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Modelling runoff and erosion for a semi-arid catchment using a multi-scale approach based on hydrological connectivity

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ABSTRACT

Runoff and erosion processes are often non-linear and scale dependent, which complicate runoff and erosion modelling at the catchment scale. One of the reasons for scale dependency is the influence of sinks, i.e. areas of infiltration and sedimentation, which lower hydrological connectivity and decrease the area-specific runoff and sediment yield. The objective of our study was to model runoff and erosion for a semi-arid catchment using a multi-scale approach based on hydrological connectivity. We simulated runoff and sediment dynamics at the catchment scale with the LAPSUS model and included plot and hillslope scale features that influenced hydrological connectivity. The semi-arid Carcavo catchment in Southeast Spain was selected as the study area, where vegetation patches and agricultural terraces are the relevant sinks at the plot and hillslope scales, respectively. We elaborated the infiltration module to integrate these runoff sinks, by adapting the parameters runoff threshold and runoff coefficient, which were derived from a rainfall simulation database. The results showed that the spatial distribution of vegetation patches and agricultural terraces largely determined hydrological connectivity at the catchment scale. Runoff and sediment yield for the scenario without agricultural terraces were, respectively, a factor four and nine higher compared to the current situation. Distributed hydrological and erosion models should therefore take account of relevant sinks at finer scales in order to correctly simulate runoff and erosion-sedimentation patterns.

1. Introduction

Scale dependency in erosion research has often been addressed as an important issue that deserves further attention (e.g. Poesen et al., 2003; Boardman, 2006). Simple extrapolations of plot measurements generally lead to large overestimations of runoff and erosion rates at catchment level, because of the non-linearity of runoff and erosion processes. Several studies demonstrated scale dependency with field experiments at different scales (e.g. Le Bissonnais et al., 1998; Cammeraat, 2002; Wilcox et al., 2003; Cerdan et al., 2004; Yair and Raz-Yassif, 2004). These studies showed a strong decrease in runoff and erosion rates with increasing plot length. Also the threshold for the occurrence of runoff increases at higher scale levels (Cammeraat, 2004). The overestimation of runoff and erosion rates can be attributed to the spatially varying influences of sinks, i.e. areas of infiltration and sedimentation. For example, plot scale studies of runoff and erosion do not reveal sediment deposition at footslopes or increased infiltration on agricultural terraces. However, runoff and erosion models mostly focus on one specific spatial scale level, i.e. field scale or catchment scale (Jetten et al., 1999), without addressing the influence of relevant sinks at other scales. Although a few conceptual models have been developed that address this scale dependency in erosion simulation (Parsons et al., 2004; Lu et al., 2005), no erosion modelling study has actually addressed this scale dependency for real catchments.

It is well known that area-specific runoff yield decreases with increasing area. For large watersheds this decrease is attributed to factors, such as rain cell size, lateral changes in lithology and channel width, and increasing storage possibilities in the valley domain. For small areas the non-uniform infiltration and spatial variability of the vegetation and surface properties are responsible for the decrease in runoff rates (Yair and Raz-Yassif, 2004; Kirkby et al., 2005). Besides, Wainwright and Parsons (2002) and Reaney et al. (2007) demonstrated that temporal variations in rainfall intensity during a storm event can also lead to scale dependency in runoff. However, for erosion this relationship is less clear. Parsons et al. (2006) experimentally demonstrated that sediment yield decreases with plot lengths >7 m, due to the limited travel distance of individual entrained particles and due to the decline in runoff coefficient as plot length increases. However, at broader scales additional erosion processes, such as gully erosion, mass movement and bank erosion, can become active and increase the area-specific sediment yield.

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Nevertheless, from a certain basin area threshold, sediment yield becomes dominated by sediment transport and sediment deposition rather than by active erosion processes, and will consequently decrease with increasing basin area (De Vente and Poesen, 2005).

The concept of hydrological connectivity is becoming increasingly applied within the field of hydrology and geomorphology (Hooke, 2006; Bracken and Croke, 2007). Hydrological connectivity can be defined as the physical linkage of water and sediment through the fluvial system (Hooke, 2003). This definition is scale independent, which makes the concept of hydrological connectivity useful to take account of scale dependency in soil erosion research. Since hydrological connectivity describes the linkage of runoff and sediment, it finally determines whether runoff and sediment will become connected at broader scales. Identification of the areas that function as a sink is therefore crucial to model runoff and erosion at the catchment scale. The connectivity of runoff and sediment are not always linked, such as on resistant substrates such as limestone, but also biological soil crusts can lead to high runoff rates but low erosion rates (Belnap, 2006). Although the term hydrological connectivity is also used for subsurface flow (Buttle et al., 2004; Ocampo et al., 2006), we only consider Hortonian overland flow in this paper, which is the main runoff generating mechanism in semi-arid environments (Bryan and Yair, 1982).

The main factors that, given a certain rainfall event, influence hydrological connectivity at the plot scale are micro-topography and vegetation. Vegetation in semi-arid ecosystems is characterised by a heterogeneous pattern of bare and vegetated patches, which make overland flow highly discontinuous owing to the non-uniform infiltration (Cerdà, 1998; Ludwig et al., 2005). Vegetation is also one of the main factors influencing connectivity at the hillslope scale. The spatial structure of these vegetation patterns finally determines the hydrological connectivity on the hillslope (Puigdefabregas et al., 1999). Results from experimental plots showed that coarsening of vegetation patterns lead to significantly higher erosion rates due to concentration of overland flow and higher flow velocities (Puigdefabregas, 2005; Bautista et al., 2007). When runoff becomes concentrated downslope it can lead to gully formation and these gullies are effective links for transferring water and sediment from hillslopes to valley bottoms and channels, and consequently increase hydrological connectivity (Poesen et al., 2003). Also human-made structures, such as ditches, agricultural terraces, paths and roads, influence hydrological connectivity (Croke and Mockler, 2001). At the catchment scale the geomorphology of a landscape and human impacts in the floodplain (e.g. check dams and reservoirs) determine hydrological connectivity. Sediment conveyance is especially impeded by fluvial barriers, buffers and discontinuities between landscape compartments (Fryirs et al., 2007).

The objective of our study was to model runoff and erosion for a semi-arid catchment using a multi-scale approach based on hydrological connectivity. Runoff and erosion have been simulated at the catchment scale, but plot and hillslope scale features that influence the hydrological connectivity were taken into account. First, we identified the relevant sinks of runoff and sediment at plot and hillslope scales and quantified their influence. Afterwards we incorporated the effects of these sinks in the LAPSUS runoff and erosion model by adjusting infiltration capacity. Finally, runoff and erosion were simulated for four different scenarios to evaluate the influence of the identified sinks on hydrological connectivity at the catchment scale.

