Environ Earth Sci (2009) 59:223–231
DOI 10.1007/s12665-009-0020-x

ORIGINAL ARTICLE

An improved correlation model for sediment delivery ratio assessment

Nazzareno Diodato · Sergio Grauso

Received: 14 October 2008 / Accepted: 10 December 2008 / Published online: 27 January 2009

Abstract In the present work, a new simplified model approach for sediment delivery ratio (SDR) assessment is proposed. Modelling and assessing SDR is still an open question. Difficulties rise from the lack of sufficient data availability, on one side, and, on the other, from the inherent uncertainties including spatial variability and temporal discontinuity of the land cover, climatic, hydrological and geomorphological variables involved. The proposed SDR_{SIM} model tries to skip over the limitations observed in other models generally adopted. A comparison with two different selected models amongst the most widespread simplified models, i.e. the area-model and the slope-model, is showed in application to a wide range of catchments extensions across different landscapes of Italy. The SDR_{SIM} estimates were also evaluated against observed SDR over a validation dataset of 11 basins sparse over different regions of the world. The results showed the effectiveness of the proposed model approach based on easily available catchment parameters.

Keywords Sediment delivery · Prediction models · Catchments · Italy

N. Diodato
TEDASS – Technologies Interdepartmental Center for Environmental Diagnostic and Sustainable Development, University of Sannio, 82100 Benevento, Italy
e-mail: scodalabdiodato@gmail.com

S. Grauso (✉)
Dipartimento Ambiente, Cambiamenti Globali e Sviluppo Sostenibile, ENEA C.R. Casaccia, via Anguillarese 301, 00123 Rome, Italy
e-mail: grauso@casaccia.enea.it

Introduction

Soil erosion rate and river sediment yield are key-factors whose estimate is essential in land and river systems management aimed to achieve the environmental sustainability of human activities. Often, given the lack of direct data, estimates are made by means of prediction models allowing to evaluate soil loss or sediment yield separately. There are a number of prediction models, conceptual, empirical or physically based which can help in this task that have been successfully tested and are currently used in different parts of the world. Therefore, one can conclude that modelling such processes is now an almost achieved result. On the contrary, linking the two processes of sediment production and delivery is still an open question.

In fact, it is not unusual that one, being provided with catchment soil loss data, has the need to convert these data in sediment yield delivered at a given river section or vice versa. Nevertheless, to date, there is not a general agreement about an universal model which can suitably explain the relationship between sediment yield and related upland soil erosion allowing to convert one quantity into the other as needed.

The river sediment yield can be defined as the total quantity of sediments eroded from the upland catchment area (referred to as gross erosion) which is routed to the basin outlet by the watercourse in a definite time period. The sediment yield per unit catchment area is the specific sediment yield (SSY). Considering that only a partial amount of gross erosion is routed to the basin outlet (otherwise referred to as the net erosion), knowing the ratio between the net erosion and the gross erosion amounts, which is worldwide known as the sediment delivery ratio or SDR, is crucial for scientific and management purposes. As already pointed out by Lu et al. (2004), methods for estimating the SDR can be roughly grouped into three categories characterized by different degrees of complexity. So, one can distinguish methods, such as sediment rating curve-flow duration and reservoir sediment deposition (Collins and Walling 2004; Fan et al. 2004), which imply that sufficient sediment yield and streamflow data are available. Sediment yield data are available for many areas of the world, but the global coverage currently is inadequate to produce a reliable and detailed world map of sediment yield (Mutchler et al. 1994). Therefore, such approaches are not suitable for the general use, because of data unavailability, especially at the subcatchment level.

A different approach is showed by methods based on empirical relationships relating the SDR to the morphological characteristics of a catchment, such as the catchment area, average local relief or lithology. These models are largely followed, given their simplified form requesting easily available data. The general limitation of these methods is given by the local influence of climatic and geomorphological characteristics which make a given relationship unsuitable in geographical areas different from the area where the relationship was calibrated.

Other methods attempt to provide a physical description of fundamental hydrological and hydraulic processes, i.e. by coupling runoff and erosion/deposition processes conditioning the sediment transport capacity. Nevertheless, their data requirements often make these complex models not suited to basin scale applications.

In order to overcome some of the difficulties mentioned above, several attempts to predict the export of sediment from catchments, by coupling catchment gross erosion to a SDR value in a spatially distributed modelling approach, have been investigated. A summary of the relevant literature is given by Lenhart et al. (2005). Complex and theoretically based relationships for evaluating the sediment delivery ratio of each morphological unit into which the basin can be divided have been proposed in different way. For example, Ferro and Minacapilli (1995) developed a model for which SDR is linked to the travel time from the morphological unit by an exponential relationship. A SDR model which is used in the Soil and Water Assessment Tool (SWAT) was proposed by Arnold et al. (1996), taking into account the peak runoff rate and the peak rainfall excess rate. Asselman et al. (2003), provided for a SDR model estimating the amount of mobilized sediment that actually reaches the stream network, and Borselli et al. (2004) used a complex connectivity index. New advances in this field are being gathered thanks to GIS technology allowing to easily apply different models in a spatially distributed form (Ouyang and Bartholic 1997).

However, the SDR still remains hard for assessing, as its estimate implies numerous uncertainties including temporal discontinuity and spatial variability characterizing the land cover, climatic, hydrological and geomorphological variables involved (Wolman 1977; Walling 1983).

As it will be cited in the following sections, many on-site investigations have been carried out at different scales, from small farm-plots to small-medium basins up to large rivers, concerning the linkage between soil erosion sub-processes on hillslopes and suspended sediment transport, in the effort to set up a general theoretical model allowing to indirectly obtain the SDR value and to derive one of the cited quantities from the other.

