Severe soil erosion during a three-day exceptional rainfall event: combining modelling and field data for a fallow cereal field

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Abstract

Exceptional rainfall events cause significant losses of soil, although few studies have addressed the validation of model predictions at field scale during severe erosive episodes. In this study we evaluate the predictive ability of the enhanced Soil Erosion and Redistribution Tool (*SERT-2014*) model for mapping and quantifying soil erosion during the exceptional rainfall event (ca. 235 mm) that affected the Central Spanish Pyrenees in October 2012. The capacity of the simulation model is evaluated in a fallow cereal field (1.9 ha) at a high spatial scale (1 x 1 meter). Validation was performed with field-quantified rates of soil loss in the rills and ephemeral gullies and also with a detailed map of soil redistribution. The *SERT-2014* model was run for the six rainfall sub-events that made up the exceptional event, simulating the different hydrological responses of soils with maximum runoff depths ranging between 40 and 1017 mm. Predicted average and maximum soil erosion was 11 and 117 Mg ha⁻¹ event⁻¹, respectively. Total soil loss and sediment yield to the La Reina gully amounted to 16.3 and 9.0 Mg event⁻¹. These rates are in agreement with field estimations of soil loss of 20.0 Mg event⁻¹. Most soil loss (86%) occurred during the first sub-event. Although soil accumulation was overestimated in the first sub-event due to the large amount of detached soil, the

enhanced *SERT-2014* model successfully predicted the different spatial patterns and values of soil redistribution for each sub-event. Further research should focus on stream transport capacity.

Key words: exceptional rainfall event; rill; ephemeral gully; *SERT* model; fallow cereal field; modelling validation

INTRODUCTION

Soil erosion is a geologic process that affects all the continents, shapes the landscapes and due to this control on soil fertility and thus food production determines the fate of the civilizations (Cerdà et al., 2010; Koch et al., 2012; Prokop and Poręba, 2012). Soil loss and sediment delivery causes a great deal of damage to fields, water quality, ecosystems and infrastructures. On agricultural land, the main on-site damage is the reduction in the depth and area of cultivated soil (Pimentel, 2006), the decrease in carbon content (Brazier et al., 2014) and nutrients such as nitrogen and phosphorous (Grismer, 2013) and finally the decrease in crop productivity (Franco, 2011) and soil quality (Navas et al., 2012). Amongst the off-site and long-term consequences are sediment supply to reservoirs (Navas et al., 2004) and rising levels of pesticides in streams (Boithias et al., 2011). The economic cost of soil loss and nutrient replenishment in fields can represent a significant percentage of farmers' total income (Cotler et al., 2011). Soil erosion is a complex and active phenomenon that needs different approaches to understand the process and to quantify or estimate the rates (Navas et al., 2008; Fernández et al., 2012; Haile and Fetene, 2012).

During exceptional (recurrence interval of ca. 100 years) and extreme (recurrence intervals of more than 500 years) rainfall events, the magnitude of the runoff increases significantly, affecting the whole landscape (Serrano-Muela et al., 2013) and causing severe soil and nutrient losses (Ramos and Martínez-Casasnovas, 2009). High-intensity rainfall episodes trigger relocation and delivery of stored sediments and, at the same time, result in surface soil loss due to interrill, rill, ephemeral gully and gully processes, as well as landslides, soil piping and bank collapse processes (Erskine and Saynor, 2012). Current studies on climate change predict future scenarios with increasingly frequent extreme climate conditions, involving recurrent dry episodes interspersed with floods and high-intensity rainfall events and rainfall depth values (Arnone et al., 2013).

Numerical simulation contributes to understand the erosion processes at different spatial and temporal scales (Keesstra et al., 2014). Soil erosion models are tools that estimate

spatially distributed rates of runoff and soil loss and redistribution, also providing scientific support for soil conservation and water management (Khoi and Suetsugi, 2014). There are many models in the literature, which take either empirical or physically-based approaches, ranging from simple to ambitious and mathematically complex models (López-Vicente and Kirkby, 2013) but all predictions need to be validated against quantified rates of soil loss, deposition and sediment yield (Palazón and Navas, 2013). The different scales of application of the models make validation procedures specific to each model. Validation data can be acquired from gauging stations located at the outlets, from reservoir bathymetry, from lake sediment cores, from radionuclides, from direct measurements with erosion pins and LIDAR-based 3D and from experimental plots. In those cases in which the models have extent databases, event scale and real-time approaches have been used to obtain accurate predictions (Kim et al., 2013).

To date, relatively few studies have been published on modelling validation for exceptional rainfall and erosive events, amongst such studies are those of Lee et al. (2013) on a typhoon hydrological model in Korea, Sanchez-Moreno et al. (2014) on the OpenLISEM model in Cape Verde (West Africa), Rodrigues et al. (2014) regarding the LISEM model in two small watersheds in Brazil or the studies by Nunes et al. (2005) in USA and Belgium on the MEFIDIS model. Very few studies performed at field scale can be cited, but some examples are the research carried out by Uhlířová et al. (2009) in the Czech Republic with the event-based runoff curve number (ERCN v2.0) model, by Dabney et al. (2009) in cotton fields in USA with the RUSLE model and by Takken et al. (1999) in the Belgium loam belt with the LISEM soil erosion model. To the best of our knowledge, there have been no studies of soil erosion modelling validation carried out at field scale under fallow conditions for exceptional rainfall events. The difficulty of data acquisition and in some cases of model performance with high magnitude input values explains this lack of studies (Boardman, 2006). Rainfall-runoff and soil erosion models typically perform better when simulation results are aggregated at a larger time scale (e.g. at a monthly time scale vs. a daily time and event scale). Thus, establishing accurate, reliable soil erosion models is a non-resolved task and a frontier field in soil erosion modelling studies and soil and water conservation research (Guo-Qiang et al., 2013).