2. Regional setting

We selected the Carcavo basin in Southeast Spain as our study area because of its representativeness of semi-arid catchments that are susceptible to erosion. The catchment is located in the Province of Murcia, near the town of Cieza (38°13′ N; 1°31′ W). It is a small catchment of 30 km^2 with altitudes ranging from 220–850 m. The area has an average annual rainfall of 300 mm and a potential

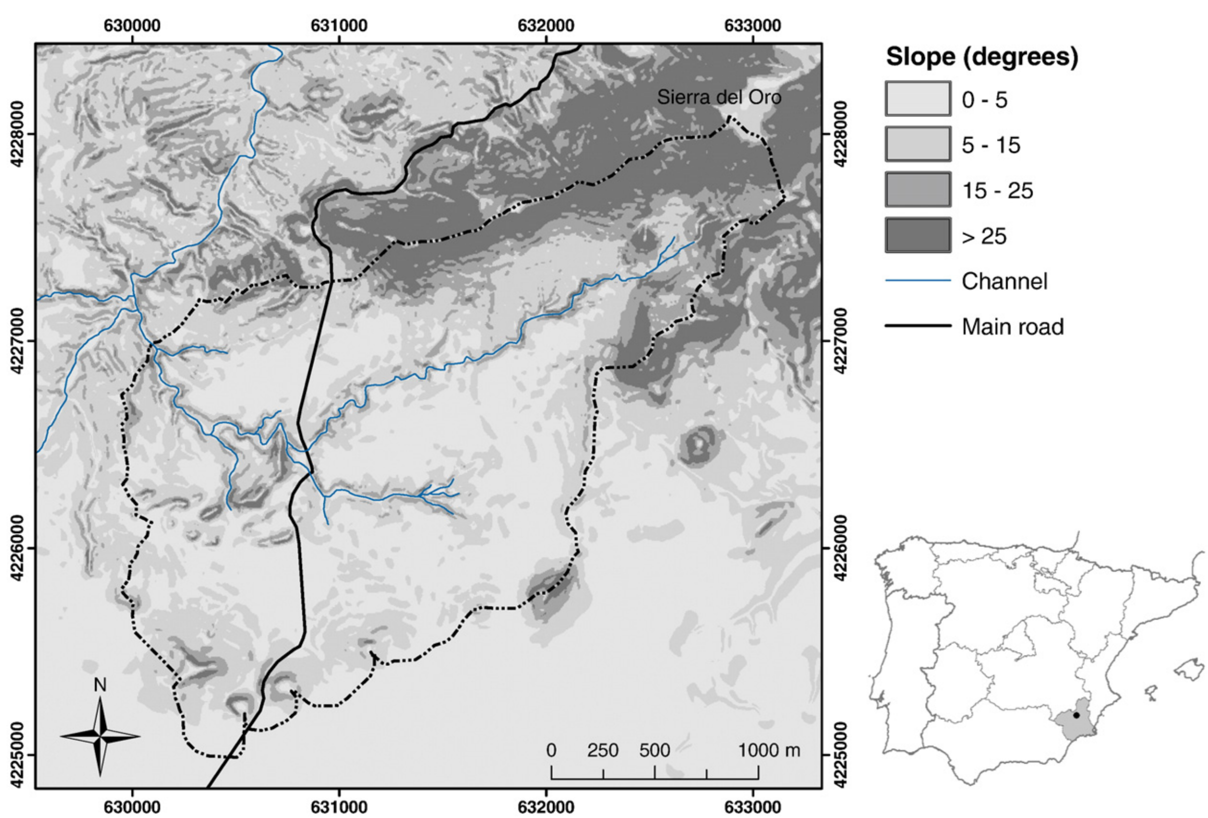

Fig. 1. Topography of the upper part of the Carcavo basin (coordinate values are in UTM European_1950 datum zone 30 N). The inset map of Spain indicates the Region of Murcia and the location of the study area.

evapotranspiration of 900 mm. Rainfall is bimodal with peaks in April and October and torrential rainstorms especially occur in autumn. The geology and geomorphology of the area consists of steep Jurassic carbonate mountains with calcareous pediments, hilly terrain with Keuper gypsum marls and Cretaceous and Miocene marls in the lower parts of the basin. Soils in the Carcavo basin are closely linked to the geology, with thin soils (Leptosols) on the limestone and dolomite mountains, weakly developed soils on marls (Regosols), other soils in which often (petro)calcic horizons have developed (Calcisols) on the stable pediments, and gypsiferious soils (Gypsisols) on the Keuper marls. Current land use in the study area consists of agricultural land (barley, olives, almonds and vineyards), abandoned land, reforested land and shrubland. In the 1970s large parts of the area were planted with pine (*Pinus halepensis*) for reforestation and soil conservation purposes. During recent decades part of the non-irrigated agriculture has been abandoned and is currently under different stages of secondary succession. For the simulation of runoff and erosion we selected the upper part of the Carcavo catchment, which comprised 498 ha (Fig. 1). This part of the basin is characterised by the steep slopes and footslopes of the Sierra del Oro, which are partly reforested, and by a less dissected part with agricultural and abandoned land.

We focused on the two most relevant sinks for runoff and sediment within the catchment, which are vegetation patches at the plot scale and agricultural terraces at the hillslope scale. Vegetation in semi-arid areas is characterised by a heterogeneous pattern of bare soil and vegetated patches, which influences hydrological connectivity and determines whether runoff is generated at the plot scale (Ludwig et al., 2005). At broader scales, the spatial configuration of vegetation determines whether runoff generated at the plot scale will become connected and reach the channel (Puigdefabregas, 2005). However, in the agricultural part of the catchment, the agricultural terraces have major impacts on hydrological connectivity, since well functioning terraces can be large sinks for runoff and sediment. These agricultural terraces and earth dams are important features of traditional agricultural systems in hilly areas in Mediterranean countries. In the Carcavo basin ~39% of agricultural land is currently terraced. Terraces have been constructed on hillslopes and in dry streambeds, while earth dams are mainly found in valley bottoms of undulating cereal fields.