In the present work, a new simplified model approach (SDR_{SIM}) is proposed trying to skip over the limitations observed in other models generally adopted. In particular, a comparison with two different selected models amongst the most widespread simplified models in the international literature, such as those here referred to as the area-model (SDR_A) and the slope model (SDR_{Slope}), is showed in application to a wide range of catchments from 1 to 3,000 km^2 across different landscapes of Italy. The SDR_{SIM} estimates were also evaluated against SDR over a validation dataset of 11 basins sparse over different regions of the world.

Approach and methodology

Study area and data sources

The study was based on data from 25 Italian river basins located from north to south of Italian peninsula and major islands (Fig. 1). Italy is centrally placed in the Mediterranean basin and characterized by land use diversity and a heterogeneous mix of geographical features (peninsular shape, Alps chain in the north, Apennines chain all along the peninsula) determined by a large latitudinal gradient along a relatively narrow land surface, with transition zones from semi-arid to humid mountain climate (Lionello et al. 2006).

Such landscape heterogeneity generates greatly varying ecological and land-degradation patterns at all spatial and temporal scales with water erosion recognized as the major land-degradation cause.

In fact, an erratic end and start to the rainy season (green couple bands in Fig. 2) along with heavy rains likely has a great impact on soil since the seasonal vegetation will not be able to intercept the rainfall during the tillage seasons (Spring and Autumn, respectively). In dry intervals (yellow bands in Fig. 2), long sun brightness periods can be associated to the Azores or sub-tropical anticyclones, often interrupted by atmospheric instability with showers and thunderstorms, especially over Northern Italy where the dry period (Fig. 2a) is shorter than in southernmost regions (Fig. 2b, c). In very long dry periods of extreme Southern

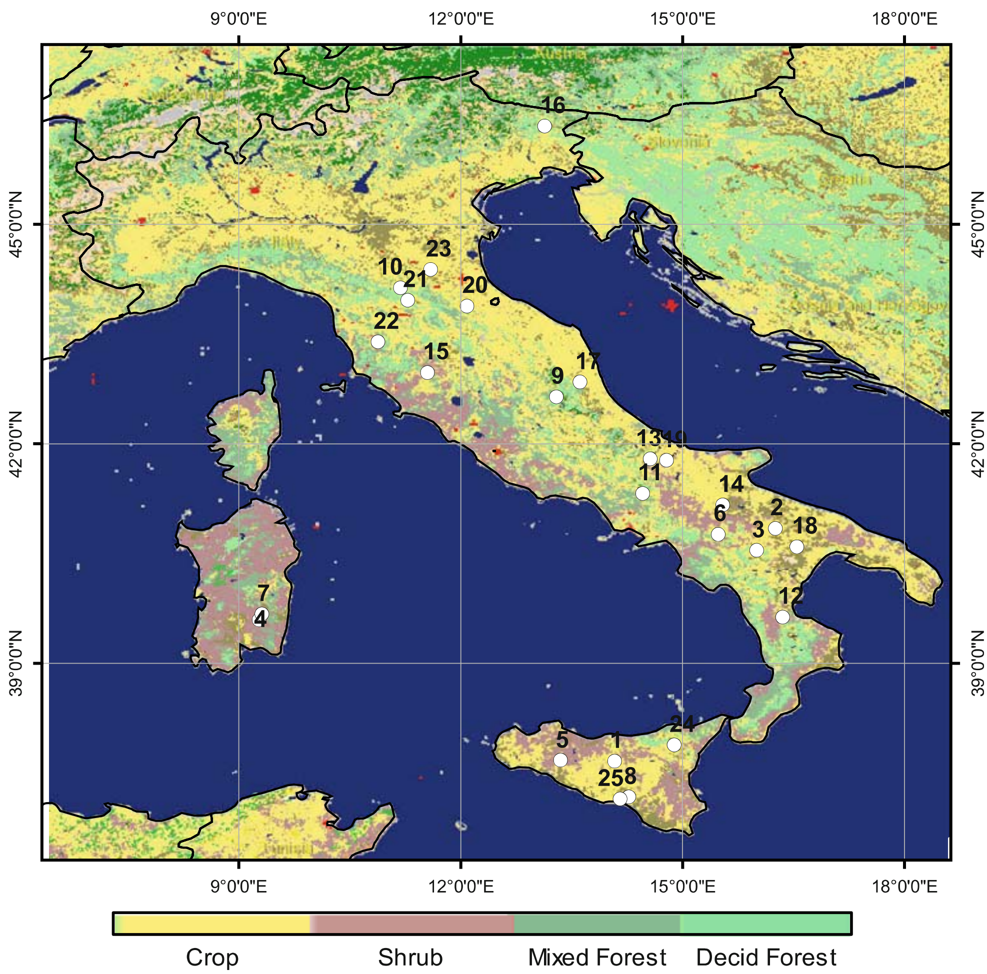

Fig. 1 Location of the Italian sediment yield sampling sites (*circles*) with related land-use pattern (*in colours*) (see Table 1 for sites coding). Land-cover source: http://hydis.eng.uci.edu/gwadi

