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Patterns of runoff and sediment production in response to land-use changes in an ungauged Mediterranean catchment

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SUMMARY

Modelling hydrology and sediment yield and its scale dependency has been limited by the quantity and quality of instrumental data. This paper aims to apply alternative methods to estimate runoff and sediment production rates at the event-scale and to characterize the hydro-sedimentary response of a highly torrential Mediterranean catchment to historical changes in land use and vegetation. A selection of well-dated and spatially-distributed check dams within the catchment were used to calibrate and validate a hydro-sedimentary distributed model (TETIS). Sediment volumes deposited by individual runoff events and trapped in check dams were estimated on the bases of detailed stratigraphic descriptions and subsequent GPS/TLS surveys. The model results showed a good agreement with the observed water flows and sediment volumes deposited behind several check dams. Management and land uses proved to be a decisive factor in the hydrological behaviour of the catchment, especially affecting erosion and sediment yield. It was observed that while the hydrological response of the catchment was sensitive to the percentage of each land use type, the sedimentary response was more dependent on the spatial distribution of land use. These differences between hydrology and sedimentary behaviour imply that the optimal soil use distribution for soil conservation may differ from the optimal soil use scenario oriented to attenuate flood peaks. This study suggest that soil use policies and erosion mitigation strategies should consider a holistic hydro-sedimentary approach, in order to become an adaptive option to reduce and mitigate the effects of erosion and flood peaks under global change.

1. Introduction

In Mediterranean regions, soil erosion and desertification studies have been mainly focused on the hill slope or small catchment (<5 km^2) scales (García-Ruiz and López-Bermúdez, 2009; Nadal-Romero et al., 2011). However, watershed and land management practices demand reliable assessment of runoff and sediment yield at the catchment and regional scales. The extrapolation of on-site erosion rates to catchment sediment yield requires attention to high level properties of the catchment and the up-scaling of the surface processes to the scale of interest (de Vente et al., 2007; Wasson, 2002). Moreover, the sediment budget at any point in a catchment is the net result of all processes occurring upstream and conveys spatial and time scale problems related to the sediment connectivity, erosion sources and depositional sinks (Walling, 1983). For instance, in SE Spain the annual sediment yield recorded in a variety of plots and catchment sizes range from 0.02 to 90.68 Mg ha^{-1} yr^{-1} (Romero-Díaz et al., 2007). This reflects an inherent difficulty to characterize sediment production across different spatial and temporal scales. Over the last decades, major research efforts have focused on the development and application of catchment scale modelling as a mean to assess sediment production rates and to analyse the sensitivity of soil erosion to environmental changes (land use/land cover under similar meteorology; de Vente and Poesen (2005). Understanding the hydro-sedimentary response of a catchment to diverse land use configurations requires the implementation of conceptual or physically based models to simulate soil erosion and sediment

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transport processes across varying spatial and temporal scales. The state-of-art generation of spatially distributed catchment models have provided promising insights concerning the simulation of sediment dynamics from slope erosion to sediment routing along stream channels at event scale over long-term simulations (Aksoy and Kavvas, 2005). One of these physically based distributed models is TETIS, which was used in this study due to its good performance in simulating Mediterranean catchments. TETIS is a distributed rainfall-runoff model that includes a sediment yield sub-model capable to simulate catchment hydrology and sediment transport budgets at event scale over long term simulations (Bussi et al., 2013) as well as for future climate scenarios (Bussi et al., 2014a).

Regardless of the hydro-sedimentary model chosen, a major methodological problem to face for its implementation is the lack of reliable benchmark data to support the calibration and validation process. To cope with this limitation, reservoir sediment volumes have been considered in the literature as an alternative indirect method to obtain sediment production rates (Avendaño et al., 1997; Boix-Fayos et al., 2008; Romero-Díaz et al., 2007). This approach provides total sediment yield over time intervals between surveys, but does not supply information of the partial contribution of individual runoff events (Bussi et al., 2013). In Mediterranean regions, large intense rainfall events, as defined by González-Hidalgo et al. (2007) and González-Hidalgo et al. (2012), are contributing a high percentage of the total sediment yield. Therefore it is important to characterize their individual hydro-sedimentary contribution (Benito et al., 2015; Lewin et al., 1995; Machado et al., 2011). In a recent study, Bussi et al. (2013) presented a new methodology for model calibration and validation based on stratigraphic records from sediments stored in a check dam following sedimentary criteria normally used in paleohydrology studies (Baker et al., 1983; Benito et al., 2010, 2003; Corella et al., 2014; Machado et al., 2011). This approach introduces additional aspects to be considered, such as the representativeness of the retained volume of sediment in one check dam compared to the total sedimentary yield from the catchment, as well as the connectivity of sediment delivered by different inhomogeneous sub-catchments. Hence, it is necessary to test this calibration method on larger and more complex catchments where sediment contribution may vary among sub-catchments in relation to the lithology and land-use/land cover conditions. In order to assess the spatial patterns of soil erosion and sediment transport, in this study we propose the use of detailed infill stratigraphy from several check dams distributed all over the catchment area. This allows quantifying with high accuracy the sediment yield of different sub-catchments, which can then be related to land-use variations in space and time.

As a result of the scarcity of data and the complexity of the processes, the hydrological response and the sediment transport in arid and semi-arid Mediterranean areas are challenging to assess. We propose to use jointly check dam infill volumes, check dam stratigraphy and a distributed sediment and hydrological model to gain insights of the hydrological and sedimentary response of a highly complex and flashy semi-arid catchment. The characteristics of the study area can be considered representative of many other Mediterranean catchments in terms of data availability and hydro-sedimentary response. The complexity of the case study requires the use of a distributed model along with indirect data estimation techniques to determine the hydro-sedimentary response of this catchment.

Thus, the purposes of this paper are: (a) to present a multidisciplinary methodological approach for implementation of a distributed hydro-sedimentary model calibrated and validated with sedimentary records from check dams infill deposits in an ungauged Mediterranean catchment, (b) to test the performance of this model to quantify the hydro-sedimentary response to different configurations and historical changes in land use and vegetation cover at the catchment scale and on the long term, and (c) to provide environmental lessons learned from past land-use/land-cover changes implemented during the 20th for water and sediment conservation practices.

2. Materials and methods

2.1. Study area

The study area is the upper Guadalentín River catchment (SE Spain), with a drainage area of 429 km^2 and elevations ranging between 2045 and 687 m a.s.l. (Fig. 1A). The study catchment comprises two main sub-catchments (Fig. 1B): the northern sector is drained by Rambla Mayor and the southern part by the Alcaide River. The Caramel River results from the junction of both streams upstream of the Valdeinfierno reservoir. The climate is Mediterranean (mean annual temperature ~13 °C) with semi-arid characteristics on the lower part of the catchment, and mountainous features in the high elevation reliefs. The mean annual precipitation ranges from 460 mm at the Sierra de Maria to 320 mm at the Valdeinfierno reservoir. Extreme rainfall (>30 mm h^{-1}) is generally characterized by short events (from a few hours to a day) and takes place mainly in spring and autumn. Summers are characterized by dry weather. Soils within the study area show a poor development in agreement with its semi-arid Mediterranean characteristics. In the northern part of the catchment, soils are highly degraded with dominant occurrence of Calcaric Regosols, Cambisols and Calcisols. In the southern part Leptosols are concentrated on the uplands and Regosols on the lowlands (the latter especially in the eastern part, where the majority of agricultural land is located). The soil organic matter content is usually moderately high, in general between 2% and 10%, with maximum values at 17%. The soils are thicker in the lowlands (depth: 50–100 cm) and thinner in the uplands (20–30 cm). The soil texture is mostly clay loam, loam and silt loam, with some sandier patches located in the central part.