3. Methodology

3.1. LAPSUS model

To simulate runoff and sediment dynamics we used the LAPSUS model (Schoorl and Veldkamp, 2001; Schoorl et al., 2002). LAPSUS is a dynamic landscape evolution model that can simulate erosion and sedimentation, based on a limited number of input parameters. The model is based on two fundamental assumptions: (1) the potential energy of overland flow is the driving force for sediment transport (Kirkby, 1986), and (2) the difference between sediment input and output of a grid cell is equal to the net increase in storage, i.e. the continuity equation for sediment movement (Foster and Meyer, 1975). The model evaluates the rate of sediment transport by calculating the transport capacity of water flowing downslope from one grid cell to another as a function of discharge and slope gradient. A surplus of capacity is compensated by sediment detachment, depending on the erodibility of the surface, which provokes erosion. When the rate of sediment in transport exceeds the local capacity, the surplus is deposited based on a sedimentability factor. The routing of runoff and resulting model calculations are based on a multiple flow algorithm, which allows a better representation of divergent and convergent properties of topography (Holmgren, 1994). The model can be used for both short and long-term applications by varying the time step. For our study we simulated runoff and erosion based on 1-h time steps for a 6 day rainfall period in November 2006.

The main input data for the LAPSUS model are a digital elevation model (DEM), rainfall data, infiltration data, erodibility characteristics and soil depth. To represent the topography we used a 5 m resolution DEM, which was derived from a 1:5000 topographic map with 5 m contour lines. Although this resolution is relatively high, it still did not sufficiently represent the agricultural terraces, since these generally have height difference of only 1–2 m. Therefore we had to adapt the DEM to include the topography of the terraces. First, we digitised the terraces in ArcGIS 9.0 (ESRI, Redlands, US) and calculated the mean altitude for each terrace using zonal statistics. The DEM was adjusted according to the difference between the mean terrace altitude and the original topography, which was multiplied by a factor 0.75 to include some influence of the original topography, because most terraces are not completely flat, especially at the sides.

For rainfall we used data from a large event in November 2006, which was recorded with a tipping bucket rain gauge in the centre of the catchment. The event included several rainstorms within 6 days with a total rainfall of 157 mm, which was half of the average annual rainfall. Although most rainfall was of low intensity (Fig. 2), the rainstorm of the last day had a higher intensity with a maximum of 50 mm h^{-1}, based on a 10-min interval. The recurrence time of this last rainstorm was about 2 years, based on a 36-year rainfall series of the Almadenes weather station. However, when rainfall of the previous days was taken into account, the recurrence time for the 10-day rainfall sum was ~23 years. Although the spatial distribution of rainfall can be highly variable (González-Hidalgo et al., 2001), we

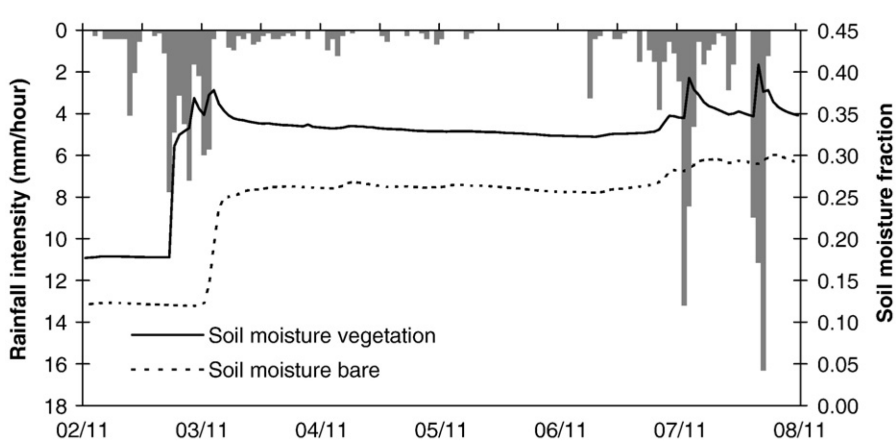

Fig. 2. Rainfall intensity (vertical bars) and Measured soil moisture under bare soil and vegetation on marl during a six-day rainfall period in November 2006.

Table 1
Occurrence of substrates within the simulated catchment and the estimated parameters.

Substrate	Occurrence (%)	Erodibility factor (m^{-1})	Soil depth (m)
Slope deposits	27.4	0.0025	0.40
Slope deposits with calcrete	13.6	0.0015	0.25
Marl	39.4	0.0050	0.40
Keuper	9.3	0.0035	0.20
Limestone/dolomite	10.3	0.0005	0.15

considered the catchment to be sufficiently small to neglect the spatial variability of rainfall.

The most important input for our modelling exercise is infiltration. Modification of the infiltration capacity enables the incorporation of runoff sinks, which finally determine whether runoff will occur. In the original version of the LAPSUS model a fixed value for infiltration is used for each soil type and land use (Schoorl et al., 2002). Buis and Veldkamp (2008) modified the infiltration parameters to better represent the spatial diversity in water redistribution and availability within arid catchments. We further elaborated the infiltration module by making it dynamic and dependent on measured parameters. The runoff threshold and coefficient were selected to describe the infiltration characteristics in the LAPSUS model. The runoff threshold was defined as the amount of rainfall until runoff starts, and the runoff coefficient is the ratio of observed runoff to applied rainfall. These parameters were derived from a database of rainfall simulations, which is described in Section 3.2. For each time-step the model first calculates the amount of rainfall available for runoff after subtracting the runoff threshold. This value is then multiplied by the runoff coefficient, which determines the amount of runoff for each grid cell. Next, the model determines the routing of runoff, based on the multiple flow algorithm, and evaluates whether infiltration capacity is still available. When runoff has been determined for the entire catchment, the model calculates the sediment transport capacity, which determines whether sediment is eroded or deposited. We estimated that 15% of the runoff threshold and 10% of the storage and infiltration capacity of the terraces is recovered per day due to evapotranspiration and drainage to deeper soil horizons.

The erodibility factor and soil depth were estimated for each substrate (Table 1). The distribution of the substrates was derived from a 1:50,000 geological map and an additional field survey, which was required in order to map the location of calcretes. The erodibility factor determines how easy sediment is detached with low values indicating low erodibility. For all agricultural land we added a value of 0.002 to the erodibility factor to take account of ploughing, which in general increases erodibility. The last input variable is a sedimentability or settlement factor, which determines how easy sediment can be deposited (Schoorl et al., 2002). For this factor we distinguished between bare soil and vegetation, since vegetation increases surface roughness and promotes sedimentation (Bochet et al., 2000). The sedimentability factor was set a factor 5 higher for vegetated areas, which means that transport capacity is lowered and sediment is more easily deposited.