In October 2012 an exceptional precipitation event occurred in the Central Spanish Pyrenees, with between 200 and 265 mm rainfall depth accumulating over a two and a half day period at several weather stations, and more than 100 mm rainfall depth at many others (Serrano-Muela et al., 2013) with maximum recorded peaks of rainfall intensity of between

24 and 45 mm h⁻¹ (Lana-Renault et al., 2014). In this study we seek two objectives: i) to evaluate the simulation ability of the soil erosion *SERT-2014* model to map and quantify runoff depth, soil loss and deposition due to this event, in a small fallow cereal crop field and its contributing area, and ii) to fill a gap in soil erosion modelling studies for exceptional events at field scale and under fallow treatment. To achieve these goals we firstly present the enhanced version (as yet unpublished) of the Soil Erosion and Redistribution Tool (*SERT-2012*) model (López-Vicente et al., 2013a), the *SERT-2014* version that includes two new sediment balance factors to refine model predictions of soil redistribution. All inputs are measured in detail, allowing sound parameterization of the *SERT-2014* model. To refine the modelling evaluation the model is run at high spatial resolution (1 x 1 m cell size) and validation of predicted rates and maps of soil erosion and redistribution is carried out with field-quantified values of total soil loss in the main rills and all ephemeral gullies, and also using the map of observed soil redistribution. We chose the *SERT* model because its ability to simulate soil erosion and redistribution at a high spatial and monthly temporal scale was proven in a previous study, where the *SERT-2012* version was run and successfully tested with ¹³⁷Cs in a Mediterranean agro-ecosystem similar to the study area in this research. The accuracy, shortcomings and strengths of the enhanced version are analyzed. We consider that this study will be of interest for further model improvements and also to plan soil conservation strategies in agricultural systems.

MATERIAL AND METHODS

Study area

A rain-fed fallow cereal field and its small upslope drainage area, known from now on in this manuscript as “the field”, were selected as the study area for this research due to their physiographic characteristics within the area affected by the exceptional event. The field, that has a total extension 1.9 ha, is located in the lower part of the La Reina gully catchment and it is classed as a closed-hydrological unit due to the cutting-connectivity effect of the landscape linear elements (LLEs) that surround the study area (Quijano et al., 2013) (Figure 1a). The La Reina gully extends to the Vandunchil gully, which is a tributary of the Castiliscar stream within the Aragón river basin in the northern part of the Ebro river basin. This landscape has numerous manmade infrastructures (paved and unpaved trails, drainage ditches, stone walls, fences, buffer strips) that modify runoff pathways and thus sediment connectivity. The field is delimited by a paved trail and a stone wall to the north and by a small drainage ditch to the west, whereas to the east and south it borders on the La Reina gully. In a previous study four

hydrological units (HU) were identified: three in the northern part of the field with several outlets to the gully and one HU that covers the southern part of the field and has one outlet (López-Vicente et al., 2013b) (Figure 1b). Soils are classified as *Haplic Calcisols* with low organic carbon content, ca. 1.3%, and texture is mainly silt loam and in some cases silty clay loam, loam and sandy loam (Quijano et al., 2012).

The field was severely affected by the exceptional event and numerous rills and ephemeral gullies appeared or clearly increased in size (Figure 1c). The cereal field was last harvested in June 2007 and from that date onwards the field has remained fallow for research purposes. Vegetation clearance practices were implemented to prevent scrub growth and so the soil surface has remained almost bare since that date. The climate is continental Mediterranean with two humid periods in spring and autumn, dry summers with occasional thunderstorms and temperate winters. During the 1988-2012 period, the average annual rainfall was ca. 531 mm. The highest rainfall depth in the study area is usually recorded in October (70 mm on average) and López-Vicente et al. (2013b) estimated that the greatest field soil erosion took place during this month, ca. $0.45 \text{ Mg ha}^{-1} \text{ month}^{-1}$, whereas average annual soil erosion was $1.8 \text{ Mg ha}^{-1} \text{ yr}^{-1}$.

Field quantification of net soil loss and soil redistribution mapping

A few days after the rainfall event we performed a field survey to identify and map the location and extent of small rills (maximum depth less than 2 cm), rills (R, maximum depth great than 2 cm), ephemeral gullies (EG), areas with depositional features, as well as those stable areas without the presence of erosive features or soil accumulation deposits. The stable areas are located on the divides between the different sedimentological units (SU) as well as on areas with low slope steepness. The resulting map, *RED-field* map, gave us the first assessment of the effects of water soil erosion due to the exceptional event. In the survey, we also measured the morphology of each R and EG using the following criteria: the cross sections were measured at about every 0.5 m or whenever a significant change in the R and EG cross section or the entry of tributaries was observed. Since the field had been set to fallow, we monitored the study area and only very small rills and interrill erosion affected the soil surface before the exceptional rainfall event. Thus, we can assume that all R and eroded soil in the EG correspond to the erosive power of the exceptional event. Before the field was set to fallow tillage practices were regularly carried out by the owner and thus the soil surface did not present either rills or ephemeral gullies. The morphological similarity between R and EG in cultivated soils under Mediterranean conditions (Capra et al., 2009) enabled us to use

the same approach to quantify their soil loss values. The R and EG cross sections were treated as trapeziums or rectangles, which meant that channel widths (upper and lower) and depths were measured with a millimetre steel tape measure. The length of each R and EG was determined from the first incision in the soil surface of a depth equal to or greater than 0.5 cm to the beginning of the depositional areas or the border of the field corresponding to the talus of the La Reina gully. The volumes of material removed in each R and EG (V , cm^3) were calculated using the end area method, that is, by multiplying the mean area of two successive cross sections by the distance between them. This approach was successfully used by Capra et al. (2012) in the study of soil erosion in EG in Sicily (Italy):

$$V = \sum_{i=1}^n V_i = \sum_{i=1}^n \frac{AX_{i+1} + AX_i}{2} \cdot L_i \quad (1)$$

where n is the number of segments, V_i (cm^3) is the volume of eroded soil from each segment, AX_{i+1} (cm^2) is the downstream cross sectional area of the segment i , AX_i (cm^2) is the upstream cross sectional area of the segment i , and L_i (cm) is the distance between adjacent cross sections. Volume values were converted to mass of eroded soil (M , g) by using their corresponding average value of bulk density (BD , g cm^{-3}):

$$M = V \cdot BD \quad (2)$$

The average BD was calculated for each R and EG system in order to refine the quantification of soil loss. Finally, the rates of soil loss (E , $\text{Mg ha}^{-1} \text{ event}^{-1}$) for each R and EG system were calculated taking into account their contributing area, revealing clear evidence of net soil loss ($A_{\text{up-loss}}$, ha) from the total upslope area. The *RED-field* map enables accurate estimation of the values of $A_{\text{up-loss}}$. Interrill erosion was not determined in the field survey given that the topographic changes related to this process are almost negligible for conventional techniques.

