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Sediment yield estimation and check dams in a semiarid area (Sierra de Gádor, southern Spain)

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Abstract The carbonate massif of the Sierra de Gádor (southern Spain) constitutes the natural recharge area of the Campo de Dalías aquifer system. The Campo de Dalías is a semiarid area covered by 20 000 ha of greenhouses yielding significant economic returns. The uncontrolled development of this agricultural activity has produced an increase in the risk of flooding. In 1977 the Spanish authorities carried out a soil and vegetation restoration programme that included the construction of 107 check dams. The effectiveness of the check dams in trapping sediment has been evaluated in the present study. The calculated sediment yield is 50 m^3 km^{-2} $year^{-1}$, although in some basins values of nearly 2100 m^3 km^{-2} $year^{-1}$ have been estimated. These results show the usefulness of check dams, which are numerous in the Mediterranean region, as a tool for quantifying water erosion in small, ungauged basins.

Key words check dams; sediment yield; southern Spain

INTRODUCTION

The sediment yield of a basin represents only a part of the total erosion within the basin, since a significant portion of the sediment is deposited before reaching the mouth of the stream network. In Spain, numerous studies have been undertaken in large reservoirs to determine sediment yield. However, there are few data that relate to small basins due to the absence of dams and the difficulty of undertaking reasonably continuous surveys of discharge and sediment load. The objective of this study was to evaluate the usefulness of check dams for determining the minimum sediment yield in ungauged basins.

STUDY AREA

The study was conducted on the southern face of the Sierra de Gádor, a water-bearing formation that is hydraulically connected with the aquifer units of the Campo de Dalías, where more than 20 000 ha of profitable extra-early crops, mostly under greenhouse cover, are currently irrigated. The area of mountain slopes studied covers 320 km^2 and rises to more than 2000 m. It is made up of 55 small basins with surface areas between 1 and 54 km^2 (Fig. 1). The distance between the highest peaks and the sea is small, which means that the slopes are very steep, giving rise to deep, narrow

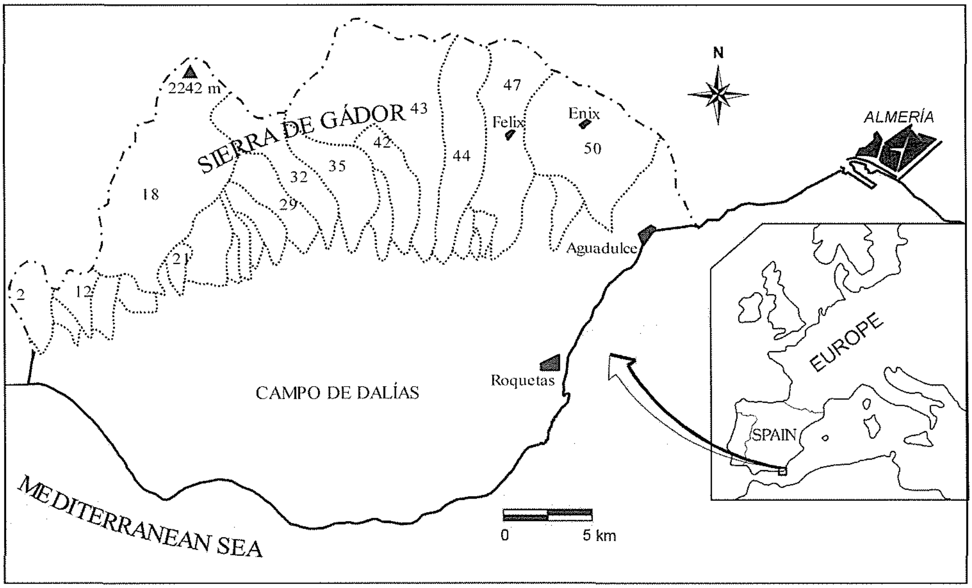

Fig. 1 Site locations. Numbered basins defined by ···· ; hydrological boundary defined by —·—·.

channels; more than 40% of the total area has a gradient in excess of 35%. On the lower slopes, the principal characteristic of the channels is their high width/depth ratio. These ephemeral, gravel streambeds (called *ramblas* in the Spanish Mediterranean region) are dry for most of the year, but become particularly active during flood events.