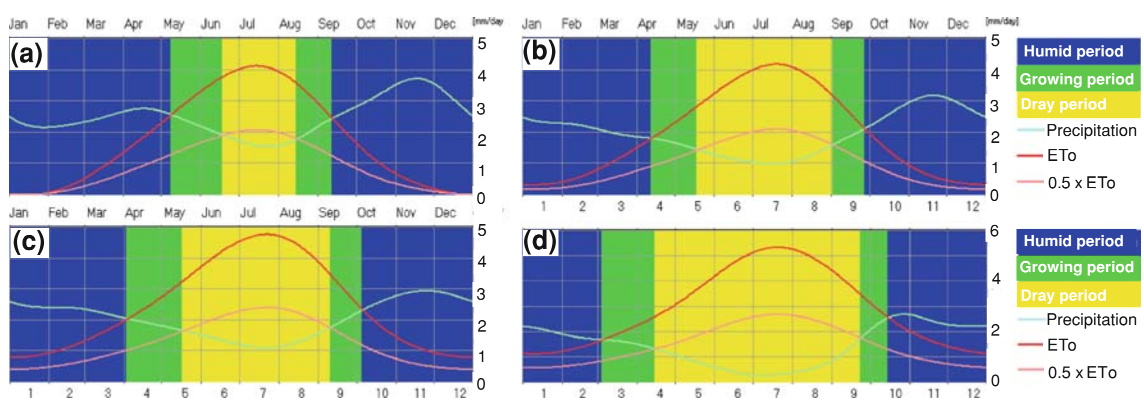

Fig. 2 Seasonal bioclimatic regime for different location of Italy: **a** Loiano (Northern Apennines), **b** Trivento (Central Apennines), **c** Grassano (Southern peninsular Italy) and **d** Caltanissetta (Sicily island). (arranged from New LocClim-FAO database 1961–1990)

Italy and major islands (Fig. 2d), precipitations are inherently variable in amount and intensity and, as a consequence, the same variability affects rainfall and run-off erosivity in a very chaotic way.

The 25 Italian river basins calibration dataset here utilized (Table 1) is a combination of different data sources available from the literature or from official sites. Of course, the sediment yield was measured by means of different techniques, ranging from reservoir sedimentation measurements to turbidity measurements, whilst the hill-slope gross erosion was indirectly assessed by means of RUSLE model and its different versions. Ten basins were extracted from the dataset by Van Rompaey et al. (2003) and de Vente and Poesen (2005), who analysed a series of watershed-reservoir systems where observed sedimentation volumes were available. Other eight watershed-reservoir

Table 1 The Italian dataset utilized in the present study for *SDR* models calibration

Code	Basin (outlet)	Geogr. (N)	Coord. (E)	A (km^2)	Slope (m m^{-1})	E (m)	P (mm)	SYEM	GEPM	f(SMI)	SDR	Years	Source
1	Simeto (Pozzillo)	37.67	14.08	580	0.17	690	658	R	WS	12.9	0.13	1950–1970	Van Rompaey et al. (2003)
2	Basentello (Serra di Corvo)	40.85	16.25	298	0.06	850	473	R	WS	1.3	0.26	1950–1971	Van Rompaey et al. (2003)
3	Camastra (Ponte Fontanelle)	40.55	16.00	352	0.20	300	823	R	WS	12.6	0.27	1950–1972	Van Rompaey et al. (2003)
4	Mulargia (Monte Su Rei)	39.60	9.27	171	0.12	300	800	R	WS	3.2	0.31	1950–1973	Van Rompaey et al. (2003)
5	Verdura (Gammauta)	37.68	13.35	112	0.24	700	792	R	WS	10.3	0.18	1950–1974	Van Rompaey et al. (2003)
6	Fiumara di Muro (Muro Lucano)	40.77	15.48	35	0.06	400	950	R	WS	0.3	0.75	1950–1975	Van Rompaey et al. (2003)
7	Flumendosa (Nuraghe Arrubiu)	39.68	9.31	700	0.27	350	950	R	WS	30.1	0.06	1950–1977	Van Rompaey et al. (2003)
8	Gela (Disueri)	37.18	14.27	239	0.11	479	450	R	WS	4.2	0.26	1950–1978	Van Rompaey et al. (2003)
9	Scandarello (Scandarello)	42.65	13.29	49	0.15	1,000	881	R	WS	2.5	0.21	1950–1979	Van Rompaey et al. (2003)
10	Limentra (Suviana)	44.14	11.18	76	0.33	800	1,631	R	WS	11.1	0.08	1950–1980	Van Rompaey et al. (2003)
11	Volturno (Amorosi)	41.33	14.46	3,000	0.10	600	1,400	TS	RUSLE(RV)	7.0	0.19	1954–1970	SIMN 1954–1970
12	Crati (Conca)	39.64	16.35	1,332	0.05	752	1,330	TS	RUSLE(RV)	1.2	0.62	1933–1948	SIMN 1933–1948
13	Trigno (Trivento)	41.80	14.56	544	0.10	700	1,100	TS	RUSLE(RV)	3.3	0.31	1931–1942	SIMN 1931–1942
14	Ofanto (Rocchetta S.Antonio)	41.17	15.54	1,028	0.07	400	1,000	TS	RUSLE(RV)	2.4	0.31	1933–1952	SIMN 1933–1952
15	Orcia (M.te Amiata)	42.98	11.55	580	0.05	400	1,000	TS	RUSLE(RV)	0.9	0.53	1953–1971	SIMN 1953–1971
16	Tagliamento (Pioverno)	46.35	13.13	1,900	0.14	500	1,500	TS	RUSLE(RV)	10.5	0.14	1936–1942	SIMN 1936–1942
17	Tronto (Tolignano di Marino)	42.85	13.61	911	0.07	500	850	TS	RUSLE(RV)	2.4	0.33	1938–1942	SIMN 1938–1942
18	Bradano (S. Giuliano)	40.60	16.54	1,631	0.09	650	992	R	WS	4.9	0.26	1957–1977	Bonora et al. (2002)
19	S. Simone	41.78	14.78	16	0.21	683	650	R	RUSLE	3.3	0.31	1971–1974	Arr. from Gentile et al. (1999)
20	Savio (Quarto)	43.89	12.08	110	0.22	597	727	R	RUSLE	9.0	0.19	1933–1936	Biagi et al. (1995)
21	Sieve (Bilancino)	43.97	11.28	143	0.06	450	1,100	R	RUSLE	0.6	0.36	1992–2002	Borselli et al. (2004)
22	Cavalcanti (Vicarello)	43.40	10.88	0.6	0.24	200	680	R	RUSLE	0.8	0.67	1960–1990	Bazzoffi et al. (1997)
23	Sillaro (infl. Reno)	44.39	1.59	138	0.11	256	942	R	RUSLE	2.2	0.21	1998–2003	Brath et al. (2002)
24	Cannata (infl. Flascio)	37.89	14.88	1.3	0.21	1,000	600	R	RUSLE	1.0	0.30	1996–2003	Licciardello et al. (2006)
25	Comunelli (Comunelli)	37.15	14.15	108	0.03	283	510	R	RUSLE	0.2	0.59	1959–1998	Onori et al. (2006)