3.2. Influence of vegetation patches

Vegetation in semi-arid environments is characterised by heterogeneous patterns of bare and vegetated patches. The bare patches are generally formed by bare rock and crusted soils with poor soil structure and low infiltration rates, whereas vegetated patches have better soil properties with higher organic matter content and a stronger aggregation, which results in a higher infiltration capacity. This makes overland flow highly discontinuous with bare patches as runoff generating areas and vegetated patches as runoff sinks (Bergkamp, 1998; Cammeraat and Imeson, 1999). Soil moisture measurements in the study area confirmed the higher infiltration capacity under vegetation (Fig. 2). FDR (Frequency Domain Reflectometry) sensors at 5 cm depth recorded soil moisture at a bare land and a vegetated patch. Soil moisture under vegetation was on average 7 vol.% higher, and reacted faster to rainfall, which indicates higher infiltration capacity (Bergkamp, 1998).

To simulate the influence of vegetation patterns on runoff and erosion, we differentiated the infiltration parameters for bare and vegetated areas. These parameters, runoff threshold and runoff coefficient, were derived from a database of rainfall simulation experiments. The database comprised data from studies that were applied in similar semi-arid areas, mostly in Southeast Spain (Boix-Fayos et al., 1995; Quinton et al., 1997; Cerdà, 1997a,b, 1998, 2001; Imeson et al., 1998; Cammeraat and Imeson, 1999; Lasanta et al., 2000; Cammeraat et al., 2002; Ceballos et al., 2002; Calvo-Cases et al., 2003; Castro et al., 2006; Seeger, 2007; Meerkerk et al., 2008). We only selected data from experiments that were applied on substrates and land uses that occur within the study area (Fig. 3), which resulted in 285 observations. Although these experiments were used to study a wide range of research questions and not all studies measured or described the same variables, the size of the database is sufficiently large to obtain general and statistically significant relationships between environmental factors and measured parameters. For each observation from this database we calculated the runoff threshold and coefficient, which together determine the amount of infiltration in the LAPSUS model. However, combining both parameters will overestimate total infiltration capacity, since part of the rainfall was already included in the runoff threshold. Hence, the runoff coefficient was recalculated based on the amount of rainfall minus the runoff threshold. Next, we classified all observations for the different combinations of land use (shrubland, abandoned land and agricultural land), substrate (marl, slope deposits and limestone) and vegetation cover (bare and vegetated). For the 11 relevant combinations we calculated the mean runoff threshold ($n = 143$) and runoff coefficient ($n = 218$), which were used in the LAPSUS model (Fig. 4).

Upscaling of the vegetation patterns was required to include the influence of vegetation patches for the entire catchment. Imeson and Prinsen (2004) and Lesschen et al. (2008a) found a linear relationship between vegetation cover and spatial metrics that described the vegetation patterns. This enabled us to use vegetation cover as a proxy for spatial vegetation structures in landscapes with spotted vegetation

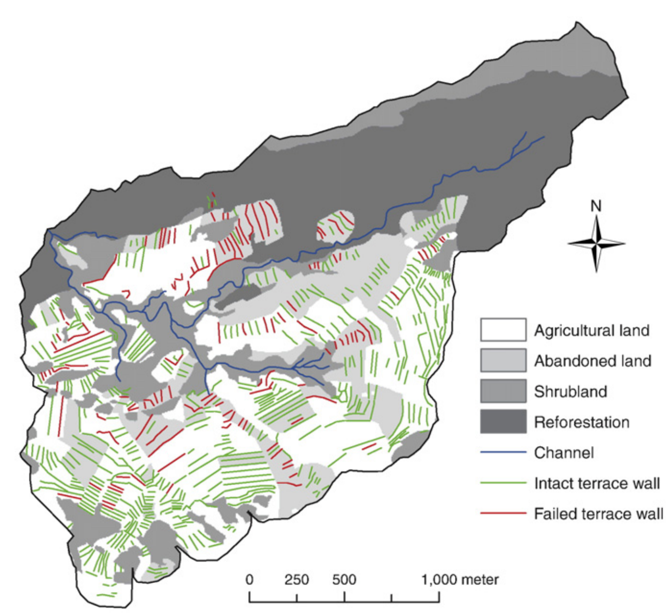

Fig. 3. Land use of the simulated catchment and locations of intact and failed terrace walls on (abandoned) agricultural land.

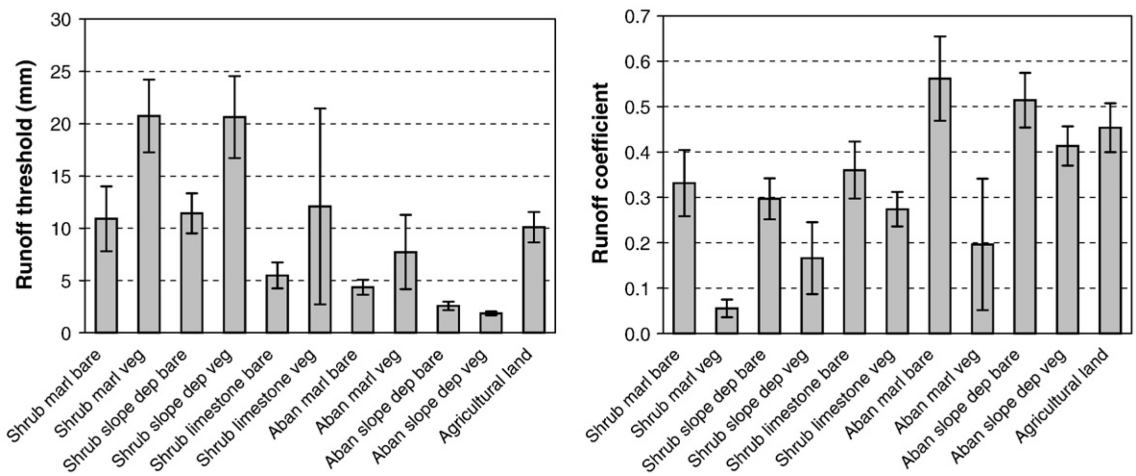

Fig. 4. Mean runoff threshold and runoff coefficient (RC) for the different combinations of land use, substrate and vegetation cover (error bars indicate standard error of the mean). Aban: abandoned land; slope dep: slope deposits; veg: vegetated.

patterns. Lesschen (2008) created a fractional vegetation cover map for the Carcavo basin based on a linear regression of vegetation cover, as derived from detailed aerial photographs, and the green and red reflectances from a QuickBird image (R^2 of 0.91|P<0.001, n=20). Since the rainfall simulation database contained insufficient data on fractional vegetation cover, we could only differentiate two classes of vegetation cover, i.e. bare and vegetated areas. The threshold between these two classes was set at 30%, since several studies showed that runoff and erosion increase drastically <30% vegetation cover (Francis and Thornes, 1990; Quinton et al., 1997; Ludwig et al., 2002).