In terms of lithostratigraphy, the oldest rocks outcropping in the area are metapelites and carbonates that belong to the Alpujarride Units and cover almost all of the southern face of the Sierra de Gádor. These rocks belong to two tectonic units, namely Gádor and Felix, of which the Gádor unit is much more widely represented. The Gádor carbonate rocks can be up to 1000 m thick, and include intercalations of calcoschists and marly limestones. Over these Alpujarride strata, which belong to the Permian and Triassic, lie Miocene rocks. These consist of calcarenites in the outcropping sectors, and marls with gypsum beneath the Pliocene-Quaternary fill. Pliocene materials are widely represented throughout the Campo de Dalías; the base is comprised of up to 700 m of blue marls, with sandy bands occurring with greater frequency towards the top of the series. Quaternary sediments are represented along the entire southern face of the Sierra, and comprise large alluvial fans that locally exceed 150 m in thickness. The deposits of both former and contemporary beaches, together with the fine sediments of the distal parts of the large alluvial fans, complete the materials that occupy the Campo de Dalías.

The area under investigation enjoys a Mediterranean climate characterized by warm, dry summers and mild winters. The scarcity of precipitation (240 mm in the Campo de Dalías and 400 mm on the southern slopes of Sierra de Gádor), the strong insolation (about 2900 h year^{-1}), the interannual variability of precipitation (22–35%) and the high potential evaporation, give a semiarid character to the area. The rainfall gradient has been estimated to be 26 mm/100 m (Martín Rosales *et al.*, 1996a). Temperature increases from an average of 16°C in the mountains to an average of 18.7°C in the Campo de Dalías. Like the rest of the Mediterranean basin, this area is susceptible to very intense precipitation, with up to 200 mm falling in 24 h on occasions (Martín Rosales *et al.*, 1996b).

DESERTIFICATION AND THE NETWORK OF CHECK DAMS

Historically, the Sierra de Gádor has been subject to intense deforestation, which has led to severe degradation of the vegetation cover. The cause of this tremendous loss of vegetation is found in the historical use of wood for boat building, extensive mining in the area during the 19th and 20th centuries, and the felling of oak and pine trees for fuel. It is worth highlighting that Almería, today one of the most deforested provinces in all of Spain, had a significant forest cover during the 18th century. Today, the vegetation in the basins consists of a degraded matorral and steppe as a result of overgrazing. A large part of the area is covered by *secano* (i.e. non-irrigated) land, which has now been almost totally abandoned.

The extensive cultivation of highly profitable greenhouse crops in the area, together with the fact that these same slopes form the natural recharge area of the Campo de Dalías aquifers, have obliged the local administration to set up a programme of reforestation. Amongst other activities, this programme provided for the construction of 165 check dams (of which 107 were built between 1976 and 1993 in 16 basins) to retain the sediments of the various basins, although in some cases they also contribute to the recharge of the aquifers (Martín Rosales, 1997). The check dams have an effective height of between 3 and 14 m, and are up to 45 m long. These dams are located at elevations of between 130 and 1435 m a.m.s.l. They are all gravity-fed structures, trapezoid in cross-section, and provided with weepholes at different levels to avoid prolonged loading during floods. The inventory lists six solid-concrete dams, 29 gabions and 72 masonry dams. Fifty-nine percent of the structures are situated in only four of the basins, namely the ramblas of Carcauz, el Cañuelo, Vícar and las Hortichuelas (Table 1).

CALCULATION OF SEDIMENTATION RATE

The capacity for sediment retention of the entire network of check dams has been calculated to be 431 000 m^3. This capacity, however, has been reduced by 53 000 m^3 (see Table 2). The reduction has been greater in the eastern basins, reflecting the larger surface area of impermeable and easily eroded outcrops (calcoschists and phyllites), as well as the greater deforestation and human impact that these areas have suffered. Moreover, these basins contain various abandoned farm fields where soil conservation practices no longer occur, and this feature further accentuates the erosion phenomenon.

Using the inventory data, the surface area of the corresponding sub-basins and the age of the check dams, we attempted to determine an approximate estimate of the minimum sediment yield (Table 2). The study excluded the sedimentation rates of those check dams that were rapidly silted up as a result of the construction of forest

Table 1 General characteristics of the main basins and summary of the engineering structures.

