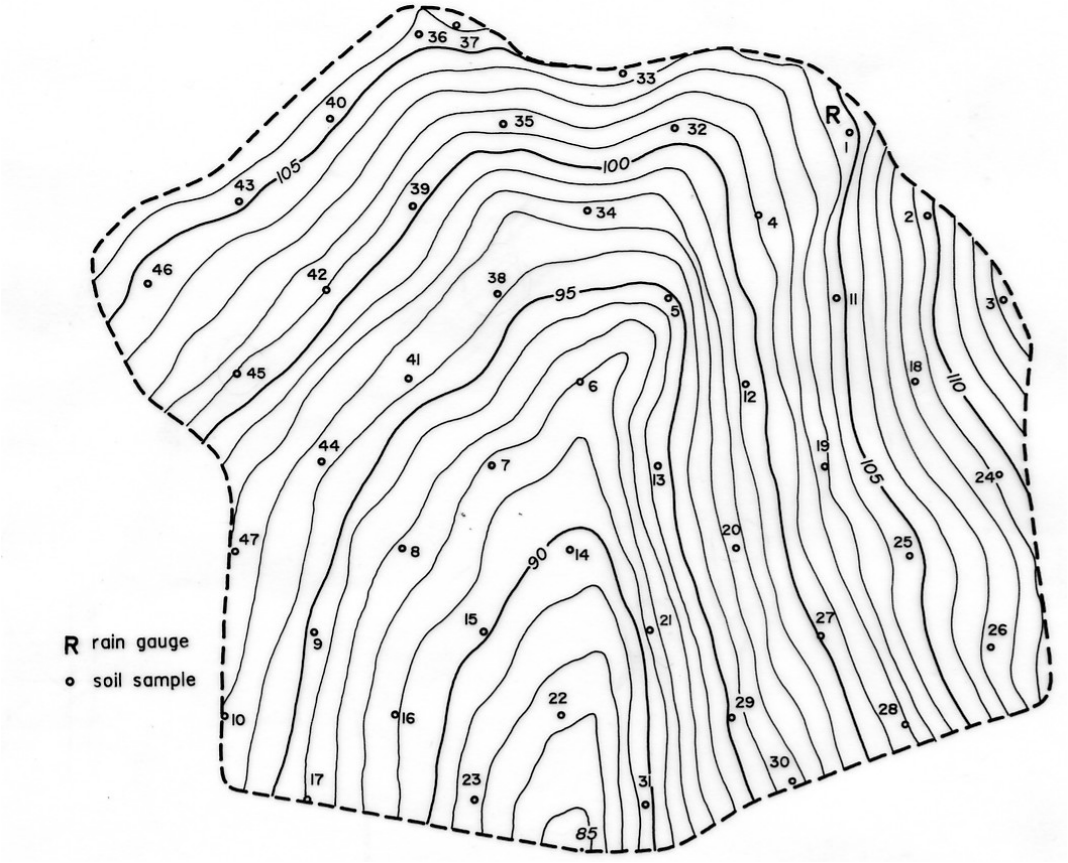

Fig. 3 The study basin showing the relief and the location of the soil sampling sites.

to map the soil erodibility spatial distribution. In particular, the GRID section of ARCInfo software facilitates the calculation of the spatial distribution of the *K* factor, such as a raster cover having a mesh size equal to 3 m.

For modelling the spatial disaggregation of sediment delivery, the basin W3 was divided into morphological units (Bagarello *et al.*, 1993; Ferro & Minacapilli, 1995) i.e. areas of clearly defined aspect, length and steepness.

For all morphological units of basin W3 the crop management factor C_i was set equal to 0.164 (Cinnirella *et al*., 1998). Conservation practices were not carried out in the experimental basin, and therefore the support practice factor of each morphological unit P_i is assumed equal to 1.

CALIBRATING THE SEDD MODEL FOR W3 BASIN

Applying a spatially-distributed strategy at the basin scale requires the choice of both a soil erosion model and a spatial disaggregation criterion for the sediment delivery processes. For modelling the within-basin variability of the hillslope sediment delivery processes, Ferro & Minacapilli (1995) proposed a sequential approach. Basically, this approach follows the sediment particle in a Lagrangian scheme and applies appropriate delivery factors to each sequential morphological unit (Novotny & Chesters, 1989; Ferro, 1997).