A drainage area, *E* elevation, *P* annual precipitation, *SYEM* sediment yield estimates method, *GEPM* gross erosion prediction method, *f*(*SMI*) hydro-morphological function, *SDR* soil delivery ratio, *R* reservoir, *WS* WaTEM/SEDEM, *RUSLE* revised universal soil loss equation, *SIMNI* Serv. Idrografico e Mareografico Nazionale Ital., *RUSLE*(*RV*) RUSLE-based Rearranged Values systems data were added from different sources (Bonora et al. 2002; Gentile et al. 1999; Biagi et al. 1995; Borselli et al. 2004; Bazzoffi et al. 1997; Brath et al. 2002; Pavanelli et al. 2004; Licciardello et al. 2006; Onori et al. 2006). In these cases, the outlet station was given by the reservoir location within the concerned watershed. Further seven river basins were selected amongst the national hydrographic monitoring network system (former SIMN, 1922–2004). In this case, the outlet station was given by the turbidimetric gauging station located at a definite river cross section. From the ratio between the observed sediment yield and the relative assessed upland gross erosion, the relative SDR was derived, which can be considered as an observed reference value for our evaluations.

The average size of the considered watersheds is about 570 km^2, ranging from 0.6 km^2 to a maximum of 3,000 km^2. The mean annual precipitation ranges from 450 to more than 1,600 mm. Then, a wide spectrum of variability for as it concerns both dimensions and climatic conditions (as well evidenced in Fig. 2) has been considered.

The 11 river basins out of Italy considered as validating dataset (Table 2) were a combination of several data sources available in the international literature. The average size of the considered watersheds is about 1,500 km^2, ranging from 2 to a maximum of about 8,000 km^2. The mean annual precipitation ranges from about 800 to 2,000 mm.

Modelling SDR

In the absence of sufficient data to accurately determine water discharge and other parameters at different scale levels or for each morphological unit of the basin, sediment delivery ratio is often estimated by means of few, easily available morphological data. One of the most followed relationship, here reported as SDR_A (Area model), is based on the simple negative assumption between SDR and basin size, which was initially developed by Vanoni (1975), by means of the following power function:

$$SDR_A = \varphi(A)^{-\kappa} \quad (1)$$

where A is area of the basin (km^2); φ and κ are two empirical parameters; for Italy, the exponent κ varies with basin geographical features, ranging from -0.69 to -0.3 (Brath et al. 2002). Notwithstanding many evidences reported in the literature (Walling 1983; Ichim and Radoane 1987; Bagarello et al. 1991; Ferro and Minacapilli 1995; Lane et al. 1997; Verstraeten and Poesen 2001; Vertstraeten et al. 2003; de Vente and Poesen 2005), the general assumption that SDR, at the same rate with SSY, shows an inverse relationship with catchment area is not always true and it cannot be adopted as an universal model. Offsets from this general rule have been observed in different parts of the world where, on the contrary, a positive correlation has been reported (Church and Slaymaker 1989; Schiefer et al. 2001; Dedkov 2004). Amongst these, Italian drainage basins also show a slightly positive relation between catchment area and SSY (de Vente and Poesen 2005; Grauso et al. 2008).

Another empirical equation for the determination of SDR using few catchment characteristics, such as the main stream channel slope, was developed by Williams and Berndt (1972) for Kenya region, here referred as the SDR_{SLP} (Channel Slope model):

$$SDR_{SLP} = \varphi'(SLP)^{\kappa'} \quad (2)$$

where SLP is the slope of main stream channel (%); the empirical coefficients φ' and κ' were originally fixed equal

Table 2 The database utilized in the present study for SDR models validation

Code	Country	Basin	A (km^2)	Slope (m m^{-1})	E (m)	P (mm)	SYEM	GEPM	f(SMI)	SDR	Years	Source
1	Kenya	Masinga	6,266	0.05	1,795	1,510	R	RUSLE	0.33	0.29	1961–1990	Mutua et al. (2006)
2	Kenya	Gikuuri	5	0.18	1,600	1,100	MMF	MMF	0.45	0.61	1966–1992	Vigiak et al. (2005)
3	Greece	Kompsatos	564	0.04	300	1,038	CLM	RUSLE	0.58	0.47	1966–1992	Hrissanthou (2005)
4	Ethiopia	May Zegzeg	2	0.30	2,300	774	MGM	RUSLE	0.32	0.38	1998–2001	Nyssen et al. (2007)
5	Korea	Bosung	274	0.22	526	1,495	R	RUSLE	0.16	0.19	1991–2000	Lee and Lee (2006)
6	Texas	Guadiana	24	0.40	1,400	1,619	R	RUSLE	0.16	0.17	1991–1995	del Mar Lopez et al. (1998)
7	USA	Rio Lempa	8,313	0.07	700	2,000	R	RUSLE	0.22	0.28	1970–1980	Kim et al. (2005)
8	Belgium	Dijle	820	0.06	50	835	R	RUSLE	0.35	0.18	1969–2003	Notebaert et al. (2008)
9	Canada	Boyer	217	0.05	300	1,100	^{137}Cs	^{137}Cs	0.66	0.62	1996–2001	Bernard and Laverdiwere (2001); Mabit et al. (2007)
10	Tanzania	Kwalei	2	0.18	1,600	1,000	MMF	MMF	0.54	0.61	1966–1992	Vigiak et al. (2005)
11	Africa	Bosboukloof	2	0.13	270	1,296	R	CLM	0.76	0.50	1970–1985	Scott (1993)