The SERT model

The Soil Erosion and Redistribution Tool (*SERT*) model (López-Vicente et al., 2013a) is a semi-physically-based approach to predict average rates of runoff depth, soil erosion in rill and interrill areas and sediment redistribution in very small ($< 1 \text{ km}^2$), small ($1\text{--}5 \text{ km}^2$) and medium ($5\text{--}50 \text{ km}^2$) size catchments without permanent streams (e.g. creeks and rivers). The model uses programmed GIS commands to calculate the water and sediment balance factors and also the cumulative upstream runoff and relocation of sediments along the hillslopes. The processes that take place on the riverbed and river talus are not contemplated, thus *SERT* is

not suitable for large catchments (50–1000 km²) or river basins (>1000 km²). One of the strengths of the model is that the simulation procedure is divided into three independent modules: i) hydrology (*SERT-Hydro*), ii) soil erosion (*SERT-Eros*) and iii) soil redistribution (*SERT-Redis*). The *SERT* model has the conceptual basis and part of the equations of the *DR2* (López-Vicente and Navas, 2012) water balance model and the *RMMF* (Morgan, 2001) and *Modified MMF* (Morgan and Duzant, 2008) soil erosion models. Another strength of the *SERT* model is the high number of earth surface processes that can be simulated (15 output maps and values) with 24 inputs (without considering data used for validation) in comparison with other similar tools, such as the open source and physically based OpenLISEM (Sanchez-Moreno et al., 2014) and the widely used SWAT (Palazón and Navas, 2014) models that are high data demanding. A further strength of the *SERT* model is that the calibration procedure is not a must to run the model whereas internal modelling calibration is totally necessary in other models such as the KINEROS-based modelling tools (Goodrich et al., 2012) and the WATEM/SEDEM (Alatorre et al., 2010) model. In this study we present the enhanced *SERT-2014* version that includes changes in the *SERT-Hydro* and *SERT-Redis* modules.

Surface hydrology (SERT-Hydro module)

The *DR2-2013* version of the GIS-based Distributed Rainfall-Runoff (*DR2*) model (López-Vicente et al., 2014) creates the hydrological module. *DR2-2013* calculates the depth of stored and infiltrated water in the soil profile and the runoff depth, considering spatial and temporal variations in rainfall intensity, soil saturation and upslope contribution factors. The *DR2-2013*[©] SAGA v1.1 software can be freely downloaded as executable file (<http://digital.csic.es/handle/10261/93543>). *DR2-2013* calculates the effective cumulative runoff (CQ_{eff} , mm) in a three-step procedure. In the first step unsaturated cells and cells saturated by direct rainfall (no runoff contribution) are differentiated. Time to ponding, Tp (s) is the time it takes for the soil surface to become saturated in conditions of rainfall intensity greater than the saturated hydraulic conductivity of the topsoil (K_{fs-Top} , cm s⁻¹) and it is calculated as the mean value between the minimum and maximum time to ponding:

$$\frac{1}{2} \frac{Sp_i^2}{K_{fs-Top}} \ln \left(\frac{I}{I - K_{fs-Top}} \right) \leq Tp_i \leq \frac{1}{2} \frac{Sp_i^2}{I - K_{fs-Top}} \quad (3)$$

$$Sp_i = \sqrt{2 \cdot (\Delta\theta_i) \phi_i} \quad (4)$$

$$\Delta\theta_i = \theta_{Seff-i} - \theta_{0-i} = \theta_{s-i} Vol_{eff} - \theta_{0-i} \quad (5)$$

where Sp is the soil sorptivity ($\text{cm s}^{-0.5}$), I (cm s^{-1}) is the average rainfall intensity, ϕ is the matrix flux potential ($\text{cm}^2 \text{s}^{-1}$) of the soil, θ_s (% vol. ranging from 0 to 1) and θ_0 (% vol. ranging from 0 to 1) are the saturated and initial volumetric water content of the soil, respectively, and Vol_{eff} is the effective volume of the soil or the volume of the fine fraction of the soil. The subscript i corresponds to each cell of the digitalized study area. The θ_{seff} parameter accounts for the maximum amount of water that can be stored within the soil, taking into account the volume of rocks. Coarse fragments play a critical role in processes of topsoil saturation and initiation of runoff (Smets et al., 2011) and are very frequent in Mediterranean cultivated soils (López-Vicente et al., 2009). Once the topsoil is saturated overland flow appears and the initial runoff per raster cell, Q_0 (mm), is estimated as a function of the depths of effective rainfall, ER (mm), rainfall to ponding, Rp (mm), and the number of rainfall events or sub-events, e (n):

$$Q_{0i} = ER_i - (Rp_i e) = ER_i - (Tp_i I e)10 \quad (6)$$

$$ER_i = R(1 - Av_i)/\cos S_i \quad (7)$$

ER values are estimated taking into account the depth of precipitation intercepted by the canopy Av (0–1), the total rainfall depth R (mm), and by calculating the effect of slope angle, S (radians), on the quantity of rain received per unit area. Once Tp_i and Q_{0i} have been calculated at each measurement point, maps for the whole study area are created with the Kriging interpolation method (ordinary type with constant trend removal) that provides the minimum standard error. In the second step, Q_{0i} is routed into the digital elevation model (DEM) using a multiple flow accumulation algorithm (MD) and the potential cumulative runoff, CQ_0 (mm), is obtained. In this study, taking into account the high spatial resolution of the DEM , the MD algorithm was chosen as it appeared to be the most suitable approach to describe the spatial patterns of overland flow (López-Vicente and Navas, 2010). The subscript $resol$ corresponds to the spatial resolution of the DEM because the runoff depth also depends on this parameter:

$$CQ_0 = f(Q_{0i}, \text{MD algorithm}, DEM_{resol}) \quad (8)$$

A water balance correction factor (α) is added so that volume of balanced potential cumulative runoff (CQ_{0B}) equal to the initial volume of available water to be accumulated in the field. Effective cumulative runoff, CQ_{eff} (mm), is calculated taking into account the saturated hydraulic conductivity of the soil profile, K_{fs} (mm s^{-1}), and the duration of the event or sub-event after the soil becomes saturated until the end of the rainfall event or sub-event, Tq (s):