For a basin divided into morphological units and neglecting the channel sediment delivery component, Ferro & Minacapilli (1995) proposed to calculate the sediment delivery ratio SDR_i of each morphological unit, i, into which the basin is divided. According to Ferro & Minacapilli (1995), SDR_i depends on the travel time $t_{p,i}$ associated with the movement of eroded particles along the hydraulic pathway from the source area (a given morphological unit) to the nearest stream reach.

The analysis carried out for 13 Sicilian and two Calabrian basins (Ferro & Minacapilli, 1995; Ferro, 1997) showed that SDR_i has the following form:

$$SDR_i = \exp\left(-\beta\, t_{p,i}\right) = \exp\left(-\beta \frac{l_{p,i}}{\sqrt{s_{p,i}}}\right) = \exp\left[-\beta \left(\sum_{i=1}^{N_p} \frac{\lambda_{i,j}}{\sqrt{s_{i,j}}}\right)\right] \tag{1}$$

where β is a coefficient and N_p is the number of morphological units located along the hydraulic path j, $\lambda_{i,j}$ and $s_{i,j}$ are, respectively, length and slope of each morphological unit i located along the hydraulic path j. Taking into account Chézy's scheme, the β coefficient lumps together the effects due to roughness and runoff along the hydraulic path. Then β is affected by the roughness distribution along the hydraulic path and is time dependent, i.e. for a given basin β is dependent on the temporal scale (event, annual and mean annual) (Ferro & Porto, 2000).

According to Walling's idea (Walling, 1983) of linking the enrichment of the fine fraction to the erosion and conveyance processes, Di Stefano & Ferro (2002) demonstrated that the delivery ratio SDR_i can be also calculated using the following equation:

$$SDR_i = \frac{C_{\text{soil},i}}{C_{\text{sed}}} \tag{2}$$

in which $C_{\text{soil},i}$ is the clay content of the soil covering the morphological unit i, which has to be derived from information on the spatial distribution of the clay content of the soils covering the basin, and C_{sed} is the clay content of the sediment arriving at the basin outlet. In other words, the SEDD model using the SDR_i concept takes into account properties of both the source soil and sediment being transported in the study basin.

For calculating the sediment yield of each morphological unit Y_i, expressed in metric tons, the SEdiment Delivery Distributed (SEDD) approach, based on USLE coupled with equation (1) (Ferro *et al*.,1998a,b,c; Ferro & Porto, 2000), was applied:

$$Y_i = SDR_i\ R_t\ K_i\ L_i\ S_i\ C_i\ P_i\ S_{u,i} \tag{3}$$

in which R_t is the rainfall erosivity factor for a given temporal scale (annual R_a, mean annual R_b) of the ith morphological unit (t ha^{-1} per unit of K_i), K_i is the soil erodibility factor, L_i is the length factor, S_i is the slope factor, C_i is the crop management factor, P_i is the support factor and $S_{u,i}$ is the area (ha) of the morphological unit.

The W3 basin was divided into 34 morphological units (Fig. 4) and each polygon within the basin discretization map was digitized. The K spatial distribution was overlain onto the basin discretization map in order to calculate the soil erodibility factor K_i of each morphological unit. For each polygon, K_i is the area weighted mean of the soil erodibility factor values corresponding to all the grid cells falling within the polygon.