The study area is representative of semi-arid Mediterranean regions with an environmental history characterized by dry land agriculture, mainly cereals with rotations of unseeded fallow, and grazing even on steep slopes. Since early 20th century, the studied catchment was the focus of extensive afforestation activities by the Spanish Water Authority to fight against soil erosion and reservoir siltation, which is already a major problem in the study area (>70% of the Valdeinfierno reservoir silted; CEDEX, 1995). The extensive afforestation led to the declaration of the Natural Park of Sierra de Maria-Los Velez as an area of high environmental and cultural value in 1987. The current land management based on forest in the mountain reliefs and agricultural lands in the valley bottoms is representative of other Mediterranean regions (MME, 1998).

2.2. TETIS model and input information description

The TETIS distributed hydrological and sediment model (Frances et al., 2007; Bussi et al., 2013; Bussi et al., 2014a, 2014b) was used to reproduce the hydro-sedimentary response of the Guadalentín River catchment up to the Valdeinfierno reservoir. This model was chosen because it has been largely used in similar catchments and it has also been previously employed for land-use change analysis (e.g. Velez et al., 2009; Salazar et al., 2013; Bussi et al., 2014a; Buendia et al., 2015).

TETIS is composed by two main sub-models: the hydrological and the sediment transport sub-models. The hydrological sub-model is based on a tank structure, where each tank represents a

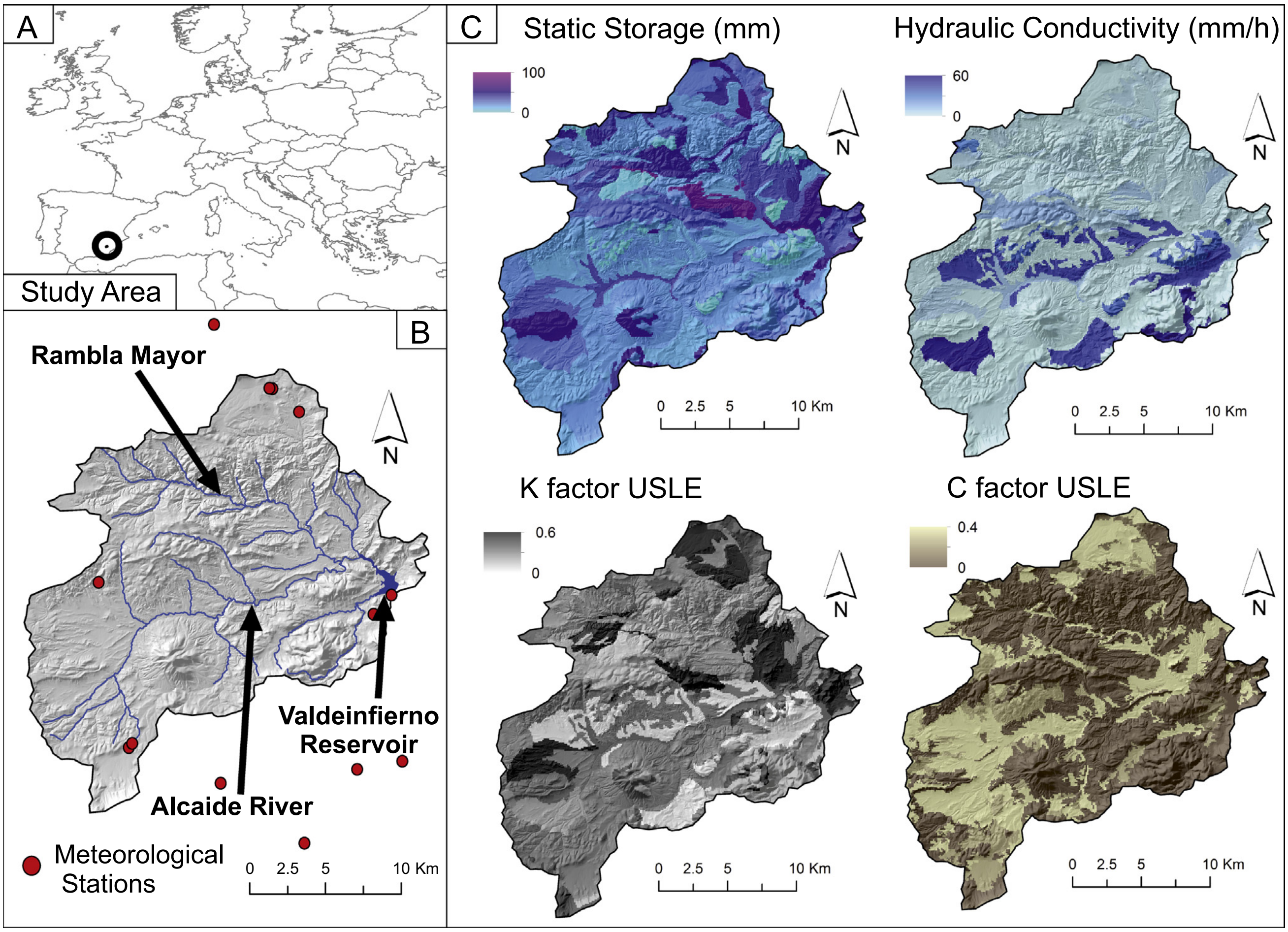

Fig. 1. (A) Location of the study area. (B) Main streams, Meteorological stations and reservoir locations. (C) Maps of the most influent model parameters.

hydrological process (snowmelt, canopy interception, soil static storage, soil gravitational storage and aquifer storage). The precipitation first fills the canopy interception and soil static storage tanks, which can only be emptied by evapotranspiration. Then, the remaining flow is divided into overland flow and infiltration, depending on the soil infiltration capacity. The water infiltrated in the soil is divided into interflow and aquifer flow depending on the soil and aquifer properties. The total flow to the drainage network is calculated by the sum of the overland flow, the interflow and the base flow. The total flow is routed downstream using the geomorphological kinematic wave methodology, which is based on the hydraulic geometry of the drainage network.

The sediment sub-model is based on the balance between sediment transport capacity by flow and sediment availability. The sediment transport capacity of the overland flow is calculated by the modified Kilinc–Richardson equation (Julien, 2010), using the overland flow computed by TETIS as input, and the river transport capacity is computed through the Engelund and Hansen (1967) equation, using the river water discharge simulated by the TETIS model as input. The available material is divided into three classes based on the grain size (sand, silt and clay), and the transport capacity is used to transport all the available material downstream. Then, the particle settling velocity is used to separate the transported material into suspended and deposited sediment.

The split-structure of the TETIS parameters (Frances et al., 2007) allows its calibration without changing the spatial structure of the parameter maps. In particular, the model parameter is the product of the observed or measured value of the parameter (the "actual" parameter value) and a correction factor, which is modified to take into account errors and uncertainty. The model calibration is carried out adjusting up to nine correction factors for the hydrological sub-model (soil static storage, evapotranspiration, infiltration capacity, overland flow velocity, percolation capacity, interflow velocity, deep aquifer percolation capacity, base flow velocity and river flow velocity), and three for the sediment sub-model (sediment transport capacity for overland flow, gully flow and river channel flow). The TETIS model is capable of simulating the hydrological response and the sediment production under different hydro-meteorological conditions, including seasonal streams such as Mediterranean rivers. To implement the TETIS model, several thematic layers and on-site data are needed, including topographical data, lithology, soils, land-use practices, vegetation cover and its seasonal phenology, and meteorological data. This information allows the determination of the hydrologic and sedimentary parameters of the TETIS model (Fig. 1C). In addition, it is necessary to collect hydrological and sedimentary information to calibrate and validate the model.

The topographical information of the catchment was obtained from a digital elevation model (DEM; Table 1). The DEM data was used to generate other raster maps of slope, accumulated cells, flow direction and overland flow velocity. Geological maps were reclassified by lithology and used to calculate the percolation capacity within the area (Table 1).