$$CQ_{0B} = \alpha \cdot CQ_0 = \frac{\sum_{i=1}^{i=k} ER_i - \sum_{i=1}^{i=k} Rp_i \cdot e}{\sum_{i=1}^{i=k} CQ_0} \cdot CQ_0 \quad (9)$$

$$CQ_{eff} = (CQ_{0B} - K_{fs} Tq_{ee} - SS_{max} ee) \sin S \quad (10)$$

$$Tq = (TER - Tp_i) + Tq_{AffER} = (ER_i / e \cdot 10 I - Tp_i) + (FIL / FLV) \quad (11)$$

as well as the maximum amount of water retained on the soil surface, SS_{max} (mm):

$$SS_{max} = 0.5 RG \frac{\sin^2(SIG - S)}{\sin(SIG)} \frac{\cot(SIG + S) + \cot(SIG - S)}{2 \cos(SIG) \cos(S)} \quad (12)$$

where ee (n) is the number of rainfall erosive events, TER (s) is the total duration of the storm event, which depends on the values of ER , Eq. (5) at each pixel, FIL (m) is the flow length, FLV (m/s) is the flow velocity, RG (mm) is the surface roughness, i.e. the maximum depth of the soil microrelief, and SIG (radians) is the surface soil and surface furrow angle. Assessment of the TER factor has been enhanced in the *SERT-2014* version in comparison to the *SERT-2012* version, as the corresponding map is calculated spatially distributed instead of using a map with a unique value. A SIG value of 30° is used in the study area in line with the value used in the previous application of the *DR2* model. The roughness values of the forest areas (random roughness, $RG = 20.3$ mm) and grass areas ($RG = 6.35$ mm) of the upslope contributing area and of the fallow field ($RG = 15.2$ mm) were taken from Renard et al. (1991).

Soil erosion (*SERT-Eros module*)

Soil erosion (E , $Mg \text{ ha}^{-1} \text{ event}^{-1}$) is predicted after comparing the runoff transport capacity (TC , $Mg \text{ ha}^{-1} \text{ event}^{-1}$) with the sum of the splash (F , $Mg \text{ ha}^{-1} \text{ event}^{-1}$) and runoff (H , $Mg \text{ ha}^{-1} \text{ event}^{-1}$) detachment rates:

$$E = \min\{(F + H), TC\} \quad (13)$$

$$F = K \cdot EE \cdot 10^{-2} \quad (14)$$

$$H = Z_i \cdot CQ_{eff}^{1.5} \cdot (1 - GC) \cdot 10^{-2} \quad (15)$$

$$Z_i = \frac{1}{0.5 \cdot COH_i} \quad (16)$$

$$TC = C \cdot P \cdot CQ_{eff}^\beta \cdot 10^{-2} \quad (17)$$

where K ($g \text{ J}^{-1}$) is the soil erodibility, EE ($J \text{ m}^{-2}$) is the total rainfall energy, Z (kPa^{-1}) is the resistance of the soil to being detached and delivered, GC (%) is the ground cover (e.g. rocks,

litter and stubble), COH (kPa) is the cohesion of the soil, estimated from the soil texture, and C and P are the factors of cover management and support practices of the *RUSLE* model (Renard et al., 1991). The β factor range [1.3–2.9] in order to model the loss of transport capacity due to runoff from the divides to the bottom of the hillslope as runoff increases the load of sediment delivered. The β factor map is obtained from the map of effective cumulative runoff. Rainfall energy is estimated as the sum of the kinetic energy of leaf drainage raindrops $E(LD)$ ($J\ m^{-2}$) and the energy of the direct throughfall rainfall $E(DT)$ ($J\ m^{-2}$):

$$EE = E(DT) + E(LD) \quad (18)$$

$$E(DT) = DT \cdot KE \quad (19)$$

$$E(LD) = (15.8 PH^{0.5}) - 5.87 \quad (20)$$

where DT (mm) is the direct throughfall volume of rainfall estimated from the total depth of effective rainfall (ER , mm) and the depth of leaf drainage (LD , mm), and KE ($J\ m^{-2}\ mm^{-1}$) is the kinetic energy of the rain:

$$DT = ER_i - LD \quad (21)$$

$$LD = ER \cdot CC \quad (22)$$

where CC (0–1) is the percentage of the soil surface protected by the canopy. The kinetic energy of the rain is a function of the rainfall intensity, I ($mm\ h^{-1}$), and is estimated in this study using the equation developed by Coutinho and Tomás (1995) and checked by direct measurements in western Mediterranean areas (Cerdà, 1997):

$$KE_m = 35.9[1 - 0.559 \exp(-0.034 I_m)] \quad (23)$$

Soil redistribution (SERT-Redis module)

Soil redistribution is the result of a balance between the amounts of soil detached and the amount of soil delivered and deposited downslope. Using this conceptual basis, the *SERT* model estimates the Remaining runoff Transport Capacity (TC_r , $Mg\ ha^{-1}\ event^{-1}$) factor that allows the relocation of sediments. Then, the potential (DEP_{pot} , $Mg\ ha^{-1}\ event^{-1}$) and net (DEP' , $Mg\ ha^{-1}\ event^{-1}$) rates of soil deposition in each cell of the modeled area are calculated. When runoff transport capacity (TC) is the limiting factor of soil erosion in a cell there is not enough energy for the downward delivery of sediments from the upslope cells (E_{up} , $Mg\ ha^{-1}\ event^{-1}$). Conversely, when the total rate of detached particles is lower than the TC rate, there is a remaining runoff Transport Capacity per cell, TC_r , and accumulated runoff Transport Capacity along the hillslope (TC_{r-up} , $Mg\ ha^{-1}\ event^{-1}$) that can deliver part or all of the sediment coming from the upslope cells:

$$TC_r = (TC - E) > 0 \quad (24)$$

$$E_{up} = E_{up'} \cdot \gamma + (E \forall \text{ surface } E_{up'} = 0) = f(E \forall \text{ surface } TC_r > 0, \text{MD algorithm}) \cdot \gamma + (E \forall \text{ surface } E_{up'} = 0) \quad (25)$$

$$\gamma = \frac{\sum_{i=1}^{i=k} E \forall \text{ surface } E_{up'} > 0}{\sum_{i=1}^{i=k} E_{up'}} \quad (26)$$

