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The impact of land use change and check-dams on catchment sediment yield

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Abstract:

Extensive land use changes have occurred in many areas of SE Spain as a result of reforestation and the abandonment of agricultural activities. Parallel to this the Spanish Administration spends large funds on hydrological control works to reduce erosion and sediment transport. However, it remains untested how these large land use changes affect the erosion processes at the catchment scale and if the hydrological control works efficiently reduce sediment export. A combination of field work, mapping and modelling was used to test the influence of land use scenarios with and without sediment control structures (check-dams) on sediment yield at the catchment scale. The study catchment is located in SE Spain and suffered important land use changes, increasing the forest cover 3-fold and decreasing the agricultural land 2·5-fold from 1956 to 1997. In addition 58 check-dams were constructed in the catchment in the 1970s accompanying reforestation works.

The erosion model WATEM-SEDEM was applied using six land use scenarios: land use in 1956, 1981 and 1997, each with and without check-dams. Calibration of the model provided a model efficiency of 0·84 for absolute sediment yield. Model application showed that in a scenario without check dams, the land use changes between 1956 and 1997 caused a progressive decrease in sediment yield of 54%. In a scenario without land use changes but with check-dams, about 77% of the sediment yield was retained behind the dams. Check-dams can be efficient sediment control measures, but with a short-lived effect. They have important side-effects, such as inducing channel erosion downstream. While also having side-effects, land use changes can have important long-term effects on sediment yield. The application of either land use changes (i.e. reforestation) or check-dams to control sediment yield depends on the objective of the management and the specific environmental conditions of each area.

KEY WORDS land use change; check-dams; sediment yield; geomorphological impact; management; reforestation

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INTRODUCTION

Two widely applied soil conservation strategies in Mediterranean environments are reforestation and the construction of check-dams in rivers and streams. It is well known that land use changes (including reforestation) and hydrological correction works may alter substantially the sediment delivery and water discharge of a catchment, influencing the geomorphological processes within the river bed, and sometimes inducing non-desirable processes for river management (Kondolf *et al.*, 2002). However, until now relatively little has been known about the effects of changing land use patterns and the introduction of hydrological correction works on sediment yield at the catchment scale. Evaluation of widely applied management measures in mountain streams is necessary in order to increase our understanding of sediment dynamics, and to allocate resources in a responsible manner. Particular attention must be paid to upstream/downstream connections, hillslope/channel connections, process domains, physical and ecological roles of disturbance, and stream resilience (Wohl, 2006).

Check-dam effects on river channels

In-channel structures such as check-dams, create segmented longitudinal profiles, alter sediment dynamics, bed and bank stability, interrupt longitudinal movement of nutrients and aquatic organisms, and alter the passage of flood waves (Wohl, 2006). Check-dams induce important morphological and granulometrical effects in the river bed (Boix-Fayos *et al.*, 2007) which change the hydraulic behaviour of the flow in extreme events (Conesa García *et al.*, 2004). Besides the control of the sedimentary load accomplished by check-dams as reported for different environments (Simon and Darby, 2002; Martín-Rosales *et al.*, 2003; Surian and Rinaldi, 2003), there are also indications that check-dams induce local erosion processes (Gómez-Villar and Martínez-Castroviejo, 1991; Porto and Gessler, 1999; Martín Rosales, 2002; Castillo *et al.*, 2007; Conesa-García and

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García-Lorenzo, 2008) affecting the sediment budget at the catchment scale. Disturbances induced by check-dams can be negative when induced erosion is high, or when they create a false stabilization image (García-Ruiz *et al.*, 1996b; White *et al.*, 1997; Gutiérrez *et al.*, 1998; Alcoverro *et al.*, 1999; Boix-Fayos *et al.*, 2007). On the contrary, the effects of check-dams can have short- and long-term benefits. For example, Xiang-Zhou *et a*l. (2004) explain how a check-dam system in gullies is one of the most effective ways to conserve soil and water in the Loess Plateau of China, where reforestation methods are not successful due to the arid climate and barren soils. The sediment retained by the dams provides a unique opportunity for high-yield croplands or orchards. A positive influence of check-dams on the riparian vegetation is reported by Bombino *et al.* (2006), who found a longitudinal diversification of vegetation types and creation of new habitats for biological and ecological communities, attributed to the geometric characteristics of check-dams.

Land use change effects on sediment yield

Mountain streams are particularly vulnerable to changes in hillslope processes because of close coupling with adjacent hillslopes. Hillslope processes are easily altered by land use changes. An increase of vegetation cover leads in general to a decrease in runoff generation and sediment detachment resulting in the medium term in the stabilization of sedimentary structures at the catchment scale (García-Ruiz *et al.*, 1996a; Beguería *et al.*, 2006). Sometimes a very limited change in land use can have a significant effect on regional soil erosion rates (Van Rompaey *et al.*, 2002). However, not only the change in the cover of different land uses induces changes on sediment yield, but also the change in landscape structure has important consequences for the sediment yield. For example, changes in temporal patterns of cultivation practices (Vezina *et al.*, 2006), changes in the spatial connectivity between sediment- producing areas and the river network (Vanacker *et al.*, 2003; 2005), changes in the combined effects of land use and field sizes (Vanacker *et al.*, 2005; Van Rompaey *et al.*, 2007) and changes in the location of field boundaries (Van Oost *et al.*, 2000) have remarkable effects on sediment yield. So although it is well known that changes in land use affect erosion and sediment yield, an integrated evaluation of the effectiveness and impacts of check-dams compared with reforestation and other land use changes is lacking. Recently an evaluation of the effect of land use changes, small farm dams and large reservoirs on sediment yield in an Australian catchment has been carried out (Verstraeten and Prosser, 2008).

Perspective and objectives

In south-east Spain significant land use changes have occurred as a result mainly of the abandonment of agricultural activities and the introduction of reforestation plans. In addition, the Spanish Administration spends large funds on hydrological control works to reduce flood risk and sedimentation of reservoirs. However, it remains untested how these land use changes and the hydrological control work affect the erosion processes at the catchment scale, and if they are really efficient. A previous study (Boix-Fayos *et al.*, 2007) analysed the combined influence of land use change and a network of check-dams on the morphological evolution of a river channel in SE Spain. This paper raises the question to what extent are (i) land use changes and/or (ii) check-dams responsible for the decreased sediment yield at the catchment scale. The main objective is to determine the effectiveness of land use changes and check-dams as management options to control sediment yield at the catchment scale.

STUDY AREA

The Rogativa catchment (Murcia, SE Spain, 38° 08′ N, 2° 13′ W), with a size of 47·2 km^2 was selected as the study area. The study area and the land use changes that have occurred within it since 1956 were described extensively in Boix-Fayos *et al.* (2007). The catchment drains the northern face of Revolcadores (2027 m) and the Cuerda de la Gitana (1829 m) mountain ranges in S–N direction. It belongs to the catchment of the Taibilla, a tributary of the Segura river, located at the Subbetic unit of the Betic Mountains. The dominant lithology consists of marls, limestones, marly limestones and sandstones of the Cretaceous, Oligocene, and Miocene (IGME, 1978). Mountains are mainly limestone while mid- and bottom-valley locations are dominated by marls. The average annual rainfall for the period 1933–2004 was 583 mm and the average annual temperature 13·3 °C.