Soil information maps were adapted from the Spanish Ministry of Agriculture project LUCDEME (Table 1). Based on the LUCDEME project map, the catchment was divided in 50 soil units. A soil unit is an area with the same type of soil, following the LUCDEME map. Soil description and sampling were carried out in 59 profiles. At

Table 1
Spatial thematic layers of the study catchment used on the model implementation.

Spatial information type	Scale	Pixel res. (m)	Periods	Source
Digital elevation model	–	25 × 25	All	National Geographical Institute (IGN)
Geological map	1:25,000	–	All	Geological Survey (IGME); (Baena Pérez, 1972; Baena Perez et al., 1976, 1978; Guzman del pino and Baena Perez, 1978)
Soil map	1:100,000		All	LUCDEME project (Pujalte et al., 1990; Pujalte et al., 1993; Universidad_de_Murcia, 1990a, 1990b)
Land use map year 1956	1:25,000	–	P1	Junta_de_Andalucía (2003)
Forest and agriculture map year 1976	1:50,000	–	P2	Ministerio de Agricultura (1976a, 1976b, 1976c, 1976d)
Land use map year 1990	–	100 × 100	P3	EEA (1995)
Land use map year 2000	–	100 × 100	P4	EEA (2000)
Land use map year 2006	–	100 × 100	P5 & P6	EEA (2006)

Table 2
Results of the hydrologic simulation for the different periods.

Period	No. years	No. days/year with Q	Vol. Obs (Hm^3)	Vol. Sim (Hm^3)	Qmax Obs (m^3/s)	Qmax Sim (m^3/s)	NS
P1 (1971–76)	5	35.8	35.6	23.5	245.6	180	0.91
P2 (1976–84)	8	17.4	21.3	10.5	56.6	41.8	0.67
P3 (1984–95)	11	17.5	33.3	15.1	43.1	24.4	0.25
P4 (1995–01)	6	44.7	9.9	9.4	35.4	28.6	0.67
P5 (2001–09)	8	21.5	13	7.8	12.8	33.4	−0.20
P6 (2009–12)	3	55	11.3	6.7	52.3	59.3	0.84
Total	41	27.3	124.3	73.1	245.6	180	0.81

least one soil sample was collected in each soil unit from the A soil horizon of each soil type, after cleaning all the superficial organic matter, from trenches of 0.1 to 1 m deep. In addition, in areas with anthropic influence such as ploughing, a second deeper sample was collected in order to analyse soil characteristics with and without human influence. All the soil samples were analysed in the laboratory. Analyses included bulk density, organic matter content, electrical conductivity and particle size. The soil sample results were extended to the all matching soil units to create maps of soil hydraulic parameters. In this way, the spatial structure of the soil maps is given by the LUCDEME map and the actual values of the soil properties are obtained from our soil sample analysis.

Temporal changes in land use were taken into account to analyse the impacts of land use and agricultural policies on the hydro-sedimentary response of the catchment. A total of five land use maps were collected and used in this study, representing major land-use changes over the 41 years (1971–2012) of the simulated time period (Table 1). They represented the land uses for specific years and time periods: 1956 to P1, 1976 to P2, 1990 to P3, 2000 to P4 and 2006 to P5 and P6 (refer to Table 2 for the beginning and end dates of the time periods). The land use was considered constant over the above mentioned periods, similarly to what was done by Buendia et al. (2015).

All the land use maps were resampled to 100 × 100 m pixel resolution with five types of land use based on level 3 of the European project "CORINE Land Cover" following the method described by Baartman et al. (2013). The five land use categories considered are Dense Forest, Forest, Scrubland, Agricultural and Urban. For each category a monthly vegetation evapotranspiration coefficient was calculated based on the local vegetation typology and its seasonal phenology, as well as its maximum rain interception. These parameters were obtained from previous studies on the local plant species (Belmonte-Serrano and Romero Díaz, 2006; Belmonte Serrano et al., 1999).

The soil information was combined with different land uses to calculate soil moisture, static storage (soil water holding capacity) and hydraulic conductivity (Fig. 1C). In particular, in this model application, land use was used to estimate three model parameters: the soil static storage (the vegetation determines the soil depth and thus the available water content), the canopy interception (different vegetation types have different interception capacity) and the C factor of the USLE (the land cover influences soil production). For the first two parameters, all the land uses were aggregated to obtain the five land uses presented above in order to simplify the spatial variability and patchiness of the catchment, as done previously in other works (Buendia et al., 2015; Bussi et al., 2014a, 2013). The C USLE factor, which represents the vegetation and management factor, was estimated considering a more detailed classification, following the guidelines provided by Almorox et al. (1994) and also used by Alatorre et al. (2010), Bussi et al. (2014) and Buendia et al. (2015) in other areas of Spain. This classification included a more detailed description of types of agricultural land as well as bare soil and badlands areas which have larger erodibility. Given that the TETIS model is a distributed model, the parameters influenced by land use are also distributed in space. Therefore, the hydro-sedimentary processes affected by land use, such as evapotranspiration, runoff generation and sediment production, are variable in space (and obviously in time). Hence, considering the model as a representation of the natural processes, the model results allow interpreting the effect of land use and its variability on the hydro-sedimentary response of the catchment. Rainfall and temperature series from thirteen meteorological stations provided a discontinuous record since 1918 and continuous since 1971 (Fig. 1B). Nine meteorological stations (Spanish Meteorological Agency; AEMET) contained the longest record at daily scale (1918-present). The other four stations belong to the Automatic Hydrological System (SAIH) of the Segura District Water Authority, with data since 1997 at a half hour resolution. The precipitation records were used to drive the model, while temperature was used to estimate potential evapotranspiration, using the Hargreaves equation (Allen et al., 1998). As the study catchment lacks of stream flow records and the calibration of TETIS model requires hydrological and sediment yield information, water and sediment data were estimated from indirect methods. In particular, the stream flow was derived from the daily water balance of the Valdeinfierno Reservoir whereas the sediment yield was estimated based on reservoir and check dam sedimentation volumes.

2.2.1. Hydrological sub-model implementation

The nine correction factors of the hydrological sub-model were adjusted in order to reproduce the estimated inflow at the Valdeinfierno Reservoir from 1976 to 1984. This period was selected because it has an extended dry period with one major flood. The model was firstly validated for a two-year period from 2011 to 2012. This period was selected for being a short dry period with one severe flooding event. The aim of the selection of this period is to determine if the model is capable of simulating correctly individual flash floods, which are responsible of sediment pulses, in short-timed simulations considering a long calibration period.

2.2.2. Sedimentary sub-model implementation

The sedimentary sub model calibration was carried out using sedimentation volumes trapped in check dams. A total of 279 check dams built from 1956 to 2009 were identified in the study area through unpublished data from Armas et al. (1996), from the Andalucía regional government and from aerial photograph identification. These check dams are over 2.5 m high and have a drainage area of at least 10 ha. A field inspection demonstrated that most of them were of none or little use for our purpose of model calibration/validation due to failing on one or several of the following four criteria: (1) Construction date known; (2) structural integrity (many of them had serious structural issues); (3) representativeness of drainage area and (4) filling capacity (most of them where completely filled and the date of filling was unknown). These criteria were established on previous studies addressing the use of check dam siltation volumes to reconstruct sediment transport in the Mediterranean area (Bellin et al., 2011; Romero-Díaz et al., 2007; Sougnez et al., 2011).

The size, capacity and drainage area of check dams are also key criteria to represent the average sediment yield at the sub-catchment, and not just of local hill slope/gully erosion processes. For instance, Romero-Díaz et al. (2007) used check dams with drainage areas between 0.2 and 3163 ha, Bellin et al. (2011) between 3.9 and 911.1 ha and Sougnez et al. (2011) from 1.5 and 311 ha. According to the above mentioned criteria, only a total of 10 check dams build between 1976 and 2009 were used as sedimentary proxies for the sedimentary sub-model calibration (Fig. 2A).