$$TC_{r-up} = TC_{r-up'} \cdot \delta = f(TC_r, \text{MD algorithm}) \cdot \delta \quad (27)$$

$$\delta = \frac{\sum_{i=1}^{i=k} TC_r \forall \text{ surface } TC_{r-up'} > 0}{\sum_{i=1}^{i=k} TC_{r-up'}} \quad (28)$$

$$DEP = DEP_{pot} - E = ((E_{up} - TC_{r-up}) - E) \forall \text{ surface } DEP > 0 \quad (29)$$

where γ and δ are the two new soil redistribution correction factors introduced in the SERT model to equal the amount of delivered soil along the hillslopes to the initial total amount of eroded soil. In most GIS software flow accumulation algorithms are not mass-conservative and thus a correction factor is necessary to avoid overestimation of runoff depths and soil redistribution rates. The γ and δ factors allow a more accurate assessment of actual delivery of detached particles. Once deposition-prone areas are identified and their corresponding rates calculated erosion-prone areas are defined ($LOSS$, $\text{Mg ha}^{-1} \text{ event}^{-1}$) and the soil redistribution map is generated (RED , $\text{Mg ha}^{-1} \text{ event}^{-1}$):

$$LOSS = E \forall \text{ surface } DEP \leq 0 \quad (30)$$

$$RED = DEP - LOSS \quad (31)$$

Values of soil redistribution at the end of the three-day rainfall event are computed as the sum of the soil redistribution processes that happen in each sub-event (se):

$$RED_{event} = \sum_{se=1}^{se=6} DEP_{se} - \sum_{se=1}^{se=6} LOSS_{se} \quad (32)$$

Finally, sediment yield to the La Reina gully is calculated as the balance between the total rates of soil loss and the sediment deposited in the field:

$$\sum_{se=1}^{se=6} LOSS_{T-se} - \sum_{se=1}^{se=6} DEP_{T-se} = SY_{T-event} \quad (33)$$

where $LOSS_{T-se}$ (Mg se^{-1}) is the total amount of net eroded soil in each sub-event se , DEP_{T-se} (Mg se^{-1}) is the total sediment deposited in each sub-event se , $SY_{T-event}$ (Mg event^{-1}) is the total sediment yield at the field outlets.

Input acquisition

There are eleven active weather stations (WS) surrounding the study area (Figure 2a), five of which belong to AEMET and record hourly values of precipitation, one belongs to SARGA (values recorded every 30 minutes), and the remaining five WS, belonging to CHEbro, record values every 15 minutes. The five CHEbro-WS provided adequate temporal resolution for numerical modelling. Of these WS only Yesa recorded a total precipitation value during the event (215 mm) that was similar to that of the precipitation recorded at Novellacos WS (235 mm), located only 1.4 km to the west of the field. The Novellacos values were manually recorded by Dr. Machín (EEAD-CSIC) and offer valuable information of the actual precipitation affecting the field soils. The *SERT-2014* model was only run with the rainfall values recorded at Yesa WS.

Soil properties and inputs were obtained in field surveys and laboratory analyses (Table I). The initial volumetric water content of the soil, θ_0 in Eq. (5), before the first sub-event (*se-1*) was measured with the Delta-T SM200 Soil Moisture Sensor (a probe with two rods inserted in the soil up to 51 mm depth; accuracy $\pm 0.03 \text{ m}^3 \text{ m}^{-3}$) 1 week before the rainfall event at 156 points, as part of a soil characterization campaign. A large number of measurements were performed due to the role played by θ_0 in soil saturation processes and because physical properties vary considerably in Mediterranean soils (López-Vicente et al., 2009). A total of 613 soil samples were collected following a regular 5x5 metre grid (Figure 1b). Bulk density was calculated with the undisturbed soil cores. Samples were air-dried, ground, homogenized and quartered to pass through a 2 mm sieve. Soil texture, rock content and the volumetric water content at saturation (θ_s) and field capacity (θ_{FC}) were determined for each sample. Given that the soil became saturated during *se-1*, for sub-events 2 to 6 θ_{FC} values were used as the initial moisture value. Infiltration properties, Kfs and ϕ , Eqs. (3) and (4), were measured at 6 representative points across the field bearing in mind the small surface area of the study site and the presence of just one soil type. Furthermore, the spatial variability of other soil hydraulic properties such as θ_s (standard deviation equals 8.0 % vol.) and θ_{FC} (sd = 6.0 % vol.) is low (Quijano, 2014; personal communication). Values of Kfs and ϕ for the forest and unpaved trail were obtained from López-Vicente et al., 2013a.

A high-resolution (1 x 1 m cell size) *DEM* was generated by resampling the free *DEM* of the region (5 x 5 m) and using field measurements every 5 meters in the whole field and every 1 and 3 meters in the areas with a gentle topography. Values of the C- and P-RUSLE factors

were obtained from López-Vicente et al. (2013a). In this study the number of events, e in Eq. (6), and erosive events, ee in Eq. (10), are the same as we ran the SERT model for the six se and not for an average month. The high number of soil samples and field measurements allowed very good parameterization of the SERT model.

RESULTS AND DISCUSSION

Exceptional rainfall and hydrological event

During 19-21 October 2012 an exceptional rainfall and hydrological event occurred in both the French and Spanish central western Pyrenees and in the central Ebro Depression, including several episodes of high rainfall intensity. The most intense rainfall occurred at the headwaters of the Aragón and Gállego rivers, where high peak discharges took place in some catchments (Lana-Renault et al., 2014), and in a small sector of the central Ebro Depression associated with the Pre-Pyrenees, in the region of Cinco Villas, with the development of large floods (Acín-Naverac et al., 2012). The return periods for this event were calculated to be between 14 and 42 years in some of the tributaries of the Aragón River, whereas in the Upper Aragón River the flood return period was calculated to be approximately 400–500 years and 142 years at the end of the Yesa reservoir (Serrano-Muela et al., 2013). Figure 2a shows the map of accumulated rainfall during the three-day event, generated using data from three sources: the Ebro river basin Water Authorities (CHEbro), the automatic system of weather stations of the Autonomous Community of Aragón (SARGA), and the Spanish Meteorology Agency (AEMET). In the Spanish watershed, cumulative precipitation of more than 200 mm affected ca. 3180 km² and many weather stations recorded total rainfall depth values that were greater than 100 mm. The hyetographs of the Vigas, Yesa and Uncastillo weather stations, located 22.5 km west, 21.2 km north and 10.4 south east of the study area, respectively (Figure 2b) describe a similar shape, with 6 rainfall sub-events and total event duration of ca. 53 hours. In Aragón, which was the most affected region, this episode caused severe damages estimated at more than 45 million euros: ca. 12 million euros in damages to private properties, ca. 24 million euros to environmental and agricultural facilities, ca. 4.5 million euros to road infrastructures, ca. 1 million euro for the reconstruction of one school, and ca. 3.5 million euros in damage to water facilities (Heraldo de Aragón, 2013). Damage to agricultural land was severe because most of the fields in these areas are cultivated with cereal crops and soils remain bare or ploughed in October.