The landscape represents a mix of dryland farming, mainly barley, plantations of walnuts (*Junglans regia*), forests and shrublands. The catchment has been affected by important land use changes since the second half of the twentieth century. These changes consist mainly of a progressive abandonment of dryland farming activities and an increase in forest cover (Boix-Fayos *et al.*, 2007). The surface area of the land use classes in 1997 is listed in Table I. Table II shows changes in surface area of the most important land uses between different periods.

Forest is dominated by *Pinus nigra salzmanii*, although also some *Pinus pinaster* and *Pinus halepensis* occur in the lower basin. *Quercus rotundifolia* was reduced due to intense wood and charcoal production and clearing for agriculture in the past. Shrublands located higher within the catchment are dominated by *Erinacea anthyllis* while at lower altitudes *Cytisus reverchonii, Rosmarinus officinalis, Thymus vulgaris* and *Genista scorpius* appear.

In the catchment area 58 check-dams were constructed in 1976 and 1977 (Figures 1 and 2). Of those, 72% are silted and 81% present erosion features directly downstream of the dam (Boix-Fayos *et al.*, 2007). In the main stream 11 check-dams are located, all of them completely silted. Further characteristics of check-dams and their drainage areas are given in Table I.

Table I. Location and main characteristics of the check-dams and their drainage areas of the Rogativa catchment. The area of the land use classes is derived from digital orthophotos of 1997

Check-dam	Check-dam condition	Location (ravine name)	Year	Sediments bulk density (g cm^{-3})[a]	Drainage area (ha)	Original storage capacity (m^3)	Trap efficiency (%)[b]	Sediment yield (t yr^{-1})	High and medium density forest (ha)	Low density forest (ha)	Shrubland (ha)	Pasture (ha)	Dryland agriculture (ha)
D1	silted	Roble	1976	1·55	15·36	676·99	87·55	30·26	1·08	7·35	—	—	6·93
D2	silted	Roble	1976	1·55	58·16	136·26	27·22	28·77	15·30	32·11	—	—	10·71
D3	silted	Umbría de las víboras	1976	1·55	125·41	625·48	44·32	81·11	48·92	60·31	16·18	—	—
D4	non-silted	Umbría de las víboras	1976	1·55	25·17	404·49	71·95	21·54	1·81	22·25	—	—	1·19
D5	non-silted	Cantarrales 1	1976	1·55	246·57	278·98	15·30	82·36	80·91	164·00	—	—	1·63
D6	non-silted	Cantarrales 1	1976	1·55	5·80	229·97	86·35	13·99	5·14	—	—	—	0·67
D7	non-silted	Cantarrales 1	1976	1·55	11·67	326·52	81·71	9·11	11·66	—	—	—	0·01
D8	non-silted	Umbría de las víboras	1976	1·55	230·56	903·34	38·47	99·45	73·72	56·66	58·81	9·20	32·18
D9	silted (+5 cm)	Cueva del Agua	1976	1·55	85·10	1261·68	70·29	104·49	63·44	1·01	13·85	—	6·81
D10	non-silted	Rogativa	1976	1·55	26·91	573·40	77·28	26·90	5·88	15·90	5·07	—	0·06
D11	non-silted	Rogativa	1977	1·55	37·29	1968·74	89·39	95·56	24·53	2·72	0·75	—	9·30
D12	silted	Barraca	1977	1·55	36·03	419·77	65·03	37·10	8·75	1·22	4·86	—	21·20
D13	non-silted	Cantarrales 2	1977	1·55	35·73	258·48	53·59	22·92	35·67	0·07	—	—	—
D14	silted	Cantarrales 2	1976	1·50	13·25	709·34	89·53	43·90	11·00	—	—	—	2·25
D15	non-silted	Pocicos	1976	1·50	86·98	238·25	30·42	21·92	24·77	53·39	8·82	—	—
D16	silted (+20.3 cm)	Solana	1977	1·52	4·73	1070·22	97·31	66·65	0·08	—	—	—	4·64
D17	silted	Solana	1977	1·52	155·65	1245·77	56·09	125·02	129·59	1·67	—	—	24·40
D18	silted	Rogativa	1977	1·55	42·31	8246·10	96·89	489·14	5·19	—	—	—	37·12
D19	silted (+10 cm)	Javanas	1977	1·52	20·25	746·48	85·47	50·70	12·91	—	1·79	—	5·55
D20	silted	Estebas	1977	1·52	181·31	132·75	10·46	71·42	51·14	62·62	4·88	46·81	15·88
D21	non-silted	Javanas	1977	1·52	11·42	789·42	91·69	42·81	3·30	—	7·45	0·02	0·65
D22	silted (+20 cm)	Javanas	1977	1·52	66·72	92·24	18·08	32·31	39·89	9·37	7·68	9·79	—
D23	silted	Loma Parrilla	1977	1·52	440·05	1058·99	27·75	214·81	245·65	120·70	8·07	50·99	14·65
D24	non-silted	Loma Parrilla	1977	1·52	17·08	703·89	86·81	34·42	15·37	—	1·65	—	—
D25	silted	Rogativa	1977	1·55	85·47	80·39	13·05	35·40	31·48	—	—	—	54·00
D26	silted	Rogativa	1977	1·55	147·72	3058·18	76·77	228·95	45·90	—	20·63	3·25	77·91
D27	silted (+20 cm)	Estebas	1977	1·50	41·31	47·94	15·63	19·12	14·17	—	5·87	—	21·26
D28	silted (+10 cm)	Almenicas	1977	1·50	361·77	432·86	16·03	154·58	263·91	25·67	61·12	9·17	1·90
D29	non-silted	Escribano	1977	1·50	7·92	2350·10	97·93	126·33	4·61	—	—	—	3·31

Table I. (*Continued*)