The selected check dams cover in different proportions all land use categories described in the study area (Table 3). Two check dam catchments are dominated by afforested areas (3 and 10), two by arable land (7 and 8), one is dominated by scrubland (2) and the rest present mixed land use. In terms of bare land or badlands area, almost all check dams present severely eroded areas within their sub-catchments, with check dams 2 and 6 having a

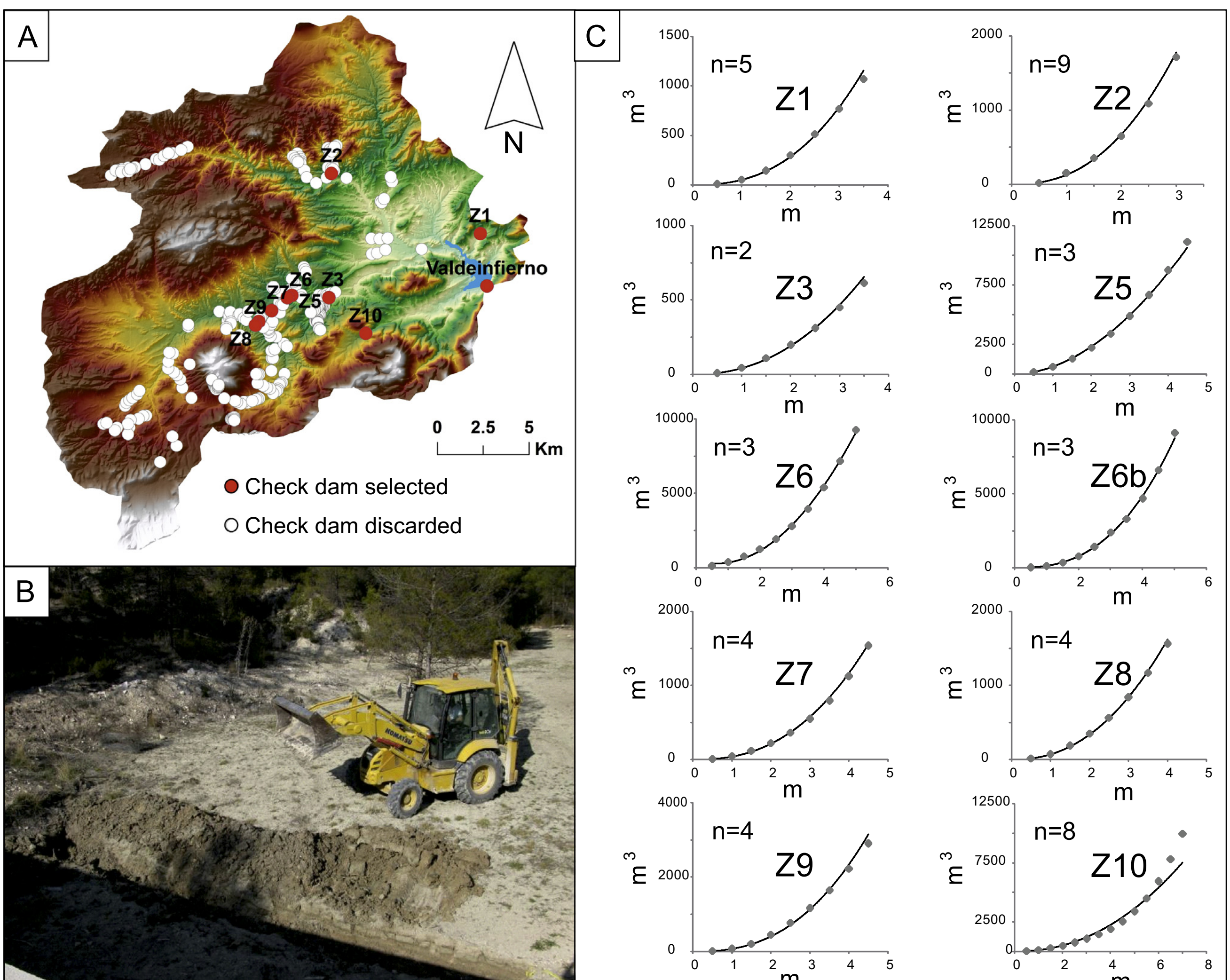

Fig. 2. (A) Check dams located inside the study area. (B) Example of a trench dug in Z5 check dam. (C) Retention curve calculated in each check-dam; n = number of depositional units identified in the stratigraphic survey.

Table 3
Soil use percentages and characteristic data and results of sediment comparison before and after the event of September 2012, for all the check-dams considered in the study.

Checkdam	Constr. year	Drainage area (km^2)	Dense forest (%)	Forest (%)	Shrubland (%)	Agriculture (%)	Urban (%)	Δ Volume (m^3)	Error (m^3)	Catchment Basinerosion (t/Haha)	Error (t/ha)
z1	2001	0.37	31	25	0	44	0	−24.8	1.5	−0.8	0.049
z2	2009	2.41	13	39	48	0	0	77.9	7.7	0.5	0.049
z3	2009	0.51	88	0	6	6	0	9.5	0.3	0.3	0.007
z5	2009	3.79	60	0	20	20	0	1116.8	111.7	3.3	0.325
z6	2009	7.51	40	8	15	36	0	431.4	43.1	0.6	0.060
z6b	2009	7.71	40	8	15	36	0	193.4	17.2	0.3	0.024
z7	2009	0.77	0	0	0	100	0	100.6	2.6	1.5	0.039
z8	2009	0.44	0	0	0	100	0	150.8	3.6	4.0	0.094
z9	2009	0.36	91	0	0	9	0	362.8	7.6	12.6	0.262
z10	1976	9.71	73	4	0	23	0	154.0	3.1	0.2	0.004

large proportion of their drainage area affected by badlands. In addition, check dam sub-catchment areas cover a broad range of catchment sizes, from 0.36 km^2 to 9.71 km^2, thus accounting for different spatial scales, and therefore different sediment produc tion–transport–deposition dynamics. Given these considerations and despite representing only just above 6% of the total surface, the selected check dams are considered representative of all the hydro-sedimentary processes in the catchment. Furthermore, it should be noticed that the hydrological sub-model (on whose results the sediment sub-model is based) was calibrated and validated on the whole catchment, using reservoir inflow data spanning a period of more than 40 years, thus providing a realistic description of the hydrological cycle at the scale of the whole Valdeinfierno catchment.

The superficial area and geometry of the sediment deposits were measured using high-resolution topography surveyed by terrestrial laser scanner (TLS) or differential GPS depending on vegetation cover, accessibility and presence of water in the dam. Where it was possible, a terrestrial laser scanner (Leica Scanstation 2) was used to acquire height point clouds for the superficial area and geometry of the sediment trapped. The instrument has a 360° horizontal and 270° vertical field-of-view, 1-mm accuracy, and can record up to 50,000 points/sec. The laser was mounted on a tripod and it was programed to record points in a 0.02 × 0.02 m grid with 1-mm precision. Different scans were made of each plot to reduce shadows and occlusion from vegetation and topography. Cyclone 7.1 software (Leica Geosystems) was used to overlap the point clouds recorded for each plot, by means of at least four targets in common between scans. In dams where the use of TLS was not possible, topographic data was taken as one point per second measures using Real-Time kinematic (RTK) with a differential GPS (Trimble 4700; between two and three thousand points measured in each dam). GPS data were also collected measuring all the edges of important morphologies within the dam sediment, and dense and spatially distributed random measures in more homogenous surfaces. TLS data were filtered to remove the vegetation signals from the laser points by using two coupled methods: (1) Generalize data resolution to 0.1 × 0.1 m pixel, assigning the lowest height value to the pixel, and (2) in 1 × 1 m areas, erase pixels with anomalous higher values and interpolating values among all neighbour cells (Rodriguez-Lloveras et al., 2014). Filtering was not needed in GPS data.