	Stream	Drainage area (km^2)	Mean slope (%)	Elevation difference (m)	No. of gabions	No. of concrete dams	No. of masonry dams	Total
2	La Estanquera	9.0	31.9	565	–	–	2	2
12	Los Infantes	10.5	30.2	626	7	–	–	7
13	Balanegra	2.9	33.3	571	–	–	1	1
17	Hornales	2.9	38.5	501	–	–	1	1
18	Almodete	49.2	30.5	2024	1	1	7	9
20	Real	1.4	30.1	295	1	–	1	2
21	Ancho	6.3	36.6	1084	–	–	2	2
28	El Capitán	4.7	39.5	1029	–	–	1	1
29	Andrés Pérez	7.0	39.9	1180	–	–	1	1
32	El Aguila	11.1	36.0	1704	–	–	6	6
35	La Maleza	13.2	45.0	1691	2	–	3	5
42	El Tartell	8.4	45.6	1027	1	–	6	7
43	Carcauz	54.1	41.3	1751		2	13	20
44	El Cañuelo	26.7	36.0	1223	4	3	10	17
47	Vícar	27.1	31.6	1259	7	–	6	13
50	Las Hortichuelas	30.3	30.9	998	1	–	12	13
Total number of check dams					29	6	72	107

Table 2 Retention capacity, retained sediments and degree of silting of the check dams.

Basin	Stream	Original capacity (m^3)	Sediments retained (m^3)	Current capacity (%)	SY1	SY2
2	La Estanquera	13 171	1 564	12	14.6	14.6
12	Los Infantes	4 375	3 375	2	11.3	11.3
13	Balanegra	664	13	77	0.7	0.7
17	Hornales	1 359	7	1	0.3	0.3
18	Almodete	21 978	1 495	7	5.8	8.2
21	Ancho	1 824	9	0	0.3	0.3
28	El Capitán	368	13	4	0.5	0.5
29	Andrés Pérez*	5 628	0	0	0.0	0.0
32	El Aguila*	40 783	4	0	0.0	0.0
35	La Maleza	15 599	140	1	0.3	0.9
42	El Tartell	12 585	684	5	6.6	11.1
43	Carcauz	106 553	3 485	3	4.1	1
44	El Cañuelo	111 947	17 942	16	37.3	108.8
47	Vícar	35 105	13 949	40	47.5	2.9
50	Las Hortichuelas	59 159	10 088	17	12.8	8.2
Totals		431 098	52 768	12	17.3	13.0

*Check dams constructed in 1991

SY1: Minimum sediment yield considering all check dams (m^3 km^{-2} year^{-1})

SY2: Minimum sediment yield considering only check dams in sub-basins containing no other works (m^3 km^{-2} year^{-1}).

tracks and roads. Another important factor that was taken into account was the effect of check dams further downstream along the river that could have given rise to errors in the estimates. For this reason, Table 2 includes estimates of minimum sediment yield based only on check dams in sub-basins where no other works had been

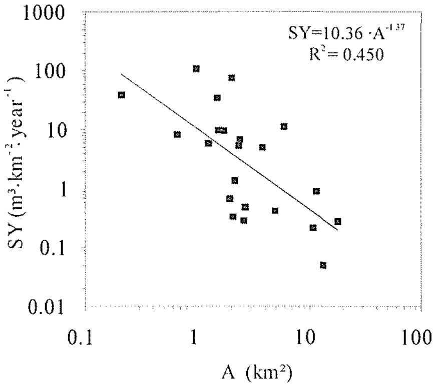

Fig. 2 Relationship between minimum specific sediment yield (*SY*) and drainage area (*A*) of the sub-basins drained by the dam headwaters.

executed. Figure 2 shows the relationship between the rate of sedimentation calculated behind each dam and the respective sub-basin area. The relationship between the calculated minimum sediment yield (*SY*) and the surface area (*A*) is:

$$SY = 10.36A^{-1.37}$$

The degree of correlation between the two variables is not significant ($R^2 = 0.450$) and so additional variables will have to be considered to arrive at an adequate prediction of sediment yield. The poor correlation is attributed to the great variability in land use and lithology, highlighted by other authors in Spain (Verstraeten *et al.*, 2003). In spite of the poor correlation, the data fulfil the theory of sediment sources and sinks (Walling, 1983), according to which the area-specific sediment yield usually decreases following a power function as basin size increases. In any event, the much higher sedimentation rate in basin 47 stands out when compared to the others, yielding a mean rate of 47.5 m^3 km^{-2} $year^{-1}$. There are numerous phyllitic outcrops in this basin, as well as abandoned fields full of rills and gullies. Proof of the significant erosive action is the present state of check dam 62. This dam is a 5-m high gabion, constructed in 1981, which by 1986 showed 100% silting with respect to its theoretical retention capacity. Downstream of dam 62, check dam 60, which in 1986 contained no sediment, was 33% silted up by 1995. This indicates rates of silting-up of the order of 743 m^3 km^{-2} $year^{-1}$, the highest rate estimated for the southern face of the Sierra de Gádor (Martín Rosales, 1997).