Check-dam	Check-dam condition	Location (ravine name)	Year	Sediments bulk density ($g\ cm^{-3}$)[a]	Drainage area (ha)	Original storage capacity (m^3)	Trap efficiency (%)[b]	Sediment yield ($t\ yr^{-1}$)	High and medium density forest (ha)	Low density forest (ha)	Shrubland (ha)	Pasture (ha)	Dryland agriculture (ha)
D30	silted	Escribano	1977	1·50	231·13	546·00	27·38	110·51	193·34	—	8·31	—	29·48
D31	silted	Escribano	1977	1·50	5·49	750·75	95·62	43·51	4·78	—	—	—	0·71
D32	silted (+25 cm)	Escribano	1977	1·50	7·65	1539·99	96·98	95·33	5·07	—	—	—	2·58
D33	silted	Ciruelos	1977	1·50	61·29	1529·82	79·93	106·06	60·38	—	—	—	0·94
D34	silted (+40 cm)	Ciruelos	1977	1·50	14·75	1528·65	94·30	99·28	12·32	—	—	—	2·41
D35	silted	Ciruelos	1977	1·50	19·94	1378·72	91·69	83·33	11·77	0·34	0·57	—	7·38
D36	silted (+50 cm)	Ciruelos	1977	1·50	1·07	1707·89	99·61	110·85	0·51	0·16		—	0·40
D37	silted	Ciruelos	1999	1·50	71·13	2506·83	84·91	163·61	43·35	—	22·92	—	4·80
D38	silted	Rogativa	1977	1·55	238·36	10841·14	87·89	708·88	128·32	33·22	11·24	1·57	64·02
D39	silted	Cementerio	1977	1·50	9·95	3019·72	97·98	170·79	8·69	—	—	—	1·26
D40	silted	Cementerio	1977	1·50	5·11	1005·74	96·92	57·51	5·11	—	—	—	—
D41	silted (+30 cm)	Cementerio	1977	1·50	156·52	925·49	48·55	116·20	68·33	88·19	—	—	—
D42	silted	Cementerio	1977	1·50	7·02	449·36	91·09	27·34	3·62	—	0·02	—	3·39
D43	silted	Salvalejo	1977	1·50	36·44	931·81	80·32	64·29	15·02	19·20	0·03	—	2·19
D44	silted (+20 cm)	Salvalejo	1977	1·50	25·79	423·67	72·39	34·83	11·21	14·58	—	—	—
D45	non-silted	Salvalejo	1977	1·50	35·91	315·14	58·34	15·52	10·99	24·92	—	—	—
D46	non-silted	Salvalejo	1977	1·50	15·18	175·25	64·82	5·99	9·60	5·58	—	—	—
D47	non-silted	Salvalejo	1977	1·50	18·58	382·17	76·65	13·40	13·34	5·24	—	—	—
D48	non-silted	Salvalejo	1977	1·55	352·42	295·53	11·80	85·27	208·11	57·61	11·52	75·19	—
D49	silted(+20 cm)	Casa Nueva	1977	1·53	123·67	1038·68	57·27	109·41	0·00	86·36	3·04	14·51	19·75
D50	silted (+10 cm)	Rogativa	1977	1·52	308·25	9589·21	83·24	670·84	116·29	111·79	7·97	13·23	59·05
D51	non-silted	Suerte Estrecha	1977	1·37	48·70	745·69	70·96	45·70	25·05	23·64	—	—	—
D52	silted	Suerte Estrecha	1977	1·37	31·80	392·45	66·33	29·93	20·22	7·35	4·23	—	—
D53	silted	Ermita	1977	1·37	9·38	1224·13	95·42	64·90	8·26	1·07	—	—	—
D54	silted	Ermita	1977	1·37	30·55	662·85	77·59	43·22	30·21	0·41	—	—	—
D55	silted (+10 cm)	Ermita	1977	1·37	11·18	1025·64	93·61	57·01	10·95	0·13	0·11	—	—
D56	silted (+50 cm)	Ruico	1977	1·37	168·52	2506·00	70·36	202·72	106·62	34·95	—	26·95	—
D57	silted (+10 cm)	Ruico	1977	1·37	6·81	1170·23	96·48	63·40	6·77	0·04	—	—	—
D58	silted (+20 cm)	Rogativa	1978	1·52	146·96	15142·38	94·27	971·16	72·67	57·95	9·87	2·39	4·09

[a] Average bulk density determined for samples taken in the alluvial wedge behind each dam

[b] Trap efficiency of the original capacity of the check-dams calculated according to Brown (1943)

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Table II. Area covered by different land uses in 1956, 1981 and 1997 and ratios between years

	Areas			Ratios		
	1956 km^2	1981 km^2	1997 km^2	1981/1956	1997/1981	1997/1956
High density forest	1·98	6·91	9·51	3·48	1·38	4·80
Medium density forest	7·09	10·07	16·52	1·42	1·64	2·33
Low density forest	15·34	8·36	10·10	0·55	1·21	0·66
Shrubland	6·00	9·92	2·47	1·65	0·25	0·41
Pasture land	4·04	2·13	2·73	0·53	1·28	0·67
Dry land agriculture	12·07	9·15	5·21	0·76	0·57	0·43