At least two trenches were dug across the dam sedimentary infill, namely at the front and middle-to-distal sectors (Fig. 2B). On these trenches, detailed stratigraphic profiles and longitudinal diagrams were elaborated. During stratigraphic analysis, a special emphasis was given to contacts between sedimentary units and to the identification of features indicating sub-aerial exposure contacts, which are indicative of post-flow surface exposure. These contacts where used to estimate the sediment volume for each layer (individual flood). In addition, sediment sampling was carried out, in order to perform physical and chemical analysis of each sedimentary layer (organic matter content, conductivity, grain size, etc.). The data collected provided the number of runoff events since the dam construction as well as the level-volume curve for each check dam (Fig. 2C).

Owing to the stratigraphic analysis, time series of sediment pulses were reconstructed at each check dam site, representing the sediment volume accumulated during floods occurred between the check dam construction and the date of the survey. The number of events recorded in the stratigraphy of the dams varied depending on the construction date (Fig. 2C) from 2 (dam Z3) to 9 (dam Z2), with volumes varying from 0.007 (check dam Z3) to 150 m^3 (check dam Z6). Given the size of the sub-catchments and the characteristics of the catchment hydrological response, it appears reasonable to think that these sediment layers were deposited during events which lasted less than one day. Therefore, daily time series of sediment deposited behind each check dam could be generated.

After the first survey campaign, an extraordinary flood event occurred in 28th of September 2012 (~50-yr return period event), and a second survey campaign was conducted. The comparison between surveys provided high precision quantification of sediment volume retained in the dams during the 2012 flood that it was later used for calibrating the TETIS sedimentary sub-model. Unfortunately, check dams Z3, Z7 and Z10 were damaged and Z1 and Z2 were completely silted during the 2012 flood event.

The three sediment sub-model correction factors were adjusted in order to reproduce the reconstructed sediment time series at each check dam. Bulk density of each layer was measured in order to convert from volume of sediment transported by the flow to volume of sediment deposited. The sediment trap efficiency of each check dam was taken into account dynamically (i.e. time-variant) by coupling a trap efficiency model (Verstraeten and Poesen, 2001) to the TETIS model, as presented by Bussi et al. (2013). The TETIS sediment sub-model was therefore used to produce time series of sediment volumes deposited behind all check dams, which were contrasted with the results of the stratigraphic analysis and the data collected before and after the 2012 event. This allowed assigning a date to each layer and to calibrate the sediment sub-model. The sediment sub-model validation was carried out using reported data of the Valdeinfierno reservoir sedimentation volumes obtained from comparison of bathymetric surveys conducted by CEDEX in 1976, 1984 and 1995 (CEDEX, 1976, 1984, 1995).

The TETIS model performance during the calibration and validation processes was evaluated using the Nash–Sutcliffe (NS) efficiency index (Nash and Sutcliffe, 1970) for the hydrological sub-model, and the percent bias (Pbias) and NS coefficients for the sediment sub-model (Moriasi et al., 2007).

3. Results

3.1. Modelling performance

3.1.1. Hydrological modelling

The hydrological model performance was satisfactory, with a Nash–Sutcliffe efficiency coefficient of 0.67 for calibration (1976–1984, P2 in Table 2) and 0.97 for the initial validation period (2011–2012). In both cases the simulated flow (Q sim) showed a good temporal and magnitude agreement with the observed flow (Q obs) and proportional to precipitation (P) (Fig. 3). When all the simulation periods are considered, it is observed that the hydrological sub-model tends to under-estimate the maximum peak flows (Qmax; Table 2). Concerning the rest of time periods, the best simulation accuracy is observed in periods P1 (NS = 0.91) and P6 (NS = 0.84) both covering short time spans with at least one high magnitude flow peak. On the contrary the simulation presents a poor accuracy in periods P3 (NS = 0.25) and 5 (NS = −0.20), representing long time intervals with low number of flows per year (P3), or low magnitude peak flows (P5). Nevertheless, low accuracy in P3 and P5 do not have a significant influence on the long term behaviour of the catchment, as the simulation for the total interval of 41 years shows a good model performance (NS = 0.81).

3.1.2. Sediment yield modelling

The analysis of the sediment accumulated behind the check dams across the catchment, combined with the hydrological simulation, allowed the analysis of sediment patterns corresponding to different land-use environments and drainage areas. Dams damaged during the 2012 event (Z1, Z2, Z3, Z7 and Z10) showed channel formation and/or sand bar progradation upstream the check dam. Check dams not damaged by the 2012 event presented a uniform sediment infill (Z5, Z6, Z6b, Z8 and Z9), with evidences of slope erosion and lateral accumulation (Fig. 4). Sediment volume accumulated during the 2012 event (Δ Volume) showed that catchment erosion was not proportional to the drainage area. In fact, the check dam with smallest drainage area (Z9) presented the highest area-specific sediment yield, while the one with largest drainage area (Z6b) presented the lowest rate of sediment yield per unit area. Other check dams as Z5 and Z8 showed similar erosion rates with very different drainage area. The calibration of sedimentary sub-model with sediment trapped in check dams gave a Nash–Sutcliffe (NS) coefficient of 0.67 and Pbias index of-13.175 whereas the validation (based on 1976 and 1984 reservoir bathymetries) provided a NS of 0.99 and Pbias index of 2.5, giving a satisfactory performance for validation and calibration, in accordance with the hydrological simulation performance (Fig. 5). Considering for validation the second period between the Valdeinfierno Reservoir bathymetries (1984–95), also showed a good performance with values of NS of 0.95 and Pbias of 7.7.

The simulation results showed that the sediment yield within a sub-catchment strongly depends on the maximum peak flow during the analysed period (Table 4). This dependence is either stronger during short periods with a high magnitude events, in which about 85% of total sediment may be displaced, or weaker during long periods with small maximum events where maximum flows transports about 25% of the total sediment.

3.2. Hydro-sedimentary response to changes on land-use

Fig. 6 shows the historical evolution of the land use. Forest land tends to correspond to steep slopes while agricultural fields cover valley bottoms or low slope areas. It can be observed that forested areas tend to decrease with time while agricultural lands tend to extend. Differences in each use extension have little effect on the total runoff volume (Δ 2.97% between minimum and maximum) and maximum daily flow (Δ 1.73% between minimum and maximum). On the contrary, the sediment yield is highly sensitive to changes in land use, presenting variations of 12.31% in sedimentary volume and 17.86% in daily maximum sediment production (Table 5).