Assuming that all of the sediment that reaches the check dam is retained behind it, the sediment yield of the basin would have a minimum value of 17 m^3 km^{-2} $year^{-1}$ (13 m^3 km^{-2} $year^{-1}$, considering only the headwater check dams). However, one must bear in mind the low trap efficiency of this type of structure, given that a large proportion of the sediment that reaches the check dam escapes by means of the weep holes, particularly the material transported in suspension. The trap efficiency of this type of structure is very difficult to estimate because the formulae available have been designed for flow regulation structures that have different characteristics (Heinemann, 1981). In addition, these models do not appear to be appropriate for small reservoirs (Verstraeten & Poesen, 2000). However, on 16 February 1994 we witnessed a small

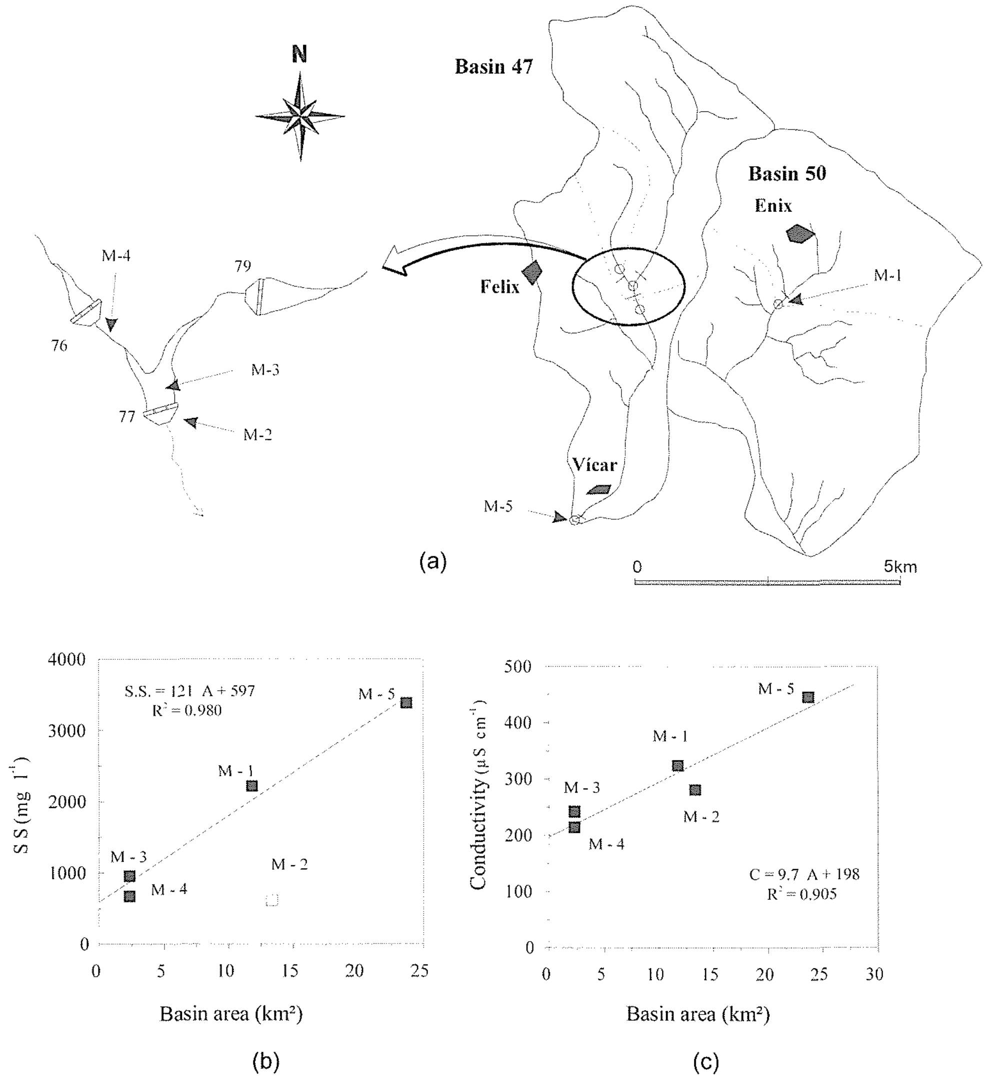

Fig. 3 Topographic map of the location of suspended solids sampling points (a), and relationships between suspended solids (*SS*) and basin area (b), and conductivity and basin area (c).