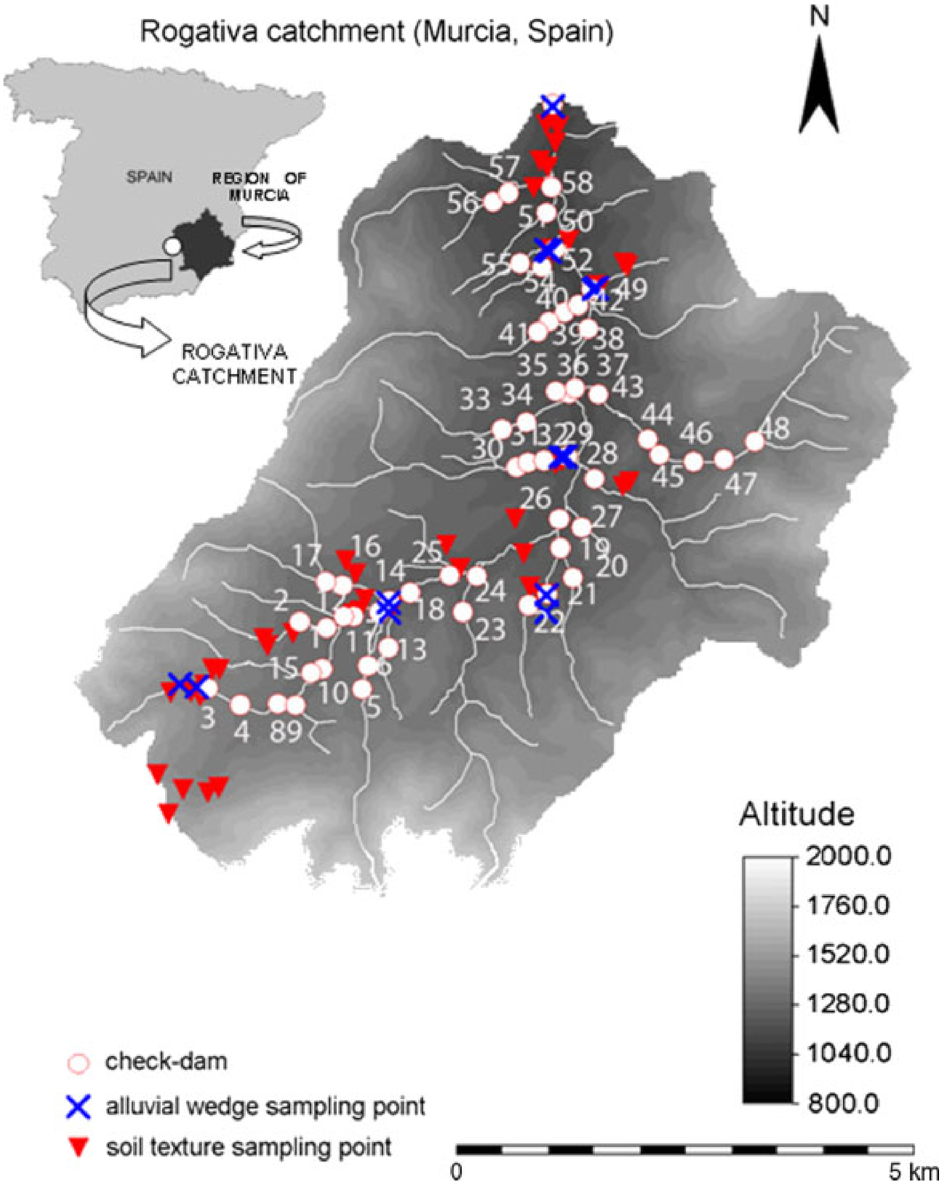

Figure 1. Location map of the study area, check-dams and sampling points within the Rogativa catchment

METHODS

The methodological approach to this work consisted of three main parts: (i) field surveys in order to estimate sediment yields at the subcatchment level and to characterize the soils within the catchment; (ii) GIS analysis to calculate various model input parameters; and (iii) a modelling exercise using the existing spatially distributed soil erosion model WATEM-SEDEM (Van Oost *et al.*, 2000; Van Rompaey *et al.*, 2001; Verstraeten *et al.*, 2002).

(i) A first field survey to locate all the check-dams constructed within the catchment was carried out. 58 check-dams were found and georeferenced with a GPS Trimble GeoXM with differential correction.

Figure 2. (A) General view of the catchment in November 2004; (B) check-dam in a tributary river at the medium catchment in May 2004; (C) check-dam in a tributary river at the upper catchment in June 2004; (D) check-dam at the outlet of the catchment in May 2005

Measurements of the dam structure (height, length), and detailed mapping of the sediment wedges behind each dam was carried out. The volume of sediments was estimated assuming that the alluvial wedge has the form of a prismatic channel with a rectangular section (Prosser and Karssies, 2001; Lien, 2003; Castillo *et al*., 2007), measuring in the field the height and area of the wedges. Undisturbed sampling of a selection of sediment wedges was carried out to estimate the average bulk densities of retained sediments. Seven sediment wedges were sampled at the front and the end of the wedge (two sampling areas per wedge) (Figure 1). Bulk samples of 100 cm^3 at 7 cm depth intervals were taken to a maximum depth of 1·25 m, and two replicates also with 7 cm depth intervals to 35 cm depth were taken at each sampling area. A total of 189 undisturbed samples were collected. With these data, the mass of sediment retained by each check-dam was estimated. In a second field survey the soil texture for different areas within the catchment was determined. A total of 70 sample locations distributed from upstream to downstream in the catchment were sampled at 0–5 and 5–10 cm depth. Soils were air dried; the organic matter was eliminated with H_2O_2, the samples were chemically dispersed with hexametaphosphate and their particle size distribution characterized by laser diffraction using a Coulter LS200. Three laboratory replicates for each sample were done. The percentage of coarse and fine sand, coarse and fine silt and clay were obtained as well as the geometric mean size of particles. Results were used to obtain a soil erodibility map (K factor) as explained below.

(ii) GIS analysis was used to derive various model input parameters. First of all, the catchment area draining to each check-dam was calculated using a digital elevation model (DEM) of the catchment. The DEM was extracted from the contour lines (10 m interval) of digital topographic maps obtained from the Spanish National Geographic Institute (IGN). The maps were published between 2000 and 2002 and based on photogrammetric information of a flight of 1988. From these maps a DEM was created at 30 m resolution using the Idrisi software. Trap efficiency for each check-dam was calculated following Brown (1943) using the initial volume of each check-dam. This method estimates trap efficiency according to the structure capacity and watershed area ratio and it is useful for estimations of mid- and long-term trap efficiencies, especially when no inflow data are available (Verstraeten and Poesen, 2000). Specific sediment yield data (SSY, t ha^{-1} yr^{-1}) and absolute sediment yield (SY, t yr^{-1}) were calculated based on the volume of sediments retained by each check-dam, the bulk density of sediments, the trap efficiency of check-dams and the drainage area of each check-dam. Similar approaches are reported by several authors to estimate sediment yield data behind small dams or check-dams (Verstraeten *et al*., 2007; Romero-Díaz *et al*., 2007a).

Furthermore, several GIS layers were prepared as input for the erosion model RUSLE (see third paragraph of this section) in the following way:

1. The land use scenarios of three years (1956, 1981 and 1997) derived from interpretation of aerial photographs (spatial resolution 1 m) of those years were adapted in size and resolution to the study area. Details of the methods to derive the land use scenarios can be found in Boix-Fayos *et al.* (2007).
2. Crop factor (C factor) map. C factors were assigned to land use classes based on the estimations of the National Inventory of Soils for the Region of Murcia (DGCONA, 2002).
3. Rainfall factor (R factor) map. This factor was calculated based on mean monthly rainfall data of the National Meteorological Institute of Spain for the period 1937–2004. The equation of Renard and Freimund (1994) as explained in de Vente *et al.* (2007b) was applied to calculate R.
4. Erodibility (K factor) map. A K factor for each soil sampling point was estimated using the algorithm proposed by Römkens *et al.* (1987). The data were extrapolated for the whole catchment using a kriging procedure. For very steep slopes (>35°), the K factor was set at a value of 20.
5. Rivers map
6. Pond map with a specific trap efficiency
7. Parcels map

All layers were resampled at 30 m resolution for the model application.

GIS analysis was also used to characterize the land use pattern for 1956, 1981 and 1997 by the application of the perimeter to area ratio and the fragmentation index (Monmomier, 1974, Eq. (1)):

$$F = \left(\sum_{i=1}^{m} \left(\frac{c-1}{n-1} \right) / n \right) \tag{1}$$

where n = number of different classes present in the kernel of 5 by 5 pixels, c = number of cells considered in the 5 by 5 pixels kernel and m = number of pixels in the image. A high perimeter to area ratio and a high fragmentation index indicate a more fragmented land use pattern with more small isolated patches of different land use.