Quantified soil loss and field mapping of soil redistribution

The in situ soil redistribution map, *RED-field* map, describes 8 sedimentological units (SU) that include 165 small rills, 36 rills (R), 6 ephemeral gullies (EG), 15 stable areas and 11 areas with soil accumulation (Figure 3a) (Table II). R and EG only affected 1% of the soil surface whereas interrill erosion and small rills appeared in 66% of the field surface. Stable and soil accumulation areas represent 21 and 12% of the total surface, respectively (Figure 3b). EG developed in the SU with concave topography whereas small rills and R were the predominant features in the SU with rectilinear topography. All R appeared within the crop field except one rill associated with the small unpaved trail located in the NW section of the study area. More than 13 m³ of soil were lost in the small area (96 m²) affected by EG and almost 7 m³ of soil were lost from the surface area (91 m²) affected by R (Table II). Total soil lost in the R of the unpaved trail added up to 1.4 m³ highlighting that soil erosion is dependent on roads and other unpaved surfaces such as Cerdà (2007) studied on road embankments in eastern Spain. Therefore, the exceptional rainfall event of October 2012 had significant implications on landforms. This was also found in similar agricultural plots as our research site (Martínez-Casasnovas et al., 2002) and even at regional scale (González Hidalgo et al., 2012).

Bulk density (*BD*) ranged between 1.23 and 2.02 gr cm⁻³, obtaining an average value of 1.69 gr cm⁻³ for the 613 soil samples (standard deviation equals 0.09 gr cm⁻³). The average *BD* for each R and EG system ranged between 1.65 and 1.78 g cm⁻³. These values are in agreement with those reported by Fernández-Ugalde et al. (2009) in cereal fields on *Haplic Calcisols* in the Ebro Valley (NE Spain) with average values of *BD* between 1.58 and 1.78 gr cm⁻³. In SU-1C one bank collapse (C) appeared at the end of the rills and more than 11 tons of soil were lost. Apart from the bank collapse, soil loss rates due to R and EG varied from 6.2 to 32.8 Mg ha⁻¹ event⁻¹ at the different SU and R and EG did not affect soils in one SU. Total soil losses due to C, R and EG during the event were estimated at 31.4 tons, which gives an average rate of 26.7 Mg ha⁻¹ event⁻¹. These values are similar to others quantified in the past in the Ebro river basin due to individual storm events affecting gentle cultivated soils (redistribution rates between -42 and 33 Mg ha⁻¹ event⁻¹) and steep, erosion-dominated mountain soils (soil losses ranged between 5.5 and 40 Mg ha⁻¹ event⁻¹) (Navas et al., 2008). All these values are much higher than the maximum value of tolerable soil loss, 1.4 Mg ha⁻¹ yr⁻¹, proposed by Verheijen et al. (2009) for European cultivated soils, indicating that soil sustainability in the field was severely threatened by the exceptional event. Stable areas were found in all SU and soil deposition mainly appeared at the end of the runoff pathways just before reaching the La Reina gully.

Simulated runoff

The application of the SERT model for each sub-event (*se*) allowed a detailed numerical simulation of the hydrological and erosive response of the soils. From the six *se* only two of them, the first (*se-1*) and fourth (*se-4*), can be considered as erosive events because their values of total rainfall depth and/or rainfall intensity were higher than 12.7 mm and 6.25 mm in 15 minutes, respectively, following the criteria of Renard et al. (1991) (Table III). During the other four *se* rainfall depth was ca. 6 mm or lower and the maximum rainfall intensity in 30 minutes (I_{30max}) remained below 10 mm h⁻¹. The most erosive sub-event was *se-1* as mean and maximum rainfall intensity was very high. The average rainfall intensity during *se-4* was much lower due to its long duration.

Predicted runoff production also described this temporal variability and only during the *se-1* the whole field become saturated (Table III). The runoff coefficient (*CQC*) during *se-1* was above 10% and the mean and maximum runoff depth was very high considering the small area of the field. During the other five *se* the *CQC* was between 2.7 and 7.4%. The maximum values of runoff appeared in *se-1* and *se-4* while during *se-5* only 5% of the soil surface was affected. Simulated runoff yield to the La Reina gully was calculated at the outlets of the field adding a total volume of 10.5 m³ at the end of the six sub-events. The remaining runoff generated during each *se* was infiltrated in the soil during and after the event throughout the field. The *SERT-2014* model does not simulate soil surface sealing processes at the beginning of rainfall events as thus this uncertainty should be considered in further research.

Simulated soil erosion

The variation in mean and maximum values of soil erosion predicted for the six *se* match the temporal pattern of high and low values of runoff production, although differences in soil erosion values were more pronounced (Table III). During *se-1* erosion values (*E*) higher than 10 Mg ha⁻¹ se⁻¹ affected 35% of the field's surface. Soil erosion was also high during *se-4* and more than 20% of the soil surface had $E > 2$ Mg ha⁻¹ se⁻¹. During the other 4 sub-events soil erosion was very low with mean values below 0.3 Mg ha⁻¹ se⁻¹ and erosion only affected rills, EG and the areas with the highest values of slope steepness. The rills that appeared in the soil deposition areas (see drawings in Figure 3b) could have been developed during these low erosive sub-events. The total amount of eroded soil during the six sub-events adds up to 20.5 tons for the whole field. Most of this soil was eroded during *se-1* (86%) and *se-4* (13%). There is a good fit between the areas affected by high erosion rates after the six sub-events

(Figure 4) and the location in the *RED-field* map of the main erosive features. A positive match was also found between the observed stable areas and those with the lowest values of predicted soil erosion. Low soil erosion values appeared in forest and grass areas.