flood, during which we were able to take samples of suspended sediments in two basins (47 and 50, Fig. 3(a)). The rainfall event lasted 20 h, during which time 72 mm fell. The estimated peak flow for this flood was 4 m^{-3} s^{-1}. The first sample (M-1) was collected in basin 50, some 300 m downstream of check dam 90. The suspended sediment concentration was 2200 mg l^{-1}, with a flow of 200 l s^{-1}. With respect to the samples corresponding to basin 47, the first sample was collected downstream of check dam 76. The suspended solids concentration of this sample was 680 mg l^{-1}, rising to 980 mg l^{-1} as a result of the input from another tributary (which could not be sampled). The sediment concentration downstream of the dam fell to 620 mg l^{-1}. The discharge over the spillway of the check dam at the time of sampling was 945 l s^{-1}. Only 5.5 km downstream, at check dam 70, the suspended solids concentration reached 3380 mg l^{-1}, probably as a result of the large area of phyllite outcrops occupied by *secano* fields draining to this dam. From these results we can deduce that the sediment load downstream of check dam 77 was nearly 65% of that recorded immediately upstream of the check dam; i.e. 35% of the suspended solids would have been retained behind the check dam. This retention effect can also be deduced from Fig. 3(b), which shows the suspended solids concentration plotted against the surface area of the sub-basins sampled. Although the degree of correlation between four of the samples (M-1, M-3, M-4 and M-5) is very high with $R^2 = 0.980$, sample M-2 did not follow this trend. This could mean that the suspended solids concentration of sample M-2 is abnormally low, at least in comparison to the other samples. A similar situation is represented in Fig. 3(c), where electrical conductivity measurements are plotted against the drainage area. In conclusion, considering the difference between the concentrations upstream (M-3) and downstream of check dam 77 (M-2) as equal to the fraction of the load retained behind the check dam, a retention coefficient of 0.35 could be deduced.

DISCUSSION

The results presented above were obtained over the whole network of check dams on the slopes that formed the study area. In an attempt to make a qualitative classification of the intensity of erosion, we have identified three different types of basins based on the mean sedimentation rate (Table 2). The first group, with a minimum sediment yield (*SY*) of between 0 and 4 m^3 km^{-2} $year^{-1}$, corresponds to the basins developed on limestone and dolomite strata and with good vegetation cover. At the opposite extreme lie the basins with sediment yields of between 12 and 50 m^3 km^{-2} $year^{-1}$, which feature significant outcrops of phyllites and calcoschists combined with abandoned *secano* farmlands. The third group shows characteristics intermediate to the first two mentioned, with minimum sediment yields of between 4 and 12 m^3 km^{-2} $year^{-1}$.

If we consider the trap efficiency deduced from the sampling survey to be representative for all the check dams, we would obtain a mean sediment yield for the southern face of the Sierra de Gádor of close to 50 m^3 km^{-2} $year^{-1}$. The maximum value in certain areas would be 2100 m^3 km^{-2} $year^{-1}$, a figure much more consistent with results obtained for the basins of various Mediterranean reservoirs. In the neighbouring basin of the River Adra, which lies on the western boundary of the study area, Carrasco *et al.* (1982) undertook a detailed survey of a retention dam over a period of six years, and obtained values of 100 m^3 km^2 $year^{-1}$. Its basin area covers 198 km^2; it contains a larger proportion of phyllite outcrops but the land use is very similar.

Check dam structures, which are very common throughout the Mediterranean region, could prove very useful for estimating sediment yield in small and ungauged basins. Though their trap efficiency is very low compared to large reservoirs, these dams can reveal the minimum values of the net erosion rate of a basin. Nevertheless, a more detailed study of their trap efficiency is required, in terms of both the suspended and bed load. Likewise, detailed studies are needed to analyse the influence of erosion on the channel and of its capacity for mobilizing sediments, as well as the distance over which these effects are manifest.

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