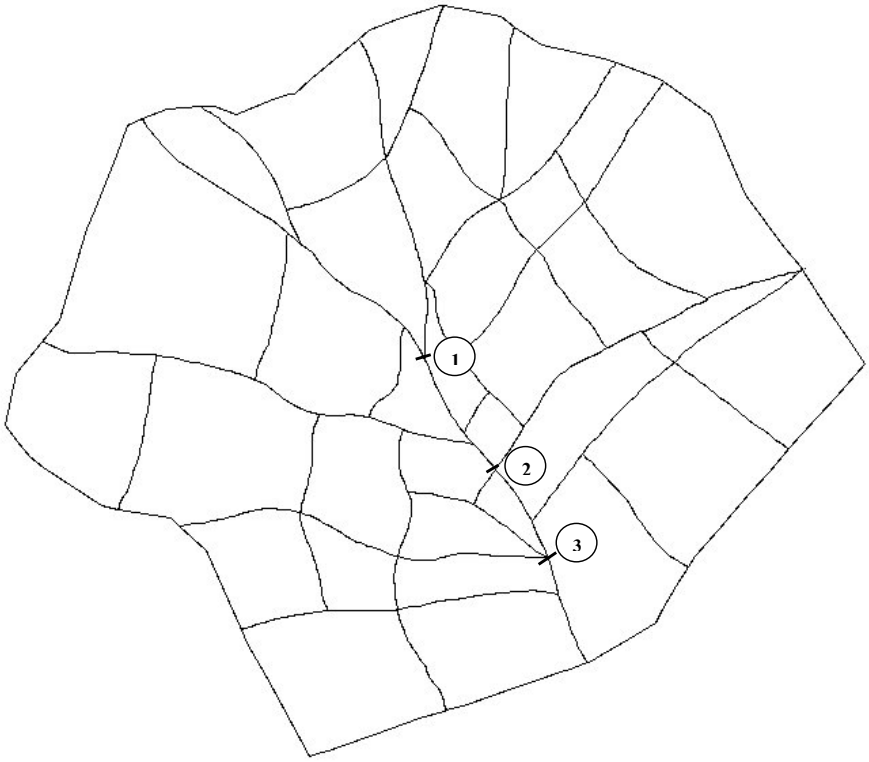

Fig. 4 The W3 basin divided into morphological units.

The topographic factors L_i and S_i for each morphological unit i were calculated using two different expressions. One, proposed by McCool *et al*. (1989), is named MCC, adopted for the revised universal soil loss equation (RUSLE) (Renard *et al*., 1994):

$$L_i S_i = \left(\frac{\lambda_i}{22.13}\right)^{m_i} \left(10.8\sin\alpha_i + 0.03\right) \qquad \text{if } \tan\alpha_i < 0.09 \tag{4a}$$

$$L_i S_i = \left(\frac{\lambda_i}{22.13}\right)^{m_i} \left(16.8\sin\alpha_i - 0.5\right) \qquad \text{if } \tan\alpha_i \geq 0.09 \tag{4b}$$

in which λ_i is the slope length of the ith morphological unit; α_i is the slope angle; $m_i = f_i/(1 + f_i)$ in which f_i represents the ratio of rill to inter-rill erosion and has the following expression:

$$f_i = \frac{\sin\alpha_i}{0.0896\left(3\sin^{0.8}\alpha_i + 0.56\right)} \tag{5}$$

The second method, named MB, was suggested by Moore & Burch (1986):

$$L_i S_i = \left(\frac{A_{s,i}}{22.1}\right)^{0.6} \left(\frac{\sin\alpha_i}{0.0896}\right)^{1.3} \tag{6}$$

where $A_{s,i}$ is the ratio between the area $S_{u,i}$ (in m^2), of the ith morphological unit and the width (in m), measured along the contour line (Moore & Wilson, 1992).

The sediment production for a given basin Y_b, expressed in metric tons, is equal to the sum of sediment yields produced by all N_u morphological units into which the basin is divided:

$$Y_b = R_t \sum_{i=1}^{N_u} K_i L_i S_i C_i \; SDR_i \; S_{u,i} = R_t \sum_{i=1}^{N_u} K_i L_i S_i C_i \exp\left(-\beta_t \frac{l_{p,i}}{\sqrt{s_{p,i}}} \right) S_{u,i} \tag{7}$$

in which β_t is the value of coefficient β at a given temporal scale t (annual, mean annual).

Calibration of the SEDD model was carried out, at an annual scale, for the recording period 1978–1994 and using the different expressions of the topographic factors (equations (4) and (6)).

For each year of the measurement period, the corresponding β_a value was calculated by equation (7) in which Y_b is set equal to the measured basin sediment yield Y_m. The annual values β_a, calculated for MCC and MB expressions of the topographic factors were used to estimate the mean annual value β_m which is equal to 0.0235 for the MCC approach and 0.0274 for the MB method.

For each expression of the topographic factors, the mean annual value of the sediment yield of each morphological unit Y_i is calculated by equation (3), with R_t = 52.6 t m mm ha^{-1} h^{-1} and using the mean annual value of the crop management factor C_i = 0.164 (Cinnirella *et al*., 1998), P_i = 1 (no soil conservation practice), and equation (1) with $\beta_t = \beta_m$. The mean annual value of the sediment production for a given basin Y_b is calculated by summing the mean annual sediment yields Y_i produced by all morphological units into which the basin is divided.