R reservoir, *MMF* modified Morgan-Finney, *137Cs* 137Cesium measurement, *LCM* locally calibrated model to 0.627 and 0.403, respectively. A different combined function of catchment area, land slope and land cover, was used by Kothyari and Jain (1997) for estimating SDR in India. Unlike the above Areal Model, the Channel Slope-based Model has been little applied. Moreover, given the observed very low correlation between the main stream channel slope parameter utilized in this model and the SDR data in the Italian basins here considered ($r^2 = 0.03$), SLP was here replaced with the basin areal mean slope, holding a stronger link with SDR ($r^2 = 0.41$). Thus, the Slope model (SDR_{Slope}) relationship was expressed as:

$$SDR_{Slope} = \varphi(\text{Slope})^{\kappa} \quad (2a)$$

where the mean basin slope is expressed in m × m^{-1} and φ and κ are the empirical coefficients to be calibrated on observed data. As it will be pointed out here, κ actually assumes a negative sign.

In the present study, a new model, the SDR_{SIM} (Spatially Invariant Model), is proposed, based on a hydro-morphological function *f*(SIM) aimed to synthesize in an unique formulation the roles played both by watershed morphology and by rainfall amount:

$$SDR_{SIM} = \varphi \cdot f(\text{SMI})^{-\kappa} \quad (3)$$

with

$$f(\text{SMI}) = \left[\frac{\sqrt{A}\left(\Omega - \sqrt{E}\right) \cdot \text{Slope}^{\alpha}}{\sqrt{P}} \right] \quad (3a)$$

where *A* is the basin area (km^2); *E* is the average elevation of the basin (m); Slope is the mean basin slope (m × m^{-1}); *P* is the annual average precipitation amount (mm); and φ, κ, Ω and α are four empirical parameters.

In order to better explain the significance of the factors combined in Eq. 3a, the single terms that summarize the SDR can be reformulated as follows: let us consider *f*(SY) as a function of the sediment yield, and *f*(GE) as a function of the gross erosion in the watershed; then, following the general empirical assumption that erosion and sediment yield are influenced by precipitation and climate factors as well as by basin area, elevation and morphology (Cooke and Doornkamp 1990; Ludwig and Probst 1998), it may be written, respectively:

$$f(\text{SY}) = A^{\chi} \cdot P^{\delta} \cdot \text{Slope}^{\beta} \quad (4)$$

and

$$f(\text{GE}) = A^{\vartheta} \cdot P^{\eta} \cdot E^{\nu} \cdot \text{Slope}^{\gamma} \quad (5)$$

Reassembling the terms, the SDR equation becomes:

$$\text{SDR} = \frac{f(\text{SY})}{f(\text{GE})} = \frac{A^{\chi} \cdot P^{\delta} \cdot \text{Slope}^{\beta}}{A^{\vartheta} \cdot P^{\eta} \cdot E^{\nu} \cdot \text{Slope}^{\gamma}} \quad (6)$$

where the area-rain-slope product function at numerator represents the final sediment delivery at the basin outlet, whilst the product-set at denominator drives the soil mobilization process function and approximates the watershed gross erosion.

In dimensional terms, Eq. 6 is equivalent to Eq. 3, in particular, they coincide in the hypothesis that the exponents are such that:

$$\chi - \vartheta = -\frac{\kappa}{2};\ \delta - \eta = \frac{\kappa}{2};\ \beta - \gamma = -\alpha;\ \nu = \frac{1}{2}$$

whilst $\varphi = \kappa = 1$.

The empirical parameters of each SDR model were determined using the calibration data set (Table 1). Basically, the parameter values were estimated against SDR_{SIM} estimates using a solver that minimized the square error of estimate. An iterative calibration process was employed for Eq. 3. First, the set of parameters was approached for *f*(SY) and *f*(GE) functions (Eqs. 4 and 5, respectively). Successively, Eq. 6 was transformed into model (3), fitting the SDR_{SIM} values keeping constant some parameters of Eq. 5. Next, the parameters of Eq. 3 were calibrated against the SDR_{SIM} estimates. The process was reiterated until a converging solution was reached.

Models application and results

Table 3 shows the model parameters determined via calibration of the three models. For the Area model, the estimated coefficient $\varphi = 0.41$ results equal to that reported in *Handbook of Hydrology* (Shen and Julien 1993), whilst $\kappa = -0.085$ is near to the superior limit of the values-range ($\kappa = -0.69/-0.3$).

For the Slope model, the estimates of φ (0.0697) and κ (−0.619) are not comparable to the SLP model. In particular, the power function exponent κ here appears with a negative sign, meaning that the SDR holds an inverse relationship with the mean basin slope, differently from what one can expect. In fact, a watershed with short and steep slopes will deliver more sediment to a channel than a watershed with a long and flat landscape (Ouyang and Bartholic 1997). The negative relationship here resulting can only be explained by considering that, with increasing

Table 3 Values of function parameters estimated for A (Area Model), Slope (Slope Model) and SIM (Spatial Invariant Model)

Parameters	Soil delivery ratio models		
	A	Slope	*f*(SIM)
φ	0.4100	0.0697	0.416
κ	−0.085	−0.619	−0.422
Ω	–	–	500
α	–	–	2.0

mean slope, the upland erosion also increases, then, a surplus of sediment is moved from the valley sides to channels which cannot be delivered towards the outlet. In particular, the higher inclination in the first treat of the curve in Fig. 3b (lower slopes) suggests that gross erosion exceeds the loading capacity by stream channels, on average, that is, the ratio is highly unbalanced towards GE, then, the SDR lowers rapidly; whilst, in the second treat of the curve (increasing slopes), the stream capacity begins to be more effective versus upland erosion, then the SDR lowering is slower.