Simulated soil redistribution

Soil redistribution was simulated for the six sub-events and clear differences in the values, spatial patterns and areas affected by net soil loss and deposition were obtained for each sub-event (Figure 5) (Table IV). The highest values of soil redistribution (net soil loss and deposition) were simulated during *se-1* in the whole field. During *se-1* the total amounts of soil loss and sediment yield to the La Reina gully were ca. 14 and 5.9 tons, respectively. However, soil deposition was predicted not only in the lower section of the channels of the R and EG but also in their middle sections. This overprediction of soil deposition areas is explained by the large amount of sediments detached and delivered during *se-1* and also by the lack of a specific power stream delivery factor in the SERT model. During *se-2*, *se-3* and *se-5* simulated soil redistribution only affected the areas surrounding the small rills, R, EG and soil deposition areas, whereas stable conditions were predicted for more than 80% of the field surface. During *se-4* and *se-6* only soil loss processes were simulated and high and severe values of soil loss were only predicted during *se-4*.

The map of total soil redistribution, *RED-SERT* map, described predominant processes of soil loss (higher than $0.5 \text{ Mg ha}^{-1} \text{ event}^{-1}$) affecting 71% of the surface area of the field, soil deposition (higher than $0.5 \text{ Mg ha}^{-1} \text{ event}^{-1}$) was predominant on 17% of the surface area whereas stable areas were predicted in the remaining 11% (Figure 6). Total soil loss and sediment yield after the exceptional event was 16.3 and 9 tons, whereas 45% of the total eroded soil was stored within the field (Table IV). Predicted eroded soil values are in the same order of magnitude as the measured total soil loss in R and EG that amounts to $20.0 \text{ Mg event}^{-1}$ without taking into account the loss of soil due to gully bank collapse that was estimated to be $11.4 \text{ Mg event}^{-1}$.

Model validation

The acceptable match found between predicted and measured rates of soil loss demonstrates the soundness of the *SERT-2014* model and the ability of its water and new sediment balance equations to predict the hydrological and soil erosion response of the soils during the exceptional event. Underestimation of total soil loss may be explained by the fact

that the actual upslope contributing area during the exceptional event could be larger than the simulated one.

The comparison between the *RED-SERT* and *RED-field* maps shows an overestimation of the soil deposition rates and areas predicted with the *SERT-2014* model in the EG although the highest rates of soil erosion were correctly predicted in these geomorphic features. This error is ascribed to the runoff transport capacity calculated by the model given that SERT was designed for interrill, R and EG water erosion but cannot successfully predict the processes that take place in the runoff layer when overland flow exceeds the typical values of runoff depth. Further research with the SERT model should focus on the sediment delivery capacity of streams. Introducing this enhancement in the model would extend its applicability to catchments with permanent water courses.

The results obtained in the present study highlight the ability of the SERT model to predict different values and patterns of soil loss and deposition in the field during the six sub-events that occurred in October 2012. The simulated soil redistribution maps provide valuable information, which cannot be obtained by direct field measurements, regarding the processes that took place during the 3-day exceptional event, allowing a more detailed description of the processes of soil erosion and sediment redistribution that affected the field's soils.

CONCLUSIONS

We conclude that: i) the exceptional rainfall event of October 2012 caused severe damage in the soils of the fallow field, producing many rills and enlarging the ephemeral gullies and even causing the collapse of the banks of the La Reina gully talus (11 tons) which, together, threaten the sustainability of agriculture in this region; ii) these very high erosion rates happened when the intensity was very high and thus extreme rainfall events are the ones that control the soil losses and landforms; iii) the enhanced *SERT* model, the *SERT-2014* version, was able to simulate the hydrological and erosive response of the soils during the six precipitation sub-events, describing different spatial patterns and values of runoff production and soil erosion; iv) the improved *SERT-2014* model predicted clear differences in the predominant processes (net soil loss and deposition) and rates that took place in the same area during each sub-event; and v) the predicting ability of the *SERT-2014* model was confirmed given that predicted (16.3 tons) and measured (20.0 tons) values of soil loss in the rills and ephemeral gullies are similar and even the spatial patterns of soil erosion coincide with field observations and the in-situ map of soil redistribution.

The main shortcomings of this study are: i) the uncertainties related to some model input data; and ii) soil deposition was overestimated in the channels of the ephemeral gullies. Further research with the *SERT-2014* model should pay attention on: i) the necessity of adding a model's stream transport capacity factor; and ii) the soil surface sealing processes at the beginning of the rainfall events. Finally, this study proves the usefulness of the *SERT-2014* model for simulating the magnitude of the runoff yield and severe soil erosion and redistribution processes that took place during an exceptional event at field scale and under fallow conditions.

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Figure 1. (a) Overland flow pattern of the La Reina gully catchment (lower part), (b) 3D view of the study area with location of the soil sampling points and the boundaries of the four hydrological units identified in a previous study and (c) photographs of the La Reina gully and the field taken during the exceptional rainfall and hydrological event.

Figure 2. (a) Values and contour lines of the precipitation accumulated during the 3-day exceptional rainfall event at regional scale and in the area surrounding the study area, in the Spanish provinces of Navarre, Huesca and Zaragoza (NE Spain), and (b) hyetographs of the event in three weather stations surrounding the study area.

Figure 3. (a) Sedimentological units and geomorphic features identified in the field survey after the 3-day rainfall and hydrological event, and (b) pictures of the rills, ephemeral gullies and soil accumulation areas taken after the event.

Figure 4. Map of predicted soil erosion using the SERT model after the six sub-events.

Figure 5. Maps of predicted soil redistribution during the six sub-events using the SERT model.

Figure 6. Map of soil redistribution after the six sub-events predicted with the SERT model.

Table I. Input parameters (except the climatic ones) of the *SERT-2014* model and range of values.