SEDIMENT DELIVERY PROCESSES AND CHEMICAL TRANSPORT

By using the 47 sample measurements of nitrogen n_j (mg per kg of soil), phosphorus p_j (mg per kg of soil) and total organic carbon toc_j (g per 0.1 kg of soil) and a kriging interpolation procedure, the spatial distribution of each chemical concentration was obtained.

By overlaying the discretization map of the basin and the spatial distribution of a chemical concentration (nitrogen, phosphorus, total organic carbon), for each morphological unit i the concentrations of nitrogen n_i (mg per kg of soil), phosphorus p_i (mg per kg of soil) and total organic carbon toc_i (g per 0.1 kg of soil) were calculated.

For each morphological unit, the load of nitrogen N_i (in g), phosphorus P_i (g) and total organic carbon TOC_i (g) was then calculated by multiplying the concentration of each chemical (n_i, p_i, toc_i) for the corresponding mean annual sediment yield Y_i (kg).

The analysis was also developed for the whole W3 basin and for three sub-basins. For each basin the total load of nitrogen N_b (g), phosphorus P_b (g) and total organic carbon TOC_b (g) at a given basin outlet was calculated by adding the load of all morphological units into which the considered sub-basin is divided:

$$N_b = \sum_{i=1}^{N_u} n_i Y_i = \sum_{i=1}^{N_u} N_i \tag{8a}$$

$$P_b = \sum_{i=1}^{N_u} p_i Y_i = \sum_{i=1}^{N_u} P_i \tag{8b}$$

$$TOC_b = \sum_{i=1}^{N_u} toc_i Y_i = \sum_{i=1}^{N_u} TOC_i \tag{8c}$$

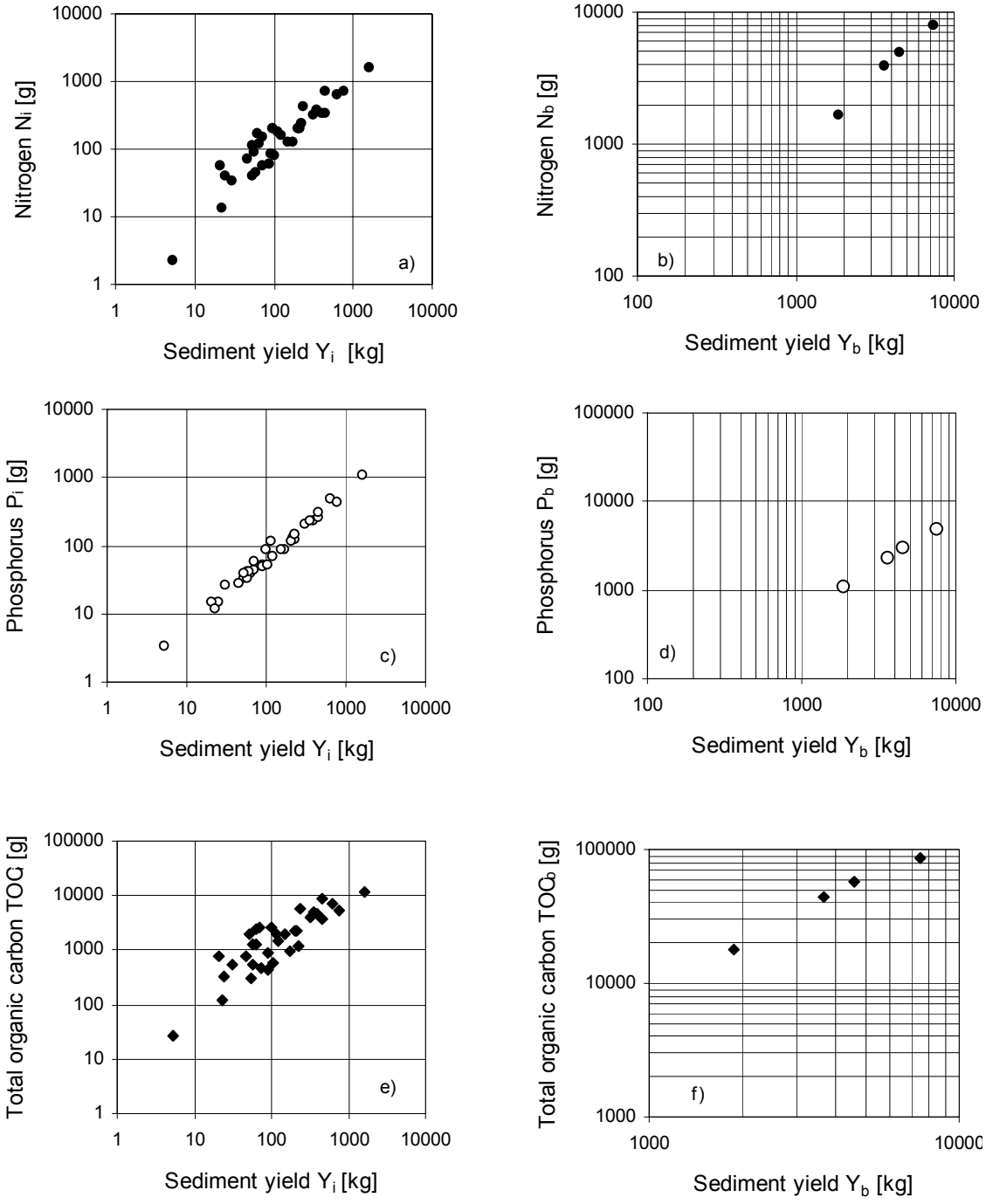

Fig. 5 Relationship between chemical load and sediment yield at both morphological unit (a, c, e) and basin scale (b, d, f) for MCC expression of the topographic factor.

For the two expressions of the topographic factors (Figs 5 and 6), at both morphological and basin scale, the analysis showed that the load of each pollutant X at a given scale (morphological unit or basin) in g is linked to the sediment yield Y in kg, at the same scale, by a power relationship (Fig. 7):