The regression coefficients values, estimated from the data, roughly matched the SDR data of both the calibration (Fig. 3a–c) and the validation (Fig. 3a$_1$–c$_1$) data sets. On the calibration dataset, different performances were exhibited from the three model approaches, with a determination coefficient r^2 equal to 0.08, 0.41 and 0.73, respectively. On the validation dataset, it is surprising to

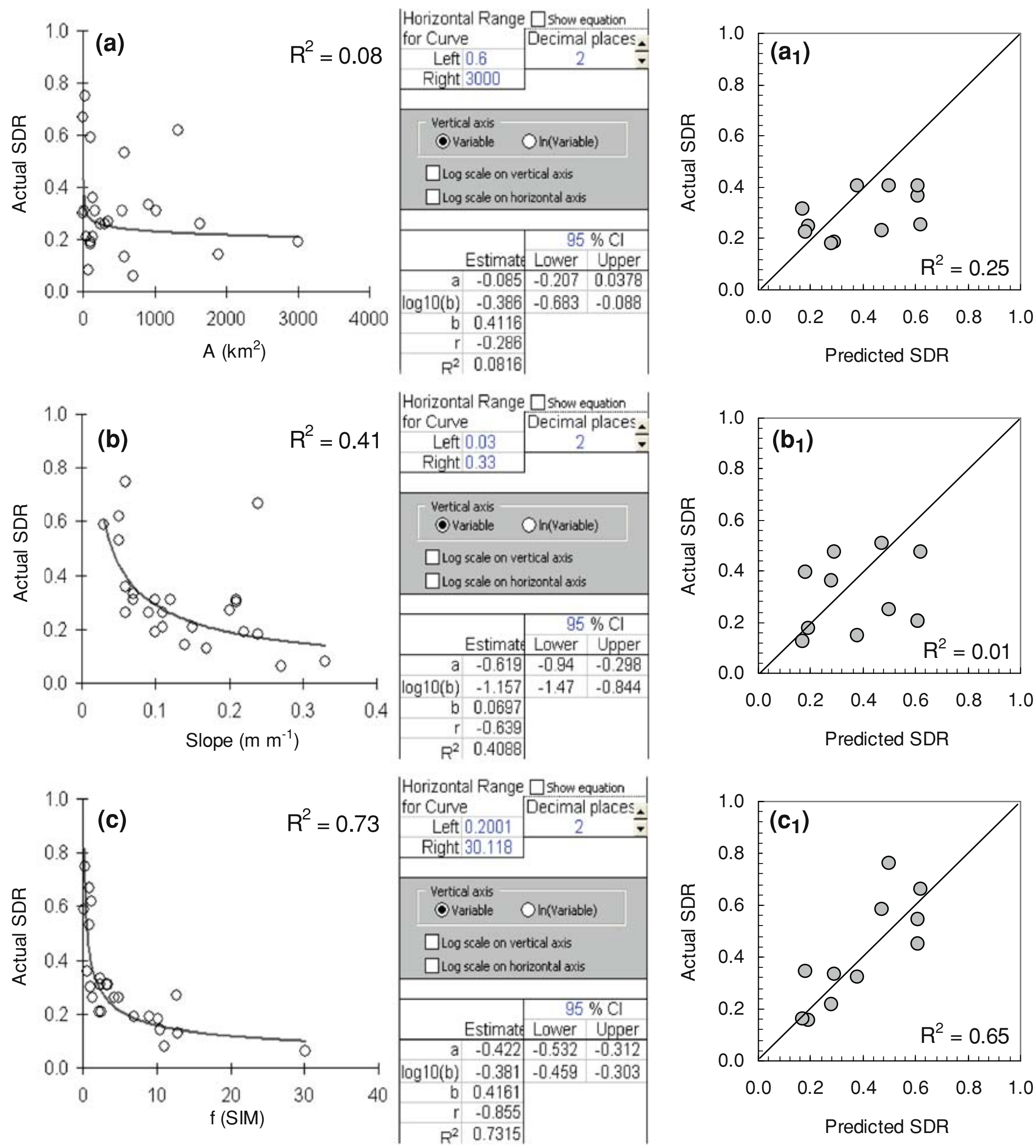

Fig. 3 SDR modelling by means of Areal Model (**a**), Slope Model (**b**), and SIM Model (**c**) from the calibration Italian data set and respective scatterplots (**a**$_1$–**c**$_1$) between predicted and actual SDR values from the validation out-side Italian data set. Modelling was supported by Rodney Carr, Excel add-in workbooks for Data Analysis, Version 5

detect as only the SIM-model holds the performance, with $r^2 = 0.65$. With the two simplified Area-and-Slope models, both validation scatterplots show, in fact, a rather poor agreement between estimated and actual SDR values, with a strong decay for the Slope model (Fig. 3b, b_1).

The SIM-model may appear more sensitive to variation in its several parameters than the A and Slope models are to their few parameters. The application of the SIM model to other world sites may therefore be limited by the ability to provide appropriate site-representative parameters able to capture the spatial variability of SDR data. Specific geographical locations (e.g., upland and forested basin, very impermeable drainage areas) may have particular characteristics which cause the parameters to deviate from reference values, and may require local optimization.