Following the model results, the highest runoff total volume (Total Vol. water) and maximum daily flow (Qmax/day water) are generated by the land use configurations with the highest percentage of agricultural lands and low cover of forest land (Fig. 7 and Table 5). Within the configurations analysed, the lowest runoff production was obtained for the 1976 land use, characterized by the highest extension of forest use and the lowest extension agricultural land cover. Conversely, the highest runoff volume occurred corresponding to the 2006 land use configuration, which contains the lowest extension of forest and the highest surface of agricultural land. Concerning sediment transport, the values of total volume (Total Vol. sediment) and maximum daily sediment flow (Qmax/day sediment; Table 5) are highly influenced by the spatial distribution of land uses. Distributions with low cover of forested areas showed the highest values of sedimentary production (i.e. land uses of 1956, 1976), while distributions with more extended forested areas on the slopes gave rise to the lowest sediment yield (i.e. land use of 2000). Differences in vegetation position on the slope between similar land use configurations also gave rise to variations in sediment production. Comparing the two land use configurations with the highest sedimentary production (1956 and 1976), it can be observed that more mature vegetation in gentle slopes, as in 1956 map, gave a higher value of total sediment volume, while distributions with more mature vegetation in the

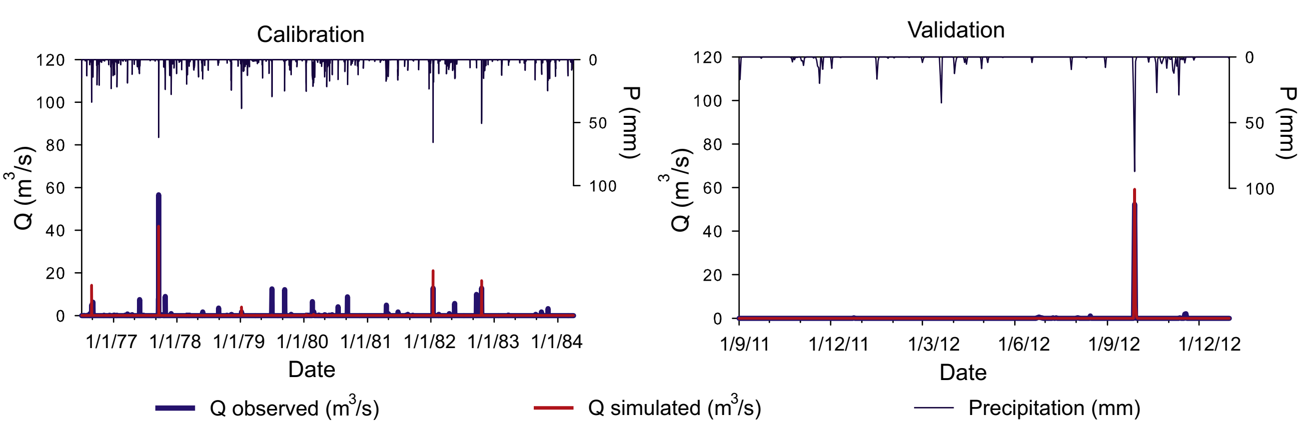

Fig. 3. Precipitation, observed flow and simulated flow for hydrologic sub-model calibration and initial validation periods.

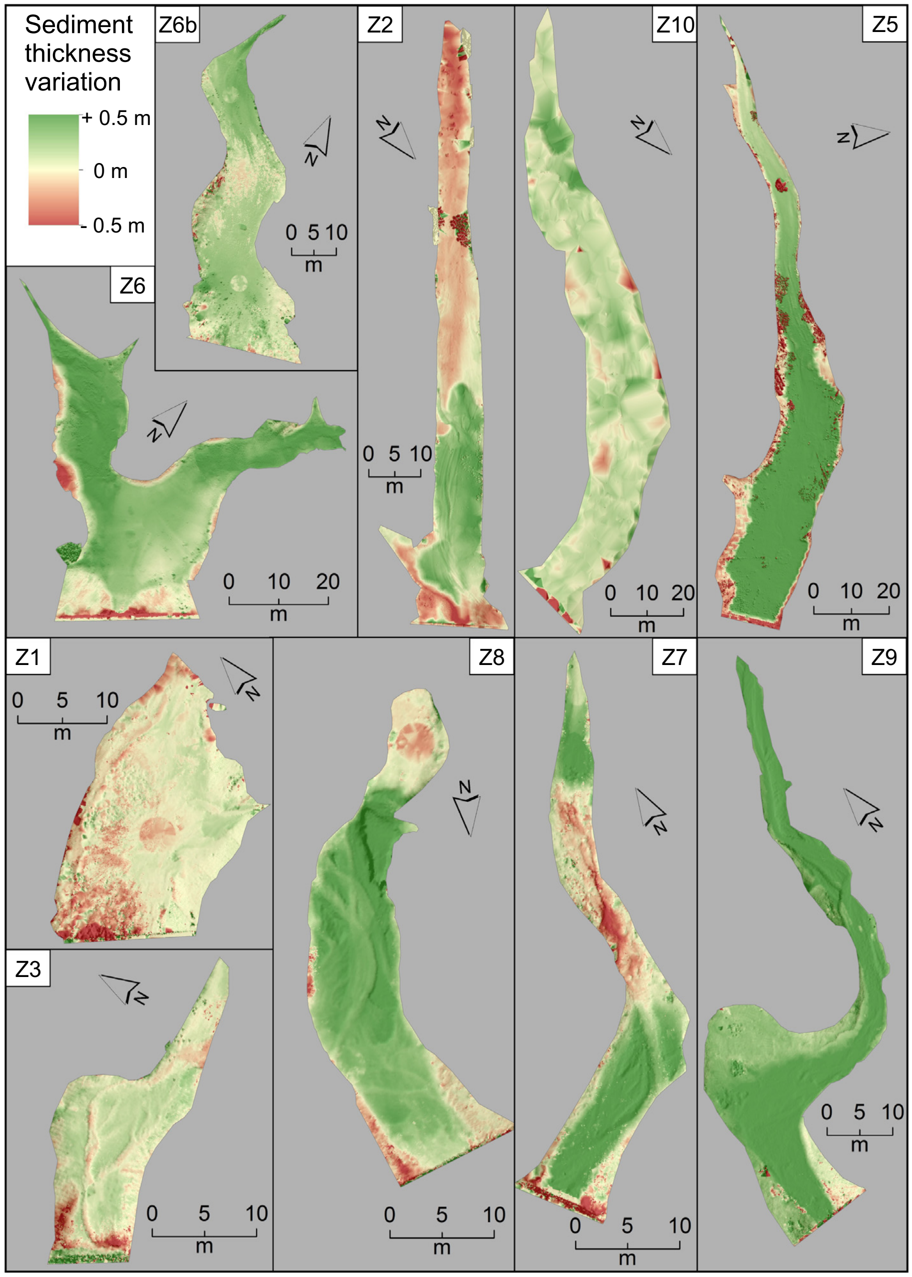

Fig. 4. Increment of sediment produced by the event of September 2012 in the study check-dams.

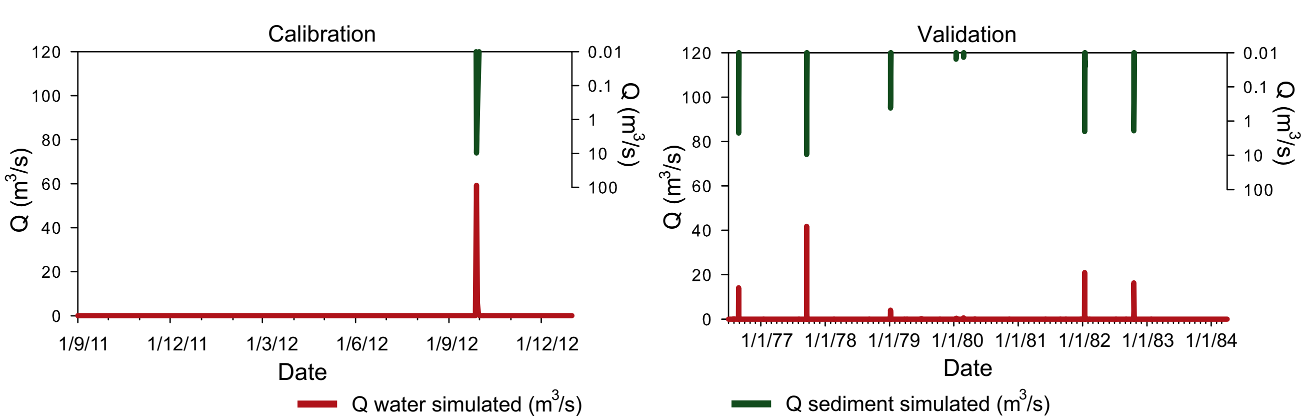

Fig. 5. Simulated water flow and sedimentary flow for sedimentary sub-model calibration and initial validation periods.