Type of data	Input	Description	Value			
			min	mean	max	sd*
Soil	θ_s	Volumetric water content at saturation (% vol.)	26.2	70.1	98.3	8.0
	θ_{FC}	Volumetric water content at field capacity (% vol.)	12.4	34.2	55.0	6.0
	θ_0	Volumetric water content before rainfall (% vol.)	2.4	19.2	28.0	3.8
	Vol_{eff}	Effective volume of the soil (0–1)	0.88	0.99	1.00	0.02
	K_{fs-Top}	Saturated hydraulic conductivity: topsoil (cm s ⁻¹)	1E-5	6E-5	18E-4	5E-5
	K_{fs}	Saturated hydraulic conductivity: soil (mm s ⁻¹)	2E-4	27E-3	79E-3	28E-3
	Φ	Matrix flux potential (cm ² s ⁻¹)	0.03	0.05	0.07	0.02
	SIG	Surface soil and surface furrow angle (radian)	0.52	0.52	0.52	0
	RG	Soil surface roughness (mm)	1.0	6.1	17.8	1.3
	$GC-rock$	Ground cover: rocks (%)	0.0	1.1	17.2	2.3
	$GC-litter$	Ground cover: litter and stubble (%)	1.0	3.9	12.0	2.8
	K	Soil detachability index (g J ⁻¹)	0.05	0.86	0.90	0.09
	COH	Soil cohesion (kPa)	2.0	3.7	12.0	2.0
Topography	S	Slope steepness (radian)	<0.01	0.10	1.01	0.09
	FIL	Flow length (m)	0.0	15.4	205.2	20.2
Land use	C	Crop management factor: RUSLE model (0–1)	0.15	0.82	1.00	0.23
	P	Support practices factor: RUSLE model (0–1)	1.00	1.00	1.00	0.00
Vegetation	Av	Rainfall interception by canopy (%)	0.0	3.2	30.8	6.5
	FIV	Flow velocity (m s ⁻¹)	0.76	2.54	6.19	0.86
	CC	Canopy cover (%)	0.0	13.7	98.0	24.8
	PH	Plant height (m)	0.00	0.58	5.50	1.64

*: standard deviation.

Table II. Volumes and rates of soil loss in the rills and ephemeral gullies and characteristics of the other geomorphic features estimated with field measurements at each sedimentological unit (SU) of the study area.

SU	Total area	Stable areas		Interrill and R < 2 cm		R > 2 cm			Ephemeral gullies			Total soil loss (R > 2 cm + EG)		Soil deposition
	m ²	n	m ²	n*	m ²	n	m ²	m ³	n	m ²	m ³	Mg / ha event	Mg / event	m ²
SU-1 C	1357	1	304	7	934	0	0	0	1 [§]	8 [§]	6.9 [§]	121.5	11.4	110
SU-1 EG	2082	2	514	14	1382	0	0	0	1	7	0.5	6.2	0.9	186
SU-1 IR	1008	1	61	15	844	0	0	0	0	0	0	----	----	102
SU-2	5756	5	1479	23	3670	11	32	2.1	1	19	1.8	17.5	6.5	556
SU-3	2127	5	316	36	1594	7	18	1.6	1	13	1.3	16.9	2.7	185
SU-4 N	2117	4	464	12	1460	17	39	2.9	0	0	0	32.8	4.9	153
SU-4 W	2194	5	636	38	1409	1	1	0.1	2	25	1.3	17.4	2.5	159
SU-4 E	2146	3	224	21	1134	0	0	0	1	25	1.4	22.0	2.6	726
Total	18787	15	3999	165	12422	36	91	6.7	7	96	13.3	26.7	31.4	2179

R: rill; EG: Ephemeral gully; *: number of small rills with maximum depth lower than 2 cm; C: collapse; IR: interrill; §: EG with presence of soil piping and bank collapse of the “La Reina” gully; N: north; W: west; E: east.

Table III. Rainfall characteristics of the three-day event calculated with the values recorded at the Yesa weather station, and values of effective runoff and soil erosion predicted with the SERT model for each sub-event in the field.

Sub-event	Yesa weather station					SERT model						
	R	I ₃₀		t	gap-t	Effective runoff (CQC_{eff})				E		
		mean	max			A	mean	max	CQC	mean	max	sum
		mm h ⁻¹	mm h ⁻¹			%	mm		%	Mg ha ⁻¹ se ⁻¹		Mg se ⁻¹
se1	122.2	15.8	53.2	7:45	----	100	12.4	1017	10.4	9.45	73.0	17.73
se2	6.2	2.5	5.6	2:30	1:15	12	0.4	92	7.2	0.03	3.2	0.05
se3	2.9	1.0	4.2	3:00	3:15	10	0.2	43	6.4	0.01	1.2	0.01
se4	74.5	3.5	17.2	21:30	1:30	89	5.4	678	7.4	1.46	43.2	2.74
se5	3.0	0.4	1.0	8:00	1:30	5	0.1	40	2.7	<0.01	1.1	<0.01
se6	5.8	4.6	9.6	1:15	1:30	52	0.2	52	3.0	<0.01	1.5	<0.01
Event	214.6	4.0	53.2	53:00	----	100	18.5	1740	8.9	10.9	117.3	20.54

R: rainfall depth; I₃₀: rainfall intensity in 30 minutes; t: duration of the rainfall sub-event; gap-t: duration of the interval without rainfall and between each sub-event; A: area; CQC : runoff coefficient; E: soil erosion.

Table IV. Soil redistribution and sediment yield values predicted for each sub-event in the field using the SERT model.

Sub-event	Stable A	Soil loss				Soil deposition				RED	SY
		A	mean	max	sum	A	mean	max	sum	mean	
		%	Mg ha ⁻¹ se ⁻¹		Mg se ⁻¹	%	Mg ha ⁻¹ se ⁻¹		Mg se ⁻¹	Mg ha ⁻¹ se ⁻¹	Mg se ⁻¹
se1	<1	78	9.6	41.0	13.94	22	19.3	458.7	8.06	-4.032	5.874
se2	82	10	0.2	3.2	0.04	8	<0.1	0.7	0.01	-0.030	0.036
se3	86	7	0.1	1.2	0.01	7	<0.1	0.3	<0.01	-0.003	0.005
se4	11	89	1.6	43.2	2.74	0	No	No	No	-1.611	2.742
se5	87	3	0.1	1.1	<0.01	10	<0.1	0.1	<0.01	-0.005	0.001
se6	57	43	<0.1	1.5	0.01	0	No	No	No	-0.008	0.009
Event	<1	80	10.9	49.6	16.27	20	19.2	445.4	7.25	-5.547	9.019

A: soil surface; RED: soil redistribution; SY: sediment yield to the La Reina gully.