Since the available land use maps from aerial photographs (1956, 1981, 1997) did not provide an image of the land use at the moment of the installation of the hydrological control works (i.e. starting 1976), a classification was performed of a historic Landsat Multispectral Scanner (MSS) satellite image of 21 January 1974 in an effort to characterize land use conditions for this time period. The MSS sensor took images in four bands of the electromagnetic spectrum: two in the visible part of the spectrum, and two in the infrared part. A false colour image based on the combination of bands 4, 2, 1 was used to perform a supervised classification of land uses. Because of the relatively low level of detail in the Landsat MSS images (spatial resolution 75 m), in this classification two of the original land use classes were merged (i.e. high and medium density forest). Because of the lower spatial resolution of the satellite image compared with the aerial photographs, the satellite image was only used to characterize the land use at the moment of construction of the control works and not as a land use scenario for modelling purposes.

(iii) The spatially distributed model WATEM-SEDEM (Van Oost *et al.*, 2000; Van Rompaey *et al.*, 2001; Verstraeten *et al.*, 2002) was used to estimate the sediment yield at the outlet of the catchment under different land use scenarios. WATEM-SEDEM provides long-term mean annual soil erosion rates by water and sediment yield. The model was extensively described in earlier publications (e.g. Van Oost *et al.*, 2000, Van Rompaey *et al.*, 2001, Verstraeten *et al.*, 2002, de Vente *et al.*, 2007b), so here we summarize the most important features. The model calculates on a pixel basis and has three main components: soil erosion assessment, sediment transport capacity and sediment routing. Within WATEM-SEDEM mean annual soil erosion is predicted with a modified version of the revised universal soil loss equation (RUSLE; Renard *et al.*, 1997) that was proposed by Desmet and Govers (1996a, b) as:

$$E = R \times K \times LS_{2D} \times C \times P \tag{2}$$

where E is the mean annual soil erosion (kg m^{-2} yr^{-1}), R is the rainfall erosivity factor (MJ mm m^{-2} h^{-1} yr^{-1}), K is the soil erodibility factor (kg h MJ^{-1} mm^{-1}), LS_{2D} is the two-dimensional topographic factor, C is the crop and management factor, and P is the erosion control practice factor. In the original WATEM-SEDEM model the sediment transport capacity is calculated as the product of the rill and interrill erosion potential and a constant factor called the transport capacity coefficient. Here we used an adapted formula to calculate transport capacity as suggested by Verstraeten *et al.* (2007):

$$TC = KTC \times R \times K \times A^{1\cdot4} \times S^{1\cdot4} \tag{3}$$

where, TC is the transport capacity (kg m^{-2} yr^{-1}), KTC is the transport capacity coefficient (−), R and K are the rainfall intensity and soil erodibility factor of the RUSLE, A is the upslope area (m^2), and S the local slope gradient (m m^{-1}). The difference between this equation and the original formulation of sediment transport capacity is that it allows a high transport capacity throughout zero-order basins, which is essential in basins where gully erosion is an important erosion process (de Vente *et al.*, 2007b, Verstraeten *et al.*, 2007).

Once soil erosion and sediment transport capacity are known for each pixel, sediments are routed through the basin towards the river along a runoff pattern that is calculated with a multiple-flow algorithm (Desmet and Govers, 1996a). The location of the check-dams within the catchment was introduced in the model as sedimentation areas within the channels using the calculated trap

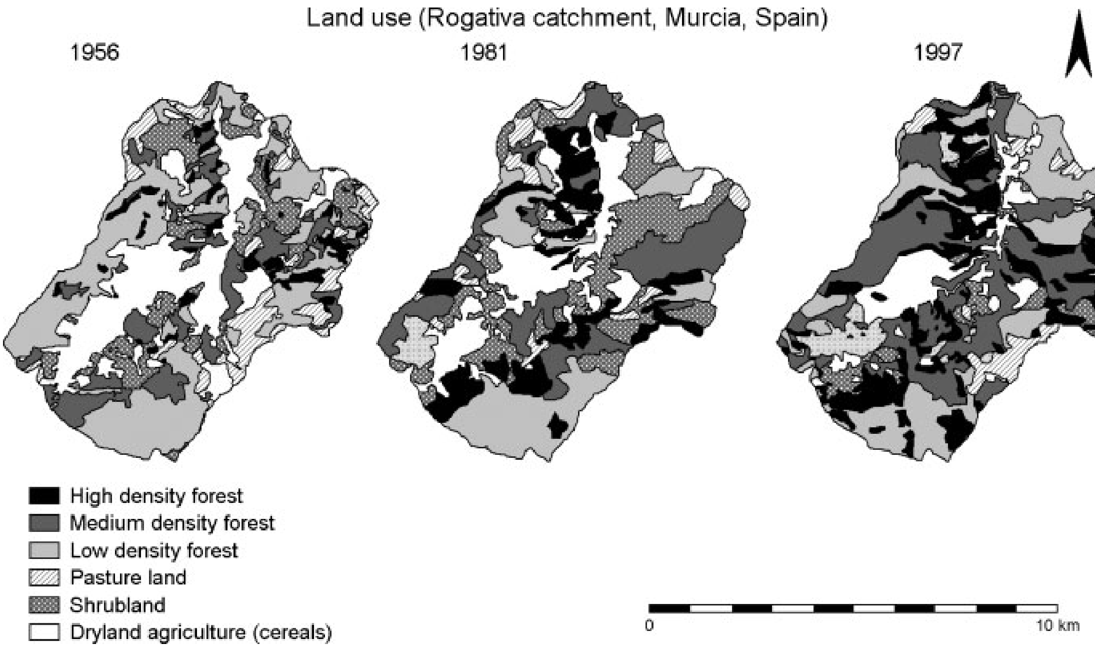

Figure 3. Land use maps 1956, 1981, 1997 (modified from Boix-Fayos *et al.*, 2007) derived from air photographs

Table III. Area covered by different land uses in 1956, 1974, 1981 and 1997 (data from different sources: 1956, 1981 and 1997 from digital air photographs, 1974 from Landsat MSS satellite image)

	1956 km^2	1974 km^2	1981 km^2	1997 km^2
Forest (total cover)	24·42	25·18	25·34	36·13
Forest (high + medium density)	9·08	16·20	16·98	26·03
Low density forest	15·34	8·98	8·36	10·10
Shrubland	6·00	7·91	9·92	2·47
Pasture land	4·04	0·90	2·13	2·73
Dry land agriculture	12·07	12·48	9·15	5·21

Table IV. Change in landscape metric indicators between the studied periods

	Perimeter to Area ratio (km km^{-2})			Fragmentation index		
	1956	1981	1997	1956	1981	1997
High density forest	25·09	11·93	4·54	0·055	0·030	0·035
Medium density forest	15·94	7·94	3·71	0·038	0·020	0·024
Low density forest	9·16	7·05	9·17	0·024	0·018	0·023
Shubland	14·73	11·43	18·41	0·037	0·027	0·041
Pasture land	15·06	14·05	13·03	0·037	0·036	0·032
Dry land agriculture	9·47	10·75	12·93	0·023	0·025	0·029
Mean values	14·91	10·53	10·30	0·036	0·026	0·031

efficiency for each dam. In this way calculation of sediment yields for each river segment upstream of each check-dam was carried out.