3.3. Influence of agricultural terraces

Agricultural terraces are important sinks for runoff and erosion at the hillslope scale. These terraces were originally constructed to reduce soil erosion and to intercept runoff by decreasing the general slope (Morgan, 1995). However, the effects of terracing are not always positive, since the area near the terrace rim is now under influence of a steep hydraulic gradient, which may lead to gully erosion and piping (Faulkner et al., 2003). To include the influence of the terraces in LAPSUS we first digitised the terrace walls in ArcGIS, based on a QuickBird satellite image of 2006. During a field survey we checked which terraces were intact and which had collapsed (Fig. 3). In total ~500 terrace walls were identified, of which 127 had collapsed. Most failed terraces were located on abandoned fields, which are more vulnerable to failure due to the lack of maintenance and increased runoff (Lesschen et al., 2008b). The terrace wall map was converted to raster and intact terraces were assigned an additional infiltration capacity. Although in reality this additional storage and infiltration capacity depends on the terrace characteristics (e.g. size and slope of the terrace and height of the terrace rim) no such data were available to create a variable storage capacity for the terraces. Instead we used a single value of 50 m^3 of water that can be additionally stored and infiltrated at each terrace, which is based on the size of an average terrace and terrace rim.

3.4. Scenarios

To evaluate the influence of the identified sinks on hydrological connectivity at the catchment scale, we used four different scenarios for the simulation of runoff and erosion. Besides a scenario that represents the current situation, two other scenarios were used to assess the influence of vegetation and agricultural terraces, respectively, and a fourth scenario was used to simulate the influence of a soil and water conservation practise in which all failed terraces are repaired. Accordingly the four scenarios are:

1. Current situation
2. No vegetation patterns
3. No terraces
4. All terraces function

The first scenario includes the influence of vegetation patterns at the plot scale as well as the influence of intact and collapsed terraces at the hillslope scale. For the second scenario, we adapted the values of the runoff threshold and runoff coefficient to exclude the influence of vegetation patterns. Based on the rainfall simulation database, we calculated new values for each combination of land use and substrate without differentiating between bare and vegetated areas. For the third scenario, we did not include the extra infiltration capacity for terraces and used the original DEM without the detailed terrace representation. Finally, for the last scenario we modified the input file with additional infiltration capacity and gave the failed terraces the same infiltration capacity as the other terraces.

3.5. Verification of the model results

To verify the spatial distribution of the model results we compared the simulated runoff map with observed concentrated flow paths. These connectivity patterns were mapped after the rainfall event of November 2006 (Meerkerk, 2009). Since the soil was already saturated from the rainfall of the previous days, the intense rainfall on 8 November resulted in significant amounts of erosion, as observed by completely filled sediment collectors, rills on agricultural fields, and failure of some agricultural terraces. Within the agricultural part of the sub-catchment all signs of concentrated flow were recorded with a handheld GPS. These flow paths were visible as rills and gullies, but also as areas with clear signs of concentrated overland flow as observed by the removal of small branches, leaves and other litter material. Although concentrated flow was also observed on roads, we excluded these flow paths since the influence of roads is not included in the model. In addition to the mapped connectivity patterns on agricultural land, we added the flow paths in the channels.

4. Results

Based on the analysis of rainfall simulation data we calculated the mean runoff threshold and runoff coefficient for the different land use–substrate–vegetation cover classes (Fig. 4). The runoff threshold

Table 2
Summary of model outputs for the simulated scenarios.

Scenario	Total runoff ($1000\ m^3$)	*RC*	Erosion ($Mg\ ha^{-1}$)	Sedimentation ($Mg\ ha^{-1}$)	Sediment yield ($Mg\ ha^{-1}$)	*SDR*
1	52.9	0.068	38.1	35.7	2.5	0.063
2	76.5	0.098	56.4	49.1	7.4	0.129
3	203.0	0.259	84.8	61.7	23.4	0.272
4	40.4	0.052	32.0	29.1	3.0	0.091

for bare conditions was lower compared to vegetated conditions. For bare areas runoff starts after ~7 mm of rainfall, while under vegetation the runoff threshold is ~13 mm. The results also showed that the threshold on abandoned fields is much lower than for shrubland and agricultural land. The runoff coefficient also clearly showed the difference between bare and vegetated areas, on average the runoff coefficient was higher by 0.19 under bare conditions. The runoff coefficient was also higher for abandoned land compared to shrubland for both vegetated and bare conditions.

The results of the runoff and erosion simulations with the LAPSUS model for the four scenarios are summarised in Table 2. Total runoff is the sum of discharge at the outlet of the catchment. *RC* is the runoff coefficient for the entire catchment, i.e. total runoff divided by the total rainfall. Erosion and sedimentation are the sum of erosion and sedimentation, respectively, for each time step. Sediment yield is the sum of the transported sediment at the catchment outlet and is consequently the net erosion for the entire catchment. Finally, *SDR* is the sediment delivery ratio, which is the fraction of erosion that is transported out of the catchment.

For the current situation (Scenario 1) a runoff coefficient of 0.068 and a sediment yield of 2.5 $Mg\ ha^{-1}$ were predicted. The sediment delivery ratio was only 0.063, which means that most sediment is deposited within the catchment. For the second scenario (without the influence of vegetation patterns) more runoff was produced and the