$$X = a\, Y^n \tag{9}$$

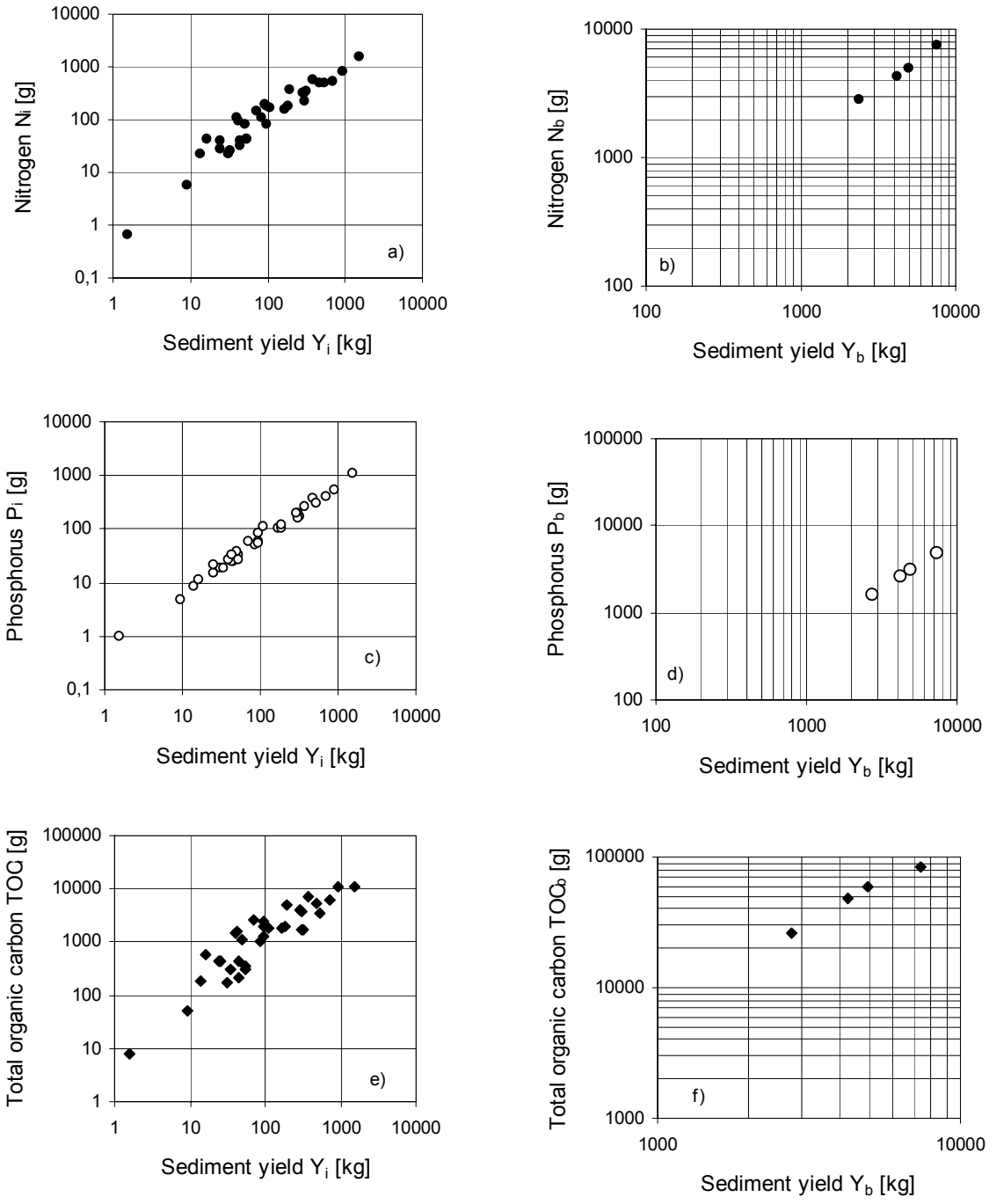

Fig. 6 Relationship between chemical load and sediment yield at both morphological unit (a, c, e) and basin scale (b, d, f) for MB expression of the topographic factor.

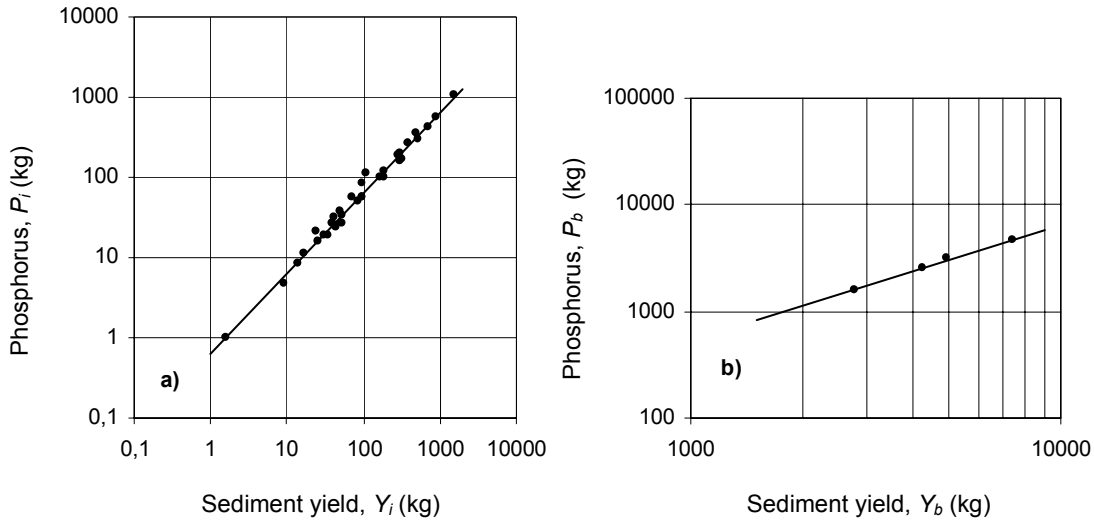

Fig. 7 Comparison between the measured pairs chemical load-sediment yield and equation (7).

Table 1 Values of coefficient a and exponent n of equation (10).

Expression of topographic factor L_iS_i	Variables	a	n
MCC method	N_i, Y_i	1.2412	0.9783
	P_i, Y_i	0.6514	0.9942
	TOC_i, Y_i	16.83	0.9322
	N_b, Y_b	0.2930	1.1498
	P_b, Y_b	0.3329	1.0756
	TOC_b, Y_b	3.2211	1.1517
MB method	N_i, Y_i	1.0898	1.0060
	P_i, Y_i	0.6321	1.0006
	TOC_i, Y_i	13.42	0.9788
	N_b, Y_b	0.1813	1.2000
	P_b, Y_b	0.2722	1.0965
	TOC_b, Y_b	2.3271	1.1838

For a given spatial scale the values of the coefficient a and exponent n for each chemical and expression of the topographic factors are listed in Table 1. This shows that the exponent n of equation (9) was practically independent of the adopted expression of the topographic factors.