RESULTS AND DISCUSSION

Land use scenarios and sediment yield data

Large differences in land use occurred between 1956 and 1997. The area occupied by high density forest increased 4·8-fold, the area covered by medium density forest increased 2·3-fold and the area dedicated to agriculture decreased by 57% (Table II, Figure 3). By 1981 many important land use changes had already occurred, the high density forest had already increased 3·5-fold, the medium density forest had increased 1·42-fold and the agricultural land had been reduced by 24% by that time. Also remarkable is that the area covered by shrubland had increased in 1981 1·65-fold.

The land use map derived from the satellite image of 1974 offers an image of the situation just before the start of the hydrological correction works (reforestation and check-dam construction) in 1976. Table III offers a comparison of the land use areas at the four dates after aggregation of the classes, high- and medium-density forest. However, the 1974 land use map is difficult to compare with those of 1956, 1981 and 1997 because of the different spatial resolution of the remote sensing sources (see methods section). In the classification of the 1974 satellite image the class 'pasture land' produced confusion with the class 'dryland agriculture', and as a result the pasture land class is probably underestimated. Nevertheless, the different land use classes in 1974 occupy areas of very similar size to those in 1981, which means that important changes in forest cover had already occurred before the initiation of the hydrological correction works of 1976. The total forest cover in 1974 had approximately the same extension as in 1956 (24·42 km^2 and 25·18 km^2, respectively) but a higher density of forest in 1974 can be observed through the increase of the area with high- and medium- density forest (9·08 km^2 and 16·20 km^2 in 1956 and 1974, respectively) and a decrease in the low-density forest. On the other hand, the area of agricultural land in 1974 had not decreased with respect to 1956 (Table III).

The spatial pattern of land use also experienced important changes during the whole study period, as indicated by the fragmentation index and the perimeter to area ratio (Table IV). The perimeter to area ratio is the highest for high density forest and medium density forest and the lowest for agricultural land in 1956. The fragmentation index is the highest for high-density forest and the lowest for agricultural land in 1956, while in 1997 the fragmentation index was still high for high-density forest but had considerably decreased with respect to 1956. For agricultural land the fragmentation index had slightly increased in 1997 with respect to 1956. All these indicators show that agricultural land had low fragmentation and was well connected in 1956. However the land use mosaic in 1997 shows a decreased area of agricultural land with higher fragmentation than in 1956. These results are comparable with those obtained by Vanacker *et al.* (2005) in a comparison of land use changes between 1963 and 1995 in the Deleg catchment in Ecuador, where the barren land was characterized by a strong increase in fragmentation during the study period.

Absolute sediment yield (Table I) and specific sediment yield for the subcatchments (Figure 4a) of all 58 check-dams within the study area was estimated based on the measured sediment volumes trapped behind the check-dams. The specific sediment yield values vary between 0·25 t ha^{-1} yr^{-1} and 107·33 t ha^{-1} yr^{-1} for subcatchments of 352·4 ha and 1·1 ha, respectively (Figure 4b). Specific sediment yield values are drastically reduced at catchment areas larger than 40 ha; above this threshold 85% of the subcatchments show specific sediment yield values lower than 2 t ha^{-1} yr^{-1} (see Table I for catchment areas and Figure 4a for specific sediment yield, subcatchments with a drainage area larger than 40 ha belong to check-dams 2, 3, 5, 8, 9, 15, 17, 18, 20, 22, 23, 25, 26, 27, 28, 30, 33, 37, 38, 41, 48, 49, 50, 51, 56, 58). A large variability in specific sediment yield was observed and in general, sediment yield decreased with increasing catchment area (Figure 4b). This situation slightly differs from the model proposed by de Vente and Poesen (2005), where an increase in specific sediment yield values was described in subcatchments until 1 km^2, and a decreasing tendency above this threshold.

The check-dams with catchment areas >40 ha and with SSY > 2 t ha^{-1} yr^{-1} are marked in Figure 4b. These correspond to the subcatchments of check-dams located in the main channel of the Rogativa catchment. In Figure 4c the specific sediment yield estimated from check-dams located in the main channel of the Rogativa are plotted from upstream to downstream. There is a slight increase in SSY in the downstream direction; it is possible that this can be caused because other erosion processes, such as channel erosion and bank erosion from a certain threshold, are introducing large sediment yields in the main channel, as has been observed for other cases (de Vente *et al.*, 2007a).

Model calibration

The WATEM-SEDEM model was calibrated for the entire study catchment using the 1981 land use map as the land use scenario and including within the model the position of the check-dams. The land use of 1981 was used for calibration because it was considered the most representative of the land use pattern at the time of construction of check-dams (1976–1977), and furthermore it has a high level of detail (i.e. more than the 1974 map). Only the subcatchments with non-silted check-dams were used for the calibration procedure, since sediment yield of subcatchments of silted dams is less accurate because it is not known when the dams were silted and so no accurate sediment yield can be calculated. The limitation of this approach is obviously that the non-silted check-dams are probably located in the less erodible subcatchments, thus an underestimation of sediment yield for the whole catchment is expected in the modelling exercise. However, given that the objective of the paper is to compare the relative impact of land use scenarios and check-dams on the total sediment yield, the suggested approach is considered valid for relative comparisons.

The WATEM-SEDEM model was run with a wide range of transport capacity coefficients (*KTc*). The *KTc* values in Equation (3) were assigned for two contrasting land cover categories, reflecting their different sensitivity to overland flow sediment transport. For well-vegetated surfaces (i.e. natural vegetation classes) a low *KTc* value was used (*KTc* Low), and for poorly-vegetated surfaces (i.e. dry land agriculture) a high *KTc* value was applied (*KTc* High). For each parameter combination (i.e. *KTc* Low and *KTc* High), the absolute sediment yield (*SY*; t yr^{-1}) was calculated for each catchment. The optimal *KTc* values were selected according to the model efficiency