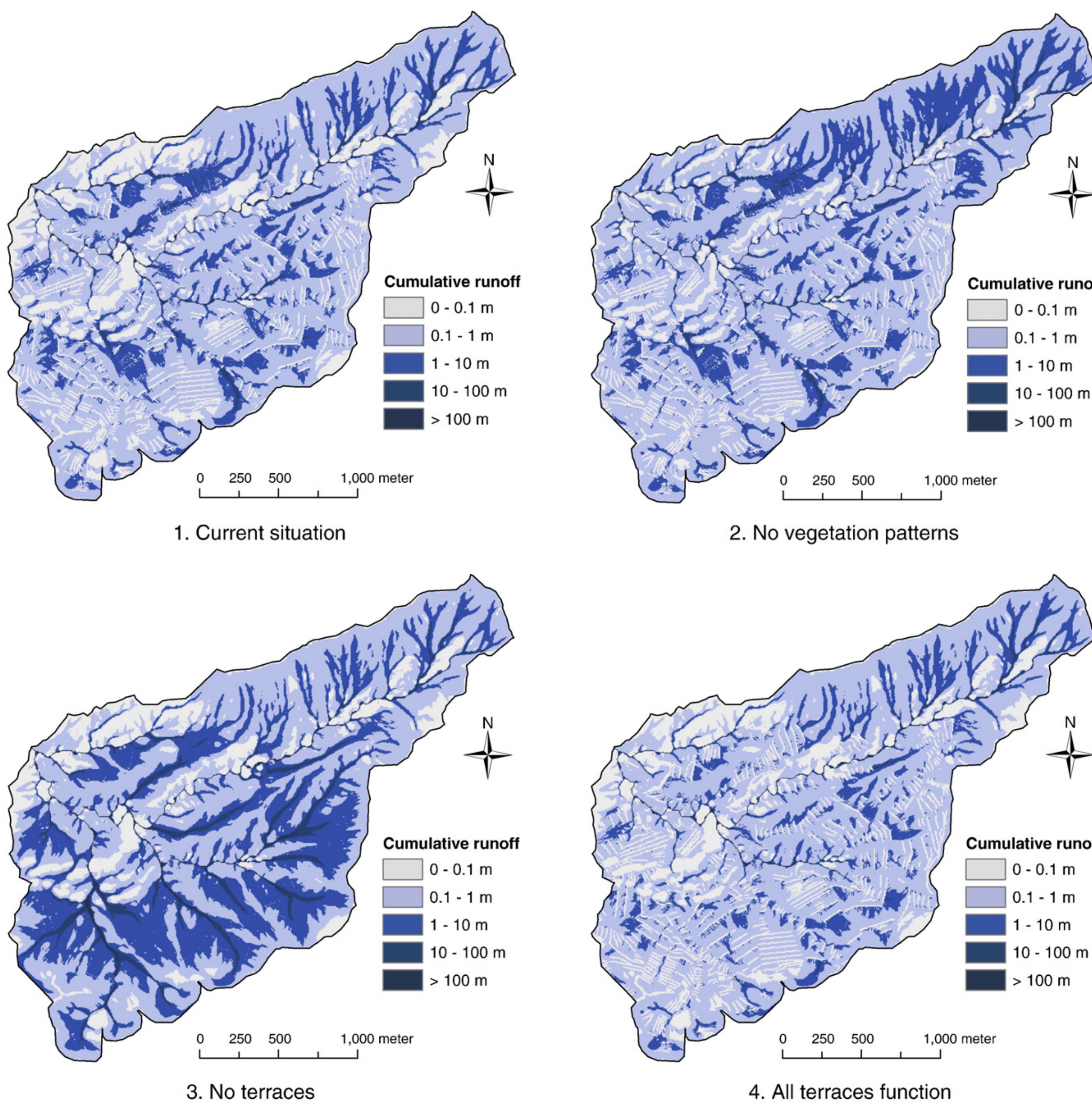

Fig. 5. Cumulative runoff for the four scenarios.

sediment yield was a factor 3 higher compared to the current situation. In the third scenario (without agricultural terraces) the runoff coefficient and sediment yield were much higher, while erosion and sedimentation remained relatively low, which means that more sediment was transported out of the catchment, as indicated by the high sediment delivery ratio. In the last scenario (with all terraces intact) less runoff was produced and erosion and sedimentation were lower. However, sediment yield and sediment delivery ratio were somewhat higher than in the scenario for the current situation.

Fig. 5 shows the results of the cumulative runoff for the four scenarios. The cumulative runoff is the sum of runoff for all time steps that passed a grid cell and is expressed in meter height. In the first scenario, representing the current situation, runoff from the Sierra del Oro was well connected to the main channel, while runoff from the agricultural fields was mainly retained by the agricultural terraces. Only fields close to the channel were connected and contributed to channel discharge. For the second scenario (without the influence of vegetation patterns), runoff intensity was higher and especially the slopes of the Sierra del Oro produced more runoff. For the southern part of the catchment somewhat more runoff was produced, but this did not increase hydrological connectivity. The third scenario (without the influence of agricultural terraces) showed a very strong increase in runoff in the southern part of the catchment where runoff of all hillslopes became connected to the channel. Runoff from the hillslopes in the last scenario (with all terraces intact) was not connected to the channel in the agricultural part of the catchment. All locally produced runoff was retained by terraces downslope and the channel was only supplied by runoff from nearby areas.

The results of the simulation of erosion and sedimentation resulted in different magnitudes of sediment dynamics, and the patterns of erosion and sedimentation were also different for the four scenarios (Fig. 6). In the current situation most erosion occurred on the steep