Table 4
Results of the sedimentary simulation for the different periods.

Period	No. years	Total Vol. (Hm^3)	Daily Qmax (m^3/s)	Erosion Qmax (t/Ha)	Annual erosion (t/Ha)	Qmax contribution on total erosion (%)
P1 (1971–76)	5	7.9	75.9	157.6	38.0	82.9
P2 (1976–84)	8	1.6	9.5	19.8	4.7	52.1
P3 (1984–95)	11	1.6	4.2	8.7	3.5	22.3
P4 (1995–01)	6	1.1	3.6	7.5	4.5	27.7
P5 (2001–09)	8	1.1	4.9	10.2	3.2	40.6
P6 (2009–12)	3	1	9.8	20.3	7.9	85.2
Total	41	14.3	75.9	157.6	8.4	46.0

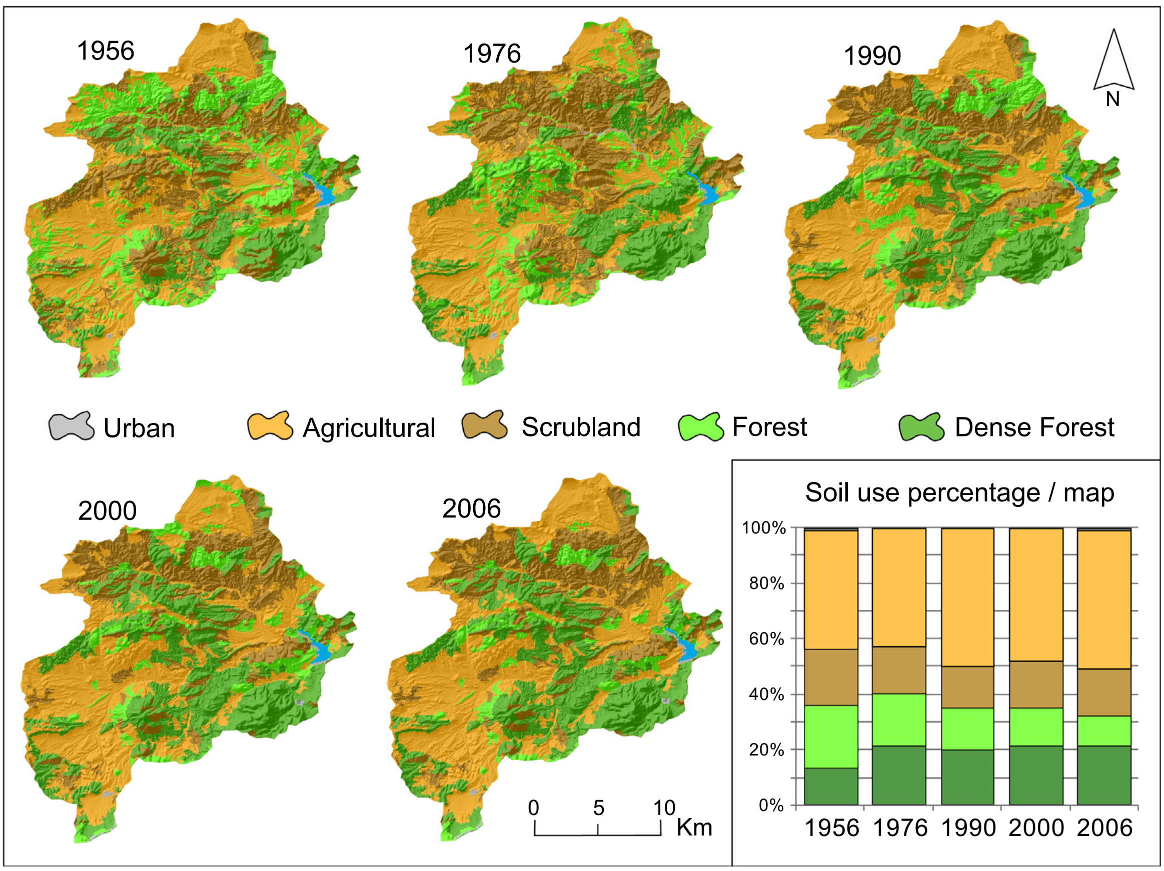

Fig. 6. Spatial distribution and percentage of the different soil use scenarios considered in the study.

Table 5
Results of the hydrologic and sedimentary simulations for the different soil use scenarios. The italic font highlight the lowest values and bold font the highest.

Variable	Allmaps	1956	1976	1990	2000	2006	Max dif. (%)
Total volwater (Hm^3)	73.1	73.2	*71.3*	73.3	73.2	**73.5**	**2.97**
Qmax/day water (m^3/s)	180.0	180.0	*177.7*	180.4	179.2	**180.8**	**1.73**
Total volsediment (Hm^3)	14.3	**14.6**	14.5	14.3	*12.8*	14.4	**12.31**
Qmax/day sediment (m^3/s)	75.9	75.9	**80.9**	75.1	*66.5*	75.1	**17.86**

high relief mountain as 1976 map present higher value of maximum daily sedimentary flow. These results demonstrate the high sensitivity of sediment transport to land use changes.

4. Discussion

The TETIS model simulations using proxy and reservoir data in an ungauged catchment showed good performance compared with the accuracy ranges for spatially distributed models presented by Moriasi et al. (2007). It was observed that the TETIS simulations are influenced by local and regional climatic conditions, precipitation volume and intensity, flow characteristics (intensity and magnitude), length of simulated period and the initial data accuracy (Bussi et al., 2014a; Velez et al., 2009). The best model performance was obtained during relatively short periods of simulation containing a high flow peak, presenting very accurate results simulating high magnitude floods. Conversely, the poorest model performance was obtained during long periods with low magnitude events.

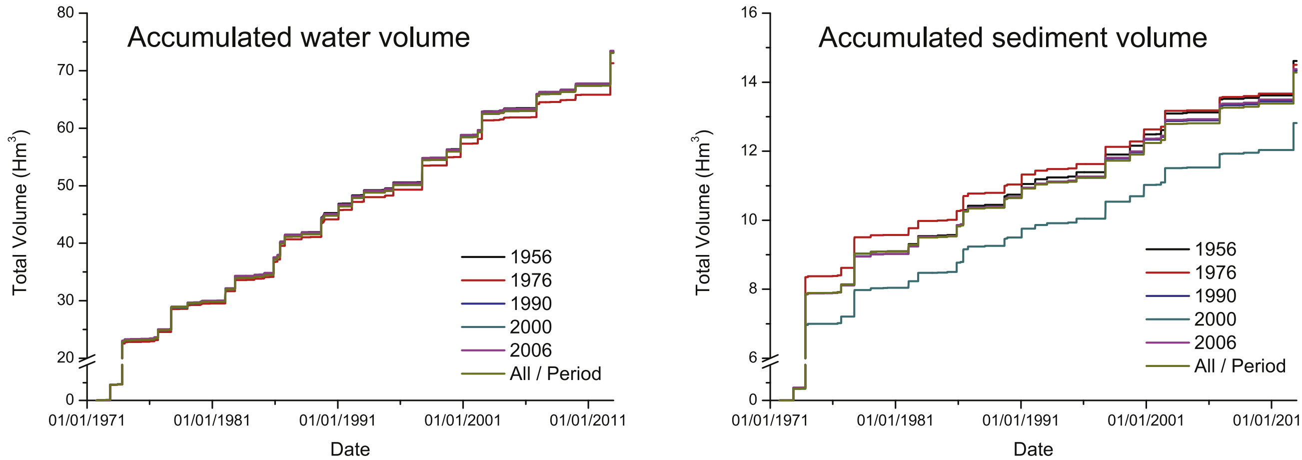

Fig. 7. Simulated water and sedimentary accumulated for each soil use configuration during all the interval considered (1971–2012), and for each use in each period (all/period).