Table 1 also shows that the exponent n of equation (9) was dependent on the studied spatial scale (morphological unit, sub-basin) and was generally different from unity, indicating a nonlinear behaviour of the basin. For each pollutant, the comparison of the values for n estimated for the two different scales (morphological unit, basin) established the scale shifting. In particular, for phosphorus (P_i, P_b) the scale shifting from morphological unit to basin scale was obtained by a simple scale factor because the two values of the exponent n are nearly equal. For nitrogen (N_i, N_b) and total organic carbon (TOC_i, TOC_b), the scale shifting from morphological unit to basin scale was not obtainable by a simple scale factor. For nitrogen this result can be explained taking into account the high spatial variability of the nitrogen load (Fig. 8).

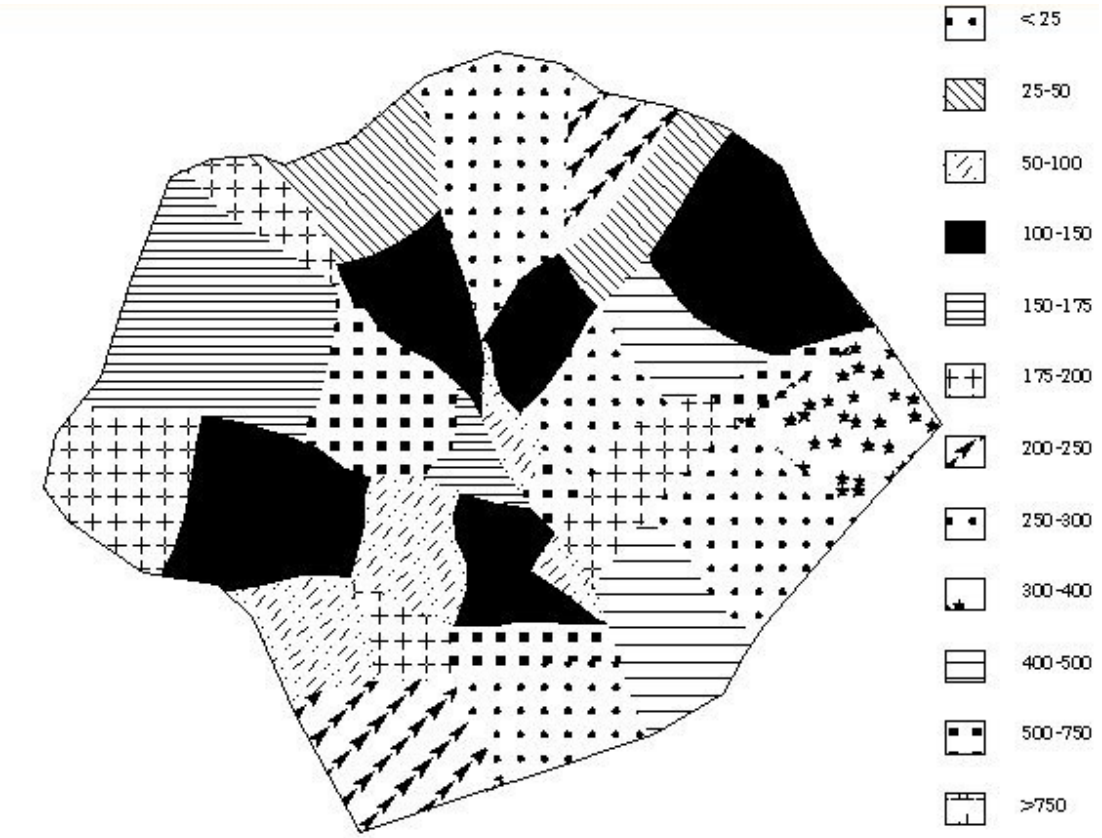

Fig. 8 Spatial distribution of the nitrogen load (g).

The different behaviour of the scale shifting for nitrogen and phosphorous can also be justified by taking into account that these chemicals have different adsorption, desorption and solution characteristics which determine a different mobility and transportability. In particular, soil nitrogen assumes nitric (NO_3^-), ammoniac (NH_4^+) and organic form. The anion NO_3^- can be transported in solution by the overland flow even if in soils without manuring this anion is negligible. The cation NH_4^+ is adsorbed into the soil exchange complex. The organic form is characterised by a low mobility and it is preferentially transported by small particles. Soil phosphorus assumes phosphate form. Phosphates are insoluble and precipitate around the soil particles. Phosphorus has a very low mobility even if it is indifferently transported by small and large particles. Therefore, any nitrogen form is more mobile than phosphorus and this property can justify that the nitrogen load has a spatial variability greater than the phosphorus load.