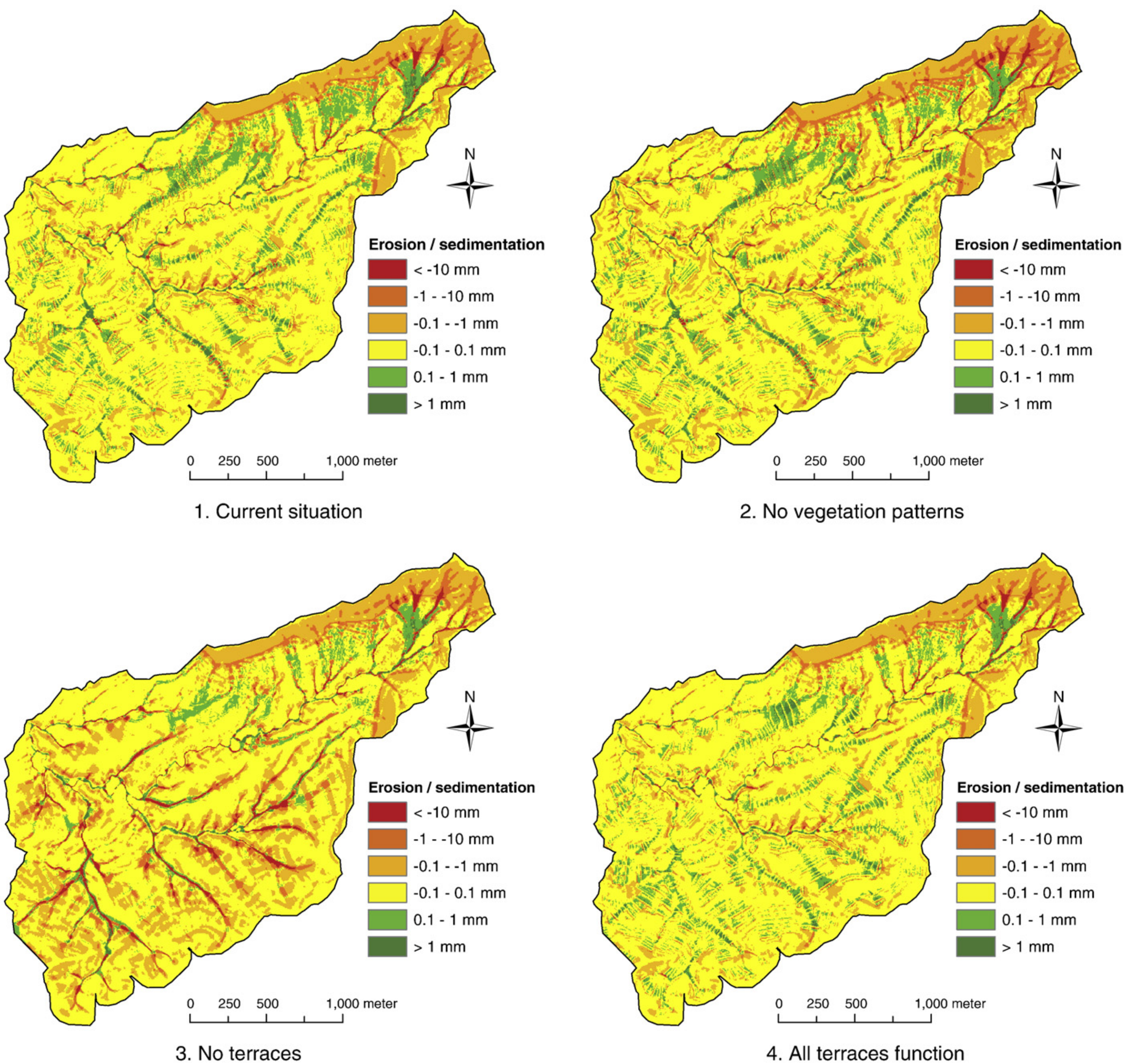

Fig. 6. Erosion (negative values) and sedimentation (positive values) patterns for the four scenarios.

slopes of the Sierra del Oro in the northern part of the catchment and on areas near the channel, while sedimentation occurred on the footslopes and on agricultural terraces. In the channel an alternation of areas with erosion and those with sedimentation was observed. For the second scenario (without the influence of vegetation patterns) the erosion and sedimentation patterns were similar, but the amount of erosion and sedimentation was higher. The third scenario (without any terrace influences) resulted in a completely different pattern in the agricultural part of the catchment. High erosion rates occurred in all valley bottoms, while sedimentation was limited to the footslopes of the Sierra del Oro and the channels. Finally, the fourth scenario showed the positive effects of well-maintained terraces, which retained sediment and prevented erosion in the agricultural part of the catchment.

5. Discussion

The results of our runoff and erosion simulations showed that vegetation patterns and agricultural terraces have major influences on the connectivity of runoff and sediment. According to the first and second scenarios, excluding the influence of vegetation patterns led to an overestimation of runoff and erosion, especially in areas with a higher vegetation cover. However, the patterns of hydrological connectivity at catchment scale did not change. In contrast, the scenario without the influence of agricultural terraces showed major impacts on hydrological connectivity at the catchment scale. For this scenario, total runoff was four times higher and sediment yield almost 10 times higher, due to lowering of the runoff threshold on agricultural fields (Cammeraat, 2004). Consequently all runoff from the hillslopes of the entire catchment was connected to the channel. Nevertheless the last scenario showed the important function of agricultural terraces for soil and water conservation. In this case most of the runoff and sediment from the agricultural part of the catchment was not connected to the channel and retained by the agricultural terraces. Although total runoff and gross erosion were lower, the sediment yield for this scenario was somewhat higher. This might be explained by a lower sediment delivery from agricultural land to the channel, which can increase the erosive force of the water in the channel, and lead to more erosion in the channel and a higher sediment transport from the catchment. This effect is similar to the 'clear water effect' behind checkdams (Castillo et al., 2007).

Although erosion on agricultural land is generally higher compared to semi-natural areas (Kosmas et al., 1997; Cammeraat, 2004), hydrological connectivity was lower, due to the influence of agricultural terraces and other water conservation structures. As a result the sediment yield from agricultural areas is limited to fields near the channel, and most sediment is retained on agricultural fields. However, during extreme events the accumulated sediment might still be transported to the channel due to the failure of terraces, which will increase hydrological connectivity. Furthermore, in case of agricultural abandonment, part of the terraces might collapse, which will also increase hydrological connectivity. This was observed in several parts of the catchment, where gullies through terrace walls increased the connectivity.

To verify the spatial distribution of the simulation, we compared the modelled runoff map of scenario 1 with the observed concentrated flow (Fig. 7). This map showed that the overall runoff pattern was fairly well simulated with low connectivity between the hillslopes and channel in the southern part of the catchment. Field observations confirmed that flow inside the channel was fully connected, as simulated by the model. Furthermore, the highest cumulative runoff class (>100 m) coincided very well with the location of the actual channels. However, not all individual flow paths were correctly simulated, probably due to lack of detailed input data. A more detailed DEM, for instance one derived by LIDAR, is necessary to capture all topographical features such as small ditches, agricultural terraces and

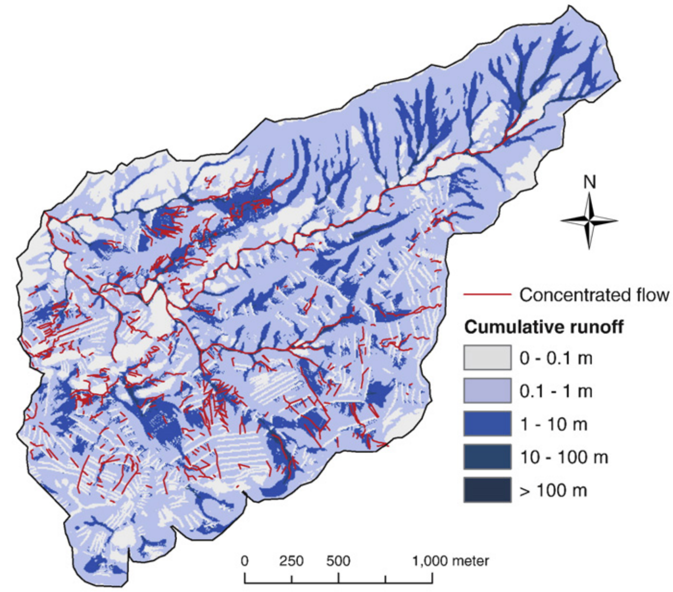

Fig. 7. Overlay of observed concentrated flow (red) based on Meerkerk et al. (submitted for publication) and simulated runoff (blue) for scenario 1 (current situation). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