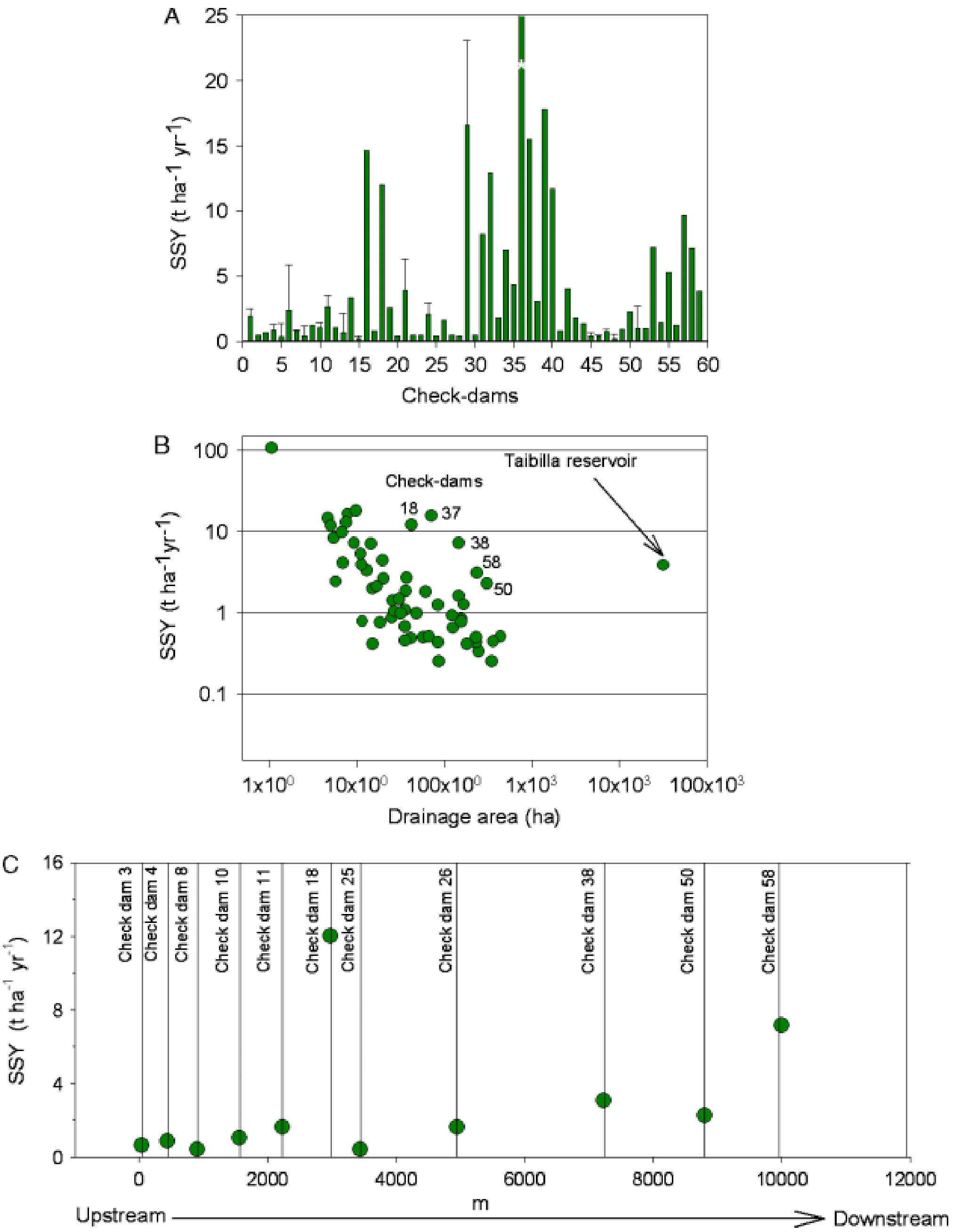

Figure 4. (a) Specific sediment yield estimated at the 58 subcatchments of the check-dams. The error bars represent the change in sediment yield estimated with the loss of trap efficiency of the check-dams since the moment of their construction (1976–1977), until the moment of sediment volume estimation (2003). The change in sediment yield due to the loss of trap efficiency is only represented for the non-silted check-dams, the silted check-dams have lost their trap efficiency completely and are supposed to let pass through all the sediment produced (∗107·33 t ha^{-1} yr^{-1}). (b) Specific sediment yield versus drainage area at the check-dams subcatchments with indication of the relation with the Taibilla reservoir. (c) Specific sediment yield in the check-dams located along the main stream of the Rogativa catchment

(ME) described by Nash and Sutcliffe (1970):

$$ME = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - O_{mean})^2} \qquad (4)$$

where n is the number of observations, O_i is the observed value, O_{mean} is the mean observed value and P_i is the predicted value. The closer the ME value approaches 1, the more efficient the model is. It was decided to calibrate on absolute sediment yield (t yr^{-1}) instead of relative sediment yield (t km^{-2} yr^{-1}) since the objective of the study was to assess the effect of land use changes and the construction of check dams on absolute sediment output from the catchment.

The optimal KTc values were 10^{-6} for KTc Low and 3×10^{-5} for KTc High, showing a model efficiency of 0·84 (Figure 6). The model efficiency obtained in this application falls within the range of model efficiencies obtained in previous applications of the WATEM-SEDEM. Model efficiencies reported oscillate between 0·14 and 0·89 for applications of WATEM-SEDEM in

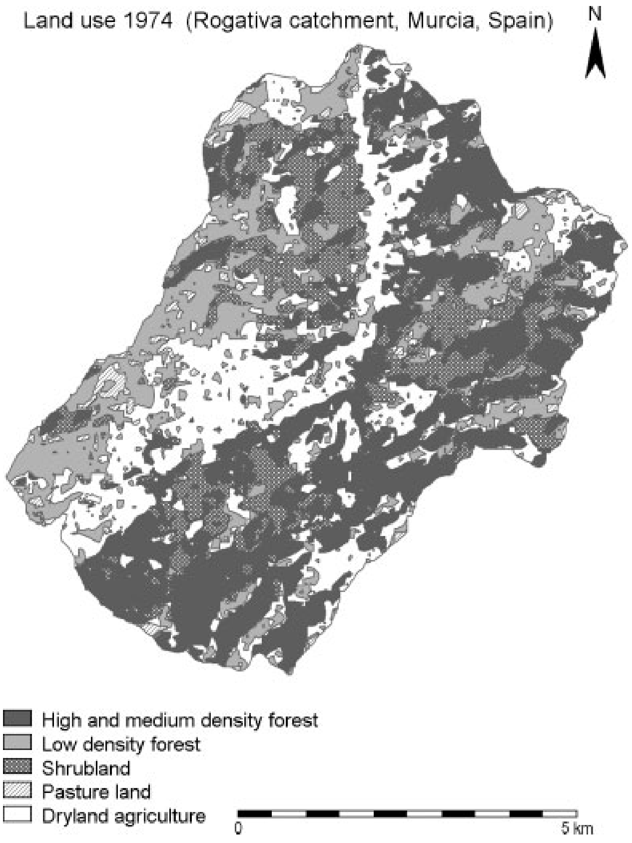

Figure 5. Land use classification extracted from the Landsat MSS image of January 1974

Italy, Belgium, Spain, Australia and Czech Republic (Van Rompaey *et al*., 2005; Verstraeten *et al*., 2006; de Vente *et al*., 2007b; Verstraeten *et al*., 2007 and Van Rompaey *et al*., 2007, respectively).