The behaviour of total organic carbon can be explained by taking into account that its mobility and transportability is only due to sediment transport phenomena. In other words, the transportability of the total organic carbon is strongly dependent on sediment particle mobility and is quasi-independent of chemical processes.

Sediment-bound phosphorus losses and organic material eroded from fields are the predominant occurrence from tilled cropland. According to Lemunyon & Daniel (2002) the soil erosion rate *A*, the sediment delivery ratio *SDR* and the sediment enrichment ratio *SER* values are needed to estimate sediment losses of phosphorus, *PL*,

from agricultural land:

$$PL = A\ SDR\ SER \tag{10}$$

in which *SER* is calculated by the ratio of the phosphorus concentration (mg kg^{-1}) of the eroded sediment and the concentration (mg kg^{-1}) of phosphorus in the original soil at the detachment site.

To take into account the spatial variability of a given pollutant in a basin (Giasson *et al*., 2002), the enrichment ratio must be calculated using the load of a given chemical fraction in the sediment eroded from the morphological unit and in the soil covering the same morphological unit.

In other words, the enrichment ratio of a given pollutant can be defined as the load of a given chemical fraction in sediment divided by the load of that fraction in an equal mass of soil, the enrichment ratio of the nitrogen ERN_b, as an example, has the following expression:

$$ERN_b = \frac{N_{\text{sed}} \sum_{i=1}^{N_u} Y_i}{\sum_{i=1}^{N_u} n_i Y_i} = \frac{N_{\text{sed}}\ Y_b}{N_b} = \frac{N_{\text{sed}}}{PSN_b} \tag{11}$$

in which N_{sed} (g) is the load of nitrogen in the eroded sediment and the ratio PSN_b equal to N_b divided by Y_b is named the *chemical–sediment ratio* of the nitrogen. In a similar way, the chemical-sediment ratio of phosphorus, PSP_b, and total organic carbon, PST_b, can be calculated. Equation (11) clearly shows that the enrichment ratio of a chemical depends on its load *(*N_{sed}) in the eroded sediment and the spatial distribution both of the chemical (n_i) in the matrix soil covering the basin and of the sediment yield (Y_i).

In conclusion, equation (11) establishes that two different components can be distinguished within the enrichment ratio of a given chemical (for example, nitrogen): the load of the chemical in the eroded sediment N_{sed} and the chemical-sediment ratio PSN_b represent the influence of the spatial distribution both of the chemical content in the matrix soil and of the sediment yield.

CONCLUSIONS

Recent research has directed attention to the properties of the eroded material (grain-size distribution, aggregate stability, etc.) because of the influence on the sediment delivery processes and the importance of sediment-associated transport in non-point pollution problems.

Since sediments, and adsorbed chemicals, are produced from different sources distributed throughout a drainage basin, improvements in modelling chemical transport phenomena can be obtained by employing a spatially-distributed approach to sediment delivery processes.

In this paper, at first, a parametric approach such as the universal soil loss equation coupled with a spatial disaggregation criterion of sediment delivery processes was calibrated using the sediment yield measurements carried out in an experimental

reafforested basin. The distributed approach allowed to calculate the sediment yield of each morphological unit into which the basin was divided. Then, by using the sample measurements of concentration of nitrogen, phosphorus and total organic carbon and a kriging interpolation procedure, the spatial distribution of each chemical load was obtained.

For each chemical, the analysis, carried out at both morphological unit and basin scale, showed that the load can be linked to the sediment yield by a power relationship, the exponent being dependent on the studied spatial scale and being generally different from unity. The analysis also showed that, for phosphorus, the scale shifting can be simply obtained by a scale factor.

The proposed definition of the enrichment ratio allowed the influence of the chemical load in the eroded sediment to be distinguished from the effects of the spatial distribution both of the chemical content in the matrix soil and of the sediment yield.

In conclusion, the influence of the sediment delivery processes has to be considered to obtain a reliable estimate of the chemical-sediment ratio.

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