field boundaries, which do determine local surface runoff. Also roads are important pathways for runoff, which frequently lead to gully initiation due to runoff concentration (Croke and Mockler, 2001; Meerkerk, 2009). Furthermore, identification of concentrated flow in the field is not always straightforward, since not all concentrated flow is visible as rills. On freshly ploughed fields the development of rills is enhanced due to higher erodibility, because soils crusts are broken down. However, on abandoned land the formation of rills is reduced by the presence of (biological) soil crusts and most overland flow will not leave clear traces. This makes identification of flow paths in the field more difficult and might lead to mismatches between simulated and observed connectivity patterns.

Besides the verification of spatial runoff patterns, the simulated total runoff and sediment yield at the catchment outlet should be assessed, since these determine the impact on off-site effects such as flash flooding risk and reservoir sedimentation. Unfortunately, no monitoring data were available yet to validate total discharge and sediment yield for the modelled catchment. However, based on other studies for comparable semi-arid catchments, we were able to assess whether the simulated runoff and sediment yield were realistic. The simulated runoff coefficient for the entire catchment was 0.068, based on the current situation scenario. Although this value is quite low, it seems a reasonable value considering the low intensity of most of the rainfall and the presence of agricultural terraces in the southern part of the catchment, which are major runoff sinks. Other studies also found rather low runoff coefficients for semi-arid catchments. Martín-Vide et al. (1999) reported runoff coefficients ranging between 0.04–0.15 for a 30 km^2 catchment in Northeast Spain, and Michaud and Sorooshian (1994) and Ye et al. (1997) found runoff coefficients of ~0.1 for the semi-arid Walnut Gulch catchment in New Mexico and ephemeral catchments in Western Australia, respectively. For sediment yield less comparable studies were available. De Vente and Poesen (2005) demonstrated the relation between drainage area and area-specific sediment yield based on Spanish data, which first shows an increase in area-specific sediment yield and afterwards a decrease for drainage areas >100 km^2. However, no data were available for catchments with drainage areas between 0.1–30 km^2, which have the highest area-specific sediment yields. Nevertheless, a maximum area-specific sediment yield of 20–40 Mg ha^{-1} $year^{-1}$ for small scale catchments (1–10 km^2) can be inferred from their graphs. This is higher than our simulated sediment yield of 2.5 Mg ha^{-1}, but as discussed before, rainfall intensity was not very high for most of the event, while in semi-arid landscapes most erosion can be attributed to extreme events (Cammeraat, 2004; Boardman, 2006).

Modelling runoff and erosion at the catchment scale makes simplifications of hydrological processes and sediment dynamics unavoidable. Runoff generation, which is the most important process for our modelling approach, was simplified by using a runoff threshold and runoff coefficient, while runoff generation in reality is controlled by complex and dynamic interactions between rainfall characteristics and soil and surface properties (Martinez-Mena et al., 1998). More sophisticated approaches, such as the Green–Ampt equation, require too much input data at the catchment scale. The values for the runoff threshold and runoff coefficient were mean values from all rainfall simulation experiments, for which we did not make a distinction between dry and wet preceding conditions. However, Cammeraat and Imeson (1999) and Cammeraat (2004) showed that runoff curves can differ greatly depending on the initial soil moisture conditions. Nevertheless, in our modelling approach, infiltration capacity was calculated dynamically and rainfall from the previous time steps was taken into account. Another simplification was the non-variable infiltration and storage capacity for the agricultural terraces, which led to underestimation of runoff on small terraces, while large terraces with well constructed rims could retain more runoff. Nevertheless, the overall runoff pattern appeared realistic, since field observations showed that only limited areas were connected to the channel and most agricultural hillslopes retained all runoff. When a more detailed DEM is available, the sink function of agricultural terraces can also be simulated dynamically based on the algorithm of Temme et al. (2006), which models the sediment buffer function of depressions. A final simplification is the exclusion of bench terraces from the reforested areas in the simulation, which might have led to an overestimation of runoff and erosion in the northern part of the catchment. However, Maestre and Cortina (2004) and Hooke (2006) have questioned the effectiveness of these terraces, and De Wit and Brouwer (1998) found higher runoff and sediment yields in reforested areas due to gullying through the bench terraces.

Modelling runoff and erosion without taking into account the relevant sinks from the plot and hillslope scale will lead to overestimation of runoff and sediment yield, as demonstrated in our study. Otherwise, models can predict acceptable soil loss and discharge at the outlet, but with incorrect patterns of source and sink areas (Jetten et al., 2003). Application of erosion models for soil and water conservation purposes requires correct simulation of runoff and erosion patterns in order to identify the hotspots where mitigation measures should be applied. Although Jetten et al. (2003) were negative about the ability of catchment based models to determine optimal locations for water conservation measures (e.g. grass strips or terraces) our simulations gave satisfactory results for the implementation of a conservation practise, i.e. restoration of existing failed terraces. In the current situation (scenario 1) several areas with high runoff production in the agricultural part can be identified, and restoration of the failed terraces at these sites (scenario 4) significantly reduced runoff and erosion. Also other measures could be evaluated (e.g. grass strips) by adapting infiltration and erodibility input data.

6. Conclusions

Our new approach is based on the identification of hydrological sinks which are integrated in a distributed runoff–erosion model. The results of the simulations show that the spatial distribution of sinks at plot and hillslope scales, in this case vegetation patches and agricultural terraces, determines much of the hydrological connectivity at the catchment scale. Runoff and sediment dynamics are therefore non-linear and scale dependent, and are to a large extent determined by the spatial distribution of hydrological sinks. Especially the additional infiltration and storage capacity of agricultural terraces should be taken into account, since their exclusion will highly overestimate runoff and erosion in catchments with these terraces, and erroneous runoff and erosion patterns will be simulated. Although LAPSUS is a relatively simple model, we have demonstrated that the model is able to reproduce the observed patterns of hydrological connectivity and to predict realistic values for total runoff and sediment yield. Distributed hydrological and erosion models should take account of relevant sinks at finer spatial scales in order to simulate patterns of runoff and erosion correctly.

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