Influence of land use changes and check-dams on sediment yield

After calibration, the WATEM-SEDEM model was run with six scenarios. First, modelling the effect of different land use patterns (scenarios with land use of 1956, land use of 1981 and land use of 1997) and check-dams (original scenario with land use of 1956 and check-dams) on sediment yield separately; and the combined effect of land use patterns and check-dams (scenario with land use of 1981 and check-dams; scenario with land use of 1997 and check-dams). Table V shows the main results of the modelling exercise. The results of the model applied to the land use scenarios without check-dams show a progressive decrease in sediment yield from 1956 to 1997, which can probably be explained by the increasing forest cover and decreasing dryland agriculture from 1956 to 1997 (Table II). With the 1981 landuse scenario a 44% decrease of sediment yield with respect to 1956 appears. In 1997 a 54% less sediment yield appears with respect to 1956. Notice that between 1981 and 1997 sediment yield was reduced only 10%, whereas a decrease of 9% in agricultural areas and an increase of 18% in forest cover was observed.

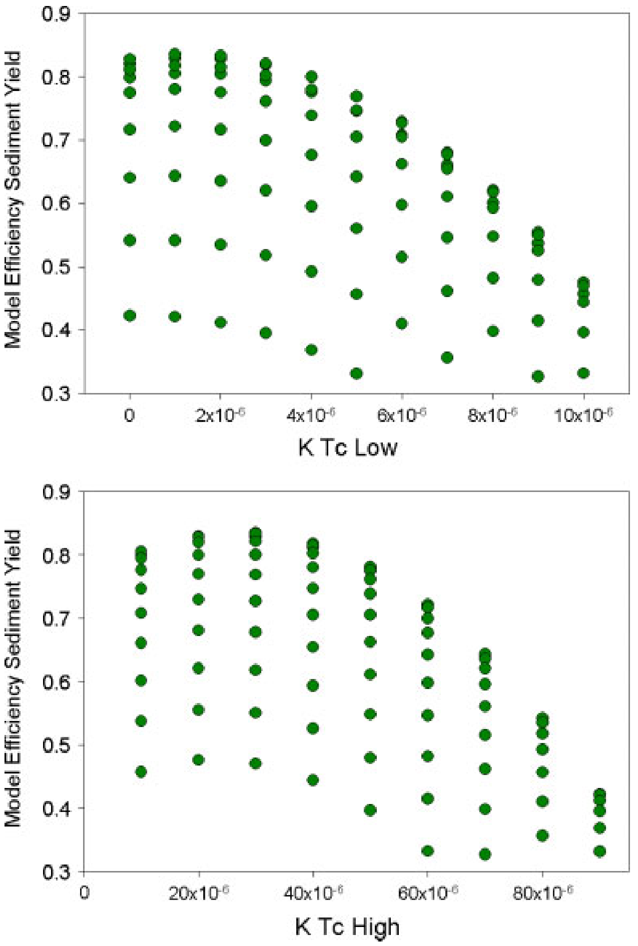

Figure 6. Calibration curves using the land use scenario of 1981 and the non-silted check-dams

Table V. Results of the modeled sediment yield at the catchment scale under different land use scenarios with and without check-dams

	Land use scenarios		
	1956	1981	1997
Sediment yield			
Without check-dams	1123 t	632 t	519 t
With check-dams	257 t	19 t	137 t
Decreased sediment yield			
Without check-dams	—	−44 %	−54 %
With check-dams	−77 %	−98 %	−88 %
Sediment retained behind check-dams	866 t	613 t	382 t
Retention of the total produced sediment	77%	97%	74%

With a scenario without land use change (maintaining the 1956 landuse scenario) but with the construction of check-dams, there is a decrease of 77% sediment yield. In a scenario of land use change and check-dams in 1981, there is a decrease of 98% of sediment yield. With a scenario of land use changes and check-dams in 1997, the sediment yield was reduced by 88%. The 58 check-dams network added a 54% reduction in sediment yield to the land use scenario of 1981, and a 34% reduction in sediment yield to the land use scenario of 1997.

The greatest control of sediment yield in the long term is made by land use; in 1981 sediment decreased 44% but most of it went to the dams (97%); in 1997 sediment yield decreased 54%, 10% more, but only 74% went to the dams (Table V). The most likely explanation for this is that there were no dams close to the most important source areas of sediment in the land use scenario of 1997. This stresses the importance of the landscape pattern and connectivity for the prediction of sediment yield, as was earlier mentioned by Van Oost *et al.* (2000) and Bakker *et al.* (2008).

The application of one type or another of sediment control measures (e.g. reforestation or check dam construction), or a combination of them, depends on the objective of the management and on the environmental conditions of each specific area. For example, when the objective is to drastically reduce sediment delivery in badland areas with high difficulties for the establishment of vegetation, it will probably be more efficient to combine check-dams with adapted revegetation strategies for the area. A recent proposal focuses on re-vegetation strategies that reduce the connectivity of overland flow, after evaluation of past reforestation experiences that induced landscape degradation (Recondes team, 2007). It must be taken into account that check-dams induce erosion processes downstream (Boix-Fayos *et al.*, 2007; Castillo *et al.*, 2007). Romero-Díaz *et al.* (2007b) estimated that up to 20% of the sediments retained by the dams could be induced by the construction of upstream check-dams and access tracks. In general check-dams are a temporary solution because they often fill up rapidly.

In contrast, in areas without urgent problems related to high sediment delivery from rivers and streams, sufficiently deep soils and favourable climatological conditions for the establishment of shrubland and forest, revegetation is a suitable and sustainable solution to reduce catchment sediment yield. In the case of the Rogativa catchment, the environmental conditions caused a very positive evolution of the forest cover detected between 1956 and 1974, just before the reforestation and hydrological control works. The model application showed an important control of land use on sediment yield in this area. Sediment yield was reduced by up to 54% only by changing land use conditions. Therefore, it is likely that the natural recovery of the forest together with the progressive abandonment of agriculture would have led to an important decrease of sediment yield before the construction of the check-dams. This makes the relevance of the construction of the check-dams as an additional measure in the Rogativa catchment questionable.

CONCLUSIONS

Both land use changes and check-dams are effective measures decreasing sediment yield in catchments, however they act at very different temporal scales. Check-dams are very effective in the short term but potentially increase erosion downstream. In the studied catchment the effect of land use changes (mainly decrease of agricultural activities and increase of forest cover) decreased the sediment yield by 44% in 25 years and 54% in 40 years. The addition of 58 check-dams to the land use pattern of 1997 meant an extra decrease of 34% in sediment yield. The construction of check-dams without land use changes with respect to the 1956 scenario controlled 77% of the sediment yield in the study area. In the case of the Rogativa catchment it seems that the change in the spatial pattern of land use at the moment of the construction of check-dams could have reduced sediment yield already by 40%.

Land use changes are long-term sustained sediment control measures compared with check-dams, which are short-term effective sediment control measures. The use of each of them should be conditioned by the environmental characteristics of the area and the specific objectives of the management project. In high erodibility areas with problems for vegetation establishment, check-dams can be effective for reducing sediment yield. In areas with favourable conditions for vegetation establishment, land use changes leading to an increased vegetation cover are sustainable measures to reduce sediment yield, and check-dams can be confined to important source areas of sediment.

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