Conclusions

The effort made hitherto by many researchers to find out a general model allowing to reliably estimate SDR have produced a number of different kinds of models, giving to each the possibility to choose the better solution to his case, mainly on the basis of actual data availability.

The SDR_{SIM} model here proposed attempted both to provide a simple method based on easily available catchment parameters and to skip over the limitations observed when applying other simplified models such as the Areal model and the Slope model. An integrated hydro-morphological function *f*(SMI) was introduced, aimed to synthesize in an unique formulation the roles played both by watershed morphology and by rainfall amount.

The comparison with the above cited models, through the application to a wide range of catchments extensions across different landscapes of Italy, demonstrated the better behaviour of the proposed model. The validation test performed by means of a 11 basins dataset sparse over different regions of the world, confirmed the effectiveness of SDR_{SIM} model against the worse results by the other models and also proved the model robustness independently from the geographic location and local conditions.

Acknowledgments We are grateful to Dr. A. Pagano (EC Joint Research Centre, IPSC, Ispra) for his suggestions in model mathematics and Dr. G. Fattoruso (ENEA, Portici) for her help in basins delineation and parameterisation.

References

Arnold JG, Williams JR, Srinivasan R, King KW (1996) The soil and water assessment tool (SWAT) User's Manual. Temple, TX

Asselman NEM, Middelkoop H, Dijk PM (2003) The impact of change in climate and land use on soil erosion, transport and deposition of suspended sediment in the River Rhine. Hydrol Process 17:3225–3244

Bagarello V, Ferro V, Giordano G (1991) Contributo alla valutazione del fattore di deflusso di Williams e del coefficiente di resa solida per alcuni bacini idrografici siciliani (Evaluation of the Williams's runoff factor and of sediment delivery ratio in some Sicilian river basins). Rivista di Ing Agr 4:238–251

Bazzoffi P, Pellegrini S, Chisci G, Papini R, Scagnozzi A (1997) Erosione e deflussi a scala parcellare e di bacino in suoli argillosi a diversa utilizzazione nella val d'Era (Plot and catchment runoff and erosion in clayey soils of Val d'Era, Tuscany). Agricoltura Ricerca XVIII(170):5–20

Bernard C, Laverdiwere MC (2001) Assessment of soil erosion at the watershed scale from 137Cs measurements. In: Stott RH, Mothar RH, Steinhardt GC (eds) Sustaining the global farm. USDA-ARS, USA, pp 1034–1038

Biagi B, Chisci G, Filippi N, Missere D, Preti D (1995) Impatto dell'uso agricolo del suolo sul dissesto idrogeologico. Area pilota collina cesenate (Influence of cultivations on hydrogeological equilibrium of soils). Collana Studi e Ricerche, Regione Emilia Romagna, Assessorato Agricoltura, Bologna, Italy, 153 pp

Bonora N, Immordino F, Schiavi C, Simeoni U, Valpreda E (2002) Interaction between catchment basin management and coastal evolution (Southern Italy). J Coast Res SI 36:81–88

Borselli L, Cassi P, Sanchis PS, Ungaro F (2004) Studio della dinamica delle aree sorgenti primarie di sedimento nell'area pilota del Bacino di Bilancino (Primary sediment sources in the Bilancino reservoir watershed area): BABI Project. Report of the Consiglio Nazionale delle Ricerche. Istituto di Ricerca per la Protezione Idrogeologica (CNR-IRPI), Florence Unit, «Pedologia Applicata», pp 104

Brath A, Castellarin A, Montanari A (2002) Assessing the effect of land-use changes on annual average gross erosion. Hydrol Earth Syst Sci 6:255–265

Church M, Slaymaker O (1989) Disequilibrium of Holocene sediment yield in glaciated British Columbia. Nature 337:452–454

Collins AL, Walling DE (2004) Documenting catchment suspended sediment sources: problems, approaches and prospects. Prog Phys Geogr 28(2):159–196

Cooke RU, Doornkamp JC (1990) Geomorphology in environmental management. Clarendon Press, Oxford, p 79

de Vente J, Poesen J (2005) Predicting soil erosion and sediment yield at the basin scale: scale issues and semi-quantitative models. Earth Sci Rev 71:95–125

Dedkov A (2004) The relationship between sediment yield and drainage basin area. In: Sediment transfer through the fluvial system, vol 288 (Proceedings of a symposium held in Moscow, August 2004), IAHS Publishing, USA, pp 197–204

del Mar Lopez T, Mitchell Aide T, Scatena FN (1998) The effect of land use on soil erosion in the Guadiana watershed in Puerto Rico. Carib J Sci 34(3–4):298–307

Fan JR, Zhang JH, Zhong XH, Liu SZ (2004) Monitoring of soil erosion and assessment for contribution of sediments to rivers in a typical watershed of the upper Yangtze river basin. Land Degrad Dev 15:411–421

Ferro V, Minacapilli M (1995) Sediment delivery processes at basin scale. Hydrol Sci J 40:703–717

Gentile F, Puglisi S, Trisorio-Liuzzi G (1999) Verifica sperimentale di modelli empirici per la valutazione della perdita di suolo in un piccolo bacino molisano (Experimental test of empirical models for soil loss assessment in a small catchment). Proceedings: La Gestione dell'Erosione: il controllo dei fenomeni torrentizi, scienza, tecnica e strumenti. Quaderni di Idronomia Montana 19/1, BIOS Edition, pp 103–117

Grauso S, De Bonis P, Fattoruso G, Onori F, Pagano A, Regina P, Tebano C (2008) Relations between climatic-geomorphological parameters and suspended sediment yield in a Mediterranean semi-arid area (Sicily, southern Italy). Env Geol 54:219–234