Comparing the results of the hydrological sub-model with the observed water discharge values obtained from reservoir level records, it was detected that the TETIS model tended to underestimate the flow peaks. This is a recurrent result as it was described in different studies using TETIS (Bussi et al., 2013; Coccia and Todini, 2011; Velez et al., 2009), but did not appear to have a major effect on the sediment model performance, which was still very good (following Moriasi et al., 2007).

Comparison of simulated sediments with sediment trapped in check dams and in the reservoir at different time length periods indicated a good performance at the catchment and check dam sub-catchments scales and reduced to acceptable levels the scale lumping described by Walling (1983). The amount of check dams with the optimal characteristics available to determine the sediment transport was smaller than in previous studies (i.e. Romero-Díaz et al., 2007; Bellin et al., 2011; Sougnez et al., 2011). It is believed that this factor adds extra value to the model results, since the combination of model with sedimentary information provided a satisfactory description of the catchment sedimentary behaviour. This information (filled check dams and/or large reservoirs) can be found in many arid and semi-arid Mediterranean catchments, and therefore the methodology presented in this study can be considered highly transferable. The results presented in this study disagree with previous works, which indicate that calibration of hydrologic and sedimentary distributed models in small catchments is not representative of larger areas (Takken et al., 1999; Van Rompaey et al., 2005). As presented by Romero-Diaz et al. (2011), different techniques for measuring erosion in similar environments may give rise to a wide range of denudation results. Several techniques and studies considered by Romero-Diaz et al. (2011) such as geomorphologic transects (Takken et al., 1999), are focalized in small areas with predominant processes such as badlands, formation or slope erosion and do not cover all the environments within the basin. Other techniques, implemented at the catchment scale, such as reservoir bathymetries (Van Rompaey et al., 2005), are not precise enough to reproduce the erosion processes during single events. In our study, these problems were minimized by using the sediment volumes deposited behind check dams for the sediment sub-model calibration in catchments covered by a variety of land-uses and erosion processes, combined with an acceptable sedimentary connectivity between the different sub-catchments.

Sediment sub-model results showed that the largest sediment volumes were produced during the largest precipitation-runoff events, which it is an inherent characteristic of the hydro-sedimentary behaviour of Mediterranean catchments (González-Hidalgo et al., 2007; González-Hidalgo et al., 2012; Baartman et al., 2013; Bussi et al., 2013). Hence, the basin sedimentary behaviour is controlled by the frequency and magnitude of these events, implying that analysis and management of erosion should consider its spatial and temporal distribution individually, since average erosion rates may not be representative of the phenomena. This statement is supported by the model results, which indicated that a single flow event can contribute most of the sediment produced over a long period. This observation is in agreement with other studies in southern Spain (Lopez-Bermudez, 1990; Puigdefábregas, 1998). This also implies that the underestimation of flow peaks may lead to the underestimation of total erosion. However, the good agreement between the observations and TETIS simulations of the hydrologic and sedimentary behaviours of the catchment suggested that TETIS model represents a good approach for characterization of a Mediterranean torrential basin with slight tendency to underestimate flow peaks.

The lack of proportionality between accumulated sediment volume and drainage area can be explained by differences in land-use and land-cover conditions in the sub-catchments, including accelerated erosion processes such as badlands formation. Results of different land use conditions demonstrated the critical role of land uses influencing the hydrology and the sedimentary behaviour of the catchment. This is in accordance with empirical evidence and the literature, as land use is known to affect runoff generation, evaporation, groundwater recharge, stream discharge and sediment production (e.g. Chase et al., 2000; Zhang et al., 2001; Benyon et al., 2006; Piao et al., 2007). It was noticed that runoff production is dependent of the percentage of each land use category considered. On the other hand, the catchment sedimentary behaviour is more dependent on the spatial distribution of each soil use category. This statement agrees with previous studies in Spain and other Mediterranean areas (Garcia-Ruiz, 2010; Van Rompaey et al., 2005), where the use, expansion and location of forest and agricultural land uses and their management have a strong influence on erosion rates (Hooke and Sandercock, 2012). Therefore, soil erosion management may be improved when optimized spatial distribution of land uses is considered (Van Rompaey et al., 2005). The setting of natural vegetation on gentle slope areas reduces runoff volume and can attenuate maximum peak flow in the lower areas of the catchment (Zhang et al., 2001), though it may have a minor influence on the sediments produced at the higher, more marked slopes of the catchment, where most of the processes of accelerated erosion take place. On the contrary, natural vegetation in areas of steep slope reduces significantly the runoff energy in these environments and, in extension, the sediment transported along the catchment (Kosmas et al., 2000; Cerdà, 2007). However, an overabundance of natural vegetation restricts the human activities, especially limiting the extension of arable land. For that reason it is necessary to analyse all the available variables influencing soil erosion to asses land use management in Mediterranean catchments.

The analysis of historical land-use and land-management evolution of the study area combined with local climate and crop cycle can help to identify the land use configurations that can reduce flow peak magnitude and improve soil conservation. In this study, we highlighted the importance of changes in the extension of agricultural land. In this study region, the land occupied by agriculture extended in time, an opposite trend compared to other mountain regions of Spain such as Pyrenees, where abandonment of agricultural land have prevailed over the last 60 years (Garcia-Ruiz, 2010; Gallart and Llorens, 2004). Furthermore, since the most extended crop of the area is cereal, set-aside land management is extensively used. As shown by Boellstorff and Benito (2005), the implementation of set-aside land management can lead to increased erosion. Given the seasonal phenology of the cereals growth in the area, the set-aside season is usually at the end of the summer – beginning of autumn, coinciding with the most important period of heavy rainfalls thus increasing soil erosion. This implies that, in this catchment, agricultural land areas respond to extreme events like abandoned agricultural land described for example by Lesschen et al. (2008) and García-Ruiz et al. (2013). The critical role of land use conditions for water and sediment production implies a high potential of land use management as an excellent adaptive option to reduce and mitigate the effects of erosion caused by climate change in torrential Mediterranean catchments.

5. Conclusions

The distributed hydro-sedimentary model TETIS was calibrated with stratigraphic and volumetric records of sediments accumulated behind check dams during recent runoff events. The TETIS model provided a good performance in reproducing the hydro-sedimentary response of the catchment, demonstrating its capability as a robust tool for the characterization of runoff and sediment yield at different time periods and spatial scales. In the study catchment, the hydrological, sedimentary and morpho-dynamical behaviour was driven by high intensity and magnitude rainfall phenomena. For this reason, in Mediterranean catchments sediment production models should provide a good performance at the event-scale, since calculating average erosion over a given period of time can result in non-representative erosion rates.

The implementation of the hydro-sedimentary model TETIS allowed the understanding of the water and sediment cycle under different historical land-use configurations. The largest runoff volume and maximum daily discharge were produced by the land-use configurations with the highest percentage of agricultural land and the lowest cover of forest. On the other hand, the sediment transport (total sediment volume and maximum daily sediment flow) showed a strong dependence on the spatial distribution of land uses, with the lowest sediment production corresponding to land-use configurations where the forested areas and shrubs covered the low parts of the hillslopes.

The differences in the impacts of land use characteristics on hydrology and sediment yield imply that the land use policies and the erosion mitigation strategies should consider holistic hydro-sedimentary scenarios, in order to optimize the response to hydrologic and sedimentary extremes, and minimize its impact on the catchments. Land use cover in the Valdeinfierno catchment proved to be a critical factor in the hydrological and sedimentological response. For that reason, and because land-use management allows a fast local action, land-use distribution and its management should be viewed as an adaptive option to reduce and mitigate the effects of erosion in torrential Mediterranean areas.

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