Hrissanthou V (2005) Estimate of sediment yield in a basin without sediment data. Catena 64:333–347

Ichim I, Radoane M (1987) A multivariate statistical analysis of sediment yield and prediction in Romania. In: Ahnert F (ed) Geomorphological models: theoretical and empirical aspects. Catena Suppl 10:137–146

Kim BJ, Saunders P, Finn JT (2005) Rapid assessment of soil erosion in the Rio Lempa Basin, Central America, using the universal soil loss equation and geographic information systems. Environ Manage 36(6):872–885

Kothyari UC, Jain SK (1997) Sediment yield estimation using GIS. Hydrol Sci J 42:833–843

Lane JL, Hernandez M, Nichols M (1997) Processes controlling sediment yield from watersheds as functions of spatial scale. Environ Modell Softw 12(4):355–369

Lee GS, Lee KH (2006) Scaling effect for estimating soil loss in the RUSLE model using remotely sensed geospatial data in Korea. Hydrol Earth Syst Discussion 3:135–157

Lenhart T, Van Rompaey A, Steegen A, Fohrer N, Frede HG, Govers G (2005) Considering spatial distribution and deposition of sediment in lumped and semi-distributed models. Hydrol Process 19(3):785–794

Licciardello F, Mazzola G, Zema DA, Zimbone SM (2006) Runoff and soil erosion modelling by ANNAGNPS in a small Mediterranean watershed. Proceedings of the 5th Iberian Congress on "Water Management and Planning". Faro, Algarve, Portugal, 04–08 December

Lionello P, Malanotte-Rizzoli P, Boscolo R, Alpert V, Li L, Luterbacher J, May W, Trigo R, Tsimplis M, Ulbrich U, Xoplaki E (2006) The Mediterranean climate: an overview of the main characteristics and issues. In: Lionello P et al (eds) Mediterranean climate variability. Elsevier, Amsterdam, pp 1–25

Lu H, Morana C, Prossera I, Sivapalan M (2004) Modelling sediment delivery ratio based on physical principles. In: Proceedings iEMS 2004 International Conference, 14–17 June 2004, University of Osnabrück, Germany, http://www.iemss.org/iemss2004/

Ludwig W, Probst JL (1998) River sediment discharge to the oceans: present-day controls and global budgets. Am J Sci 298:265–295

Mabit L, Bernard C, Laverdiere MR (2007) Assessment of erosion in the Boyer River watershed (Canada) using GIs iruented sampling strategy and ^{137}Cs measurements. Catena 71:242–249

Mutchler CK, Murphree CE, Mcgregor KC (1994) Laboratory and field plots for erosion research. In: Lal S (ed) Soil erosion. Research method. CRC Press, USA, pp 11–38

Mutua BM, Klik A, Loiskandl W (2006) Modelling soil erosion and sediment yield at a catchment scale: the case of Masinga catchment, Kenya. Land Degrad Dev 17(5):557–570

Notebaert B, Verstraeten G, Govers G, Poesen J (2008) Qualitative and quantitative applications of LiDAR imagery in fluvial geomorphology. Earth Surf Process Landforms (in Press)

Nyssen J, Poesen J, Moeyersons J, Haile M, Deckers J (2007) Dynamics of soil erosion rates and controlling factors in the Northern Ethiopian Highlands—towards a sediment budgets. Earth Surf Process Landforms 33(5):695–711

Onori F, De Bonis P, Grauso S (2006) Soil erosion prediction at the basin scale using the revised universal soil loss equation (RUSLE) in a catchment of Sicily (southern Italy). Environ Geol 50(9):1129–1140

Ouyang D, Bartholic J (1997) Predicting sediment delivery ratio in Saginaw Bay watershed. 22nd National Association of Environmental Professionals Conference Proceedings. 19–23 May 1997, Orlando, pp 659–671

Pavanelli D, Pagliarani A, Bigi A (2004) Monitoraggio idrotorbidimetrico per la stima dell'erosione nel bacino montano del Reno (Sediment yield monitoring for erosion estimate in the river Reno watershed). Suppl ARPA J 6:3–7

Schiefer E, Slaymaker O, Klinkenberg B (2001) Physiographically controlled allometry of specific sediment yield in the Canadian cordillera: a lake sediment-based approach. Geogr Ann 83:55–65

Scott DF (1993) The hydrological effects of fire in South African mountain catchments. J Hydrol 150:409–432

Shen HW, Julien PY (1993) Erosion and sediment transport In: Maidment DR (ed) Handbook of Hydrology, Chap 12. McGraw-Hill, New York

Van Rompaey AJJ, Bazzoffi P, Jones RJA, Montanarella L, Govers G (2003) Validation soil erosion risk assessment in Italy. European Soil Bureau Research Report No. 12, EUR 20676 EN, 25 pp

Vanoni VA (1975) Sediment deposition engineering. ASCE Manuals and Reports on Engineering Practices, p 54

Verstraeten G, Poesen J (2001) Factors controlling sediment yield from small intensively cultivated catchments in a temperate humid climate. Geomorphology 40:123–144

Vertstraeten G, Poesen J, de Vente J, Koninckx X (2003) Sediment yield variability in Spain: a quantitative and semiqualitative analysis using reservoir sedimentation rates. Geomorphology 50:327–348

Vigiak O, Okoba BO, Sterk G, Stroosnijder L (2005) Water erosion assessment using farmers' indicators in the West Usambara Mountains, Tanzania. Catena 64:307–320

Walling DE (1983) The sediment delivery problem. J Hydrol 65:209–237

Williams JR, Berndt HD (1972) Sediment yield computed with Universal equation. J Hydraulic Div ASCE98 (HY2), pp 2087–2098

Wolman MG (1977) Changing needs and opportunities in the sediment field. Water Resour Res 13(1):50–54