EFFECT OF SALVAGE LOGGING AND CHECK-DAMS ON SIMULATED HYDROLOGICAL CONNECTIVITY IN A BURNED AREA

SHORT TITLE: MODELLING HYDROLOGICAL CONNECTIVITY IN BURNED AREAS

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ABSTRACT

This study assessed the effect of a wildfire and different post-fire practices (salvage logging, skid trails and check-dams) and vegetation recovery (eight scenarios) on the hydrological connectivity (HC) in eleven sub-catchments (330 ha) affected by a wildfire (213 ha) in 2012 in Spain. According to the Landsat 8 OLI/TIRS images, moderate, high and extreme burn severity affected 42.1% of the area. HC was calculated with an updated version of the Borselli's index. Within the burned area (BA), HC increased in all sub-catchments (SubC) after the wildfire (*PostF-1*), the salvage logging and the new skid trails (*PostF-2*), and the development of new gullies (*PostF-3*). Check-dams reduced connectivity but did not prevent the general trend. Afterwards, the incipient (*PostF-4* and *-5*) and future vegetation recovery made slightly decrease HC. In the three forestry SubC with check-dams and large BA (67% of the study area), connectivity markedly increased (11.4, 18.2 and 22.9%) during the three first post-fire scenarios. In the 3 SubC with urban areas and small BA (5%), HC decreased a little because the linear elements connected the hillslopes between them. In the 3 SubC with

urban areas and large BA (12%), HC increased less than in the forestry SubC (3.0, 8.2 and 9.1%). In the 2 forestry SubC without check-dams and small BA (16%), the increment of connectivity was low (2.5, 4.6 and 6.3%). Monitoring of check-dam siltation and of the actual vegetation regrowth is necessary to minimize the off-site consequences of high HC.

KEY WORDS: hydrological connectivity; wildfire; salvage logging; rill erosion; post-fire scenarios

INTRODUCTION

Dependent on fire severity, wildfires modifies the physical, chemical and hydrological soil properties (Shakesby & Doerr, 2006; Shakesby, 2011; Robichaud *et al.*, 2013; Malvar *et al.*, 2016a). Soil surface conditions also change, and runoff and erosion processes enhance, especially, when ash cover is completely removed (Bodí *et al.*, 2012; Martínez-Murillo *et al.*, 2016a). The post-fire spatial distribution of soils and vegetation patterns plays an important role from the hydro-geomorphic point of view. If no obstacle exists to overland flow and eroded sediment progression, the fluxes from hillslopes reach the catchment channel easily, producing higher runoff compared to unburned areas (Ferreira *et al.*, 2008). This results in an increment in the hydrological (runoff and sediment) connectivity (HC) through different spatial scales, from patches and hillslopes to the entire catchment (Estrany *et al.*, 2016; Prats *et al.*, 2016).

The interaction between topography and processes occurring within catchments is key to understanding dynamics of HC (Bracken & Croke, 2007; Wainwright *et al.*, 2011). Turnbull *et al.* (2008) defined structural connectivity as the spatial patterns in the landscape (e.g., the spatial distribution of landscape units which influence water transfer patterns and flow paths) and functional connectivity as how these spatial patterns interact with catchment processes to produce runoff, connected flow and hence water transfer in catchments. However, the spatial and temporal variability of other elements within the landscape, such as land uses and human infrastructures, can modify that dynamic of runoff generation and sediment delivery (López-Vicente *et al.*, 2011). This is especially remarkable when wildfires occur and modify vegetation cover.

In burned Mediterranean ecosystems, it is not so frequent the rilling and gully processes compared to others as reported for the USA (Robichaud, 2000; Cannon & Gartner, 2005).

The great volume of stones in the soil surface and profile is given as the main reason for that (Shakesby, 2011). However, this rarity in the formation of rills and gullies can be modified due to the post-fire management of the burned area, especially, when burned trees are removed. Salvage logging has been reported as one of the major problems which can greatly enhanced post-fire erosion and soil losses as well as making possible the development of rills and gullies (Malvar *et al.*, 2016b). The opening of new skid trails, regardless the equipment type and the amount of traffic, increases the risk of sedimentation (Wagenbrenner *et al.*, 2016). Therefore, areas disturbed by ground-based salvage logging after high severity fires need additional mitigation practices (Wagenbrenner *et al.*, 2015).

These eco-geomorphological processes become dramatically relevant when wildfires affect what has been called ‘Wildland-Urban Interface’ (WUI), defined as the area where structures and other human development meet or intermingle with undeveloped wildland (Lein & Stump, 2009). The study of HC within the burned area in WUI becomes especially complex due to the itself-complexity of HC within urban areas (Ferreira *et al.*, 2016). Additionally, the increase of HC in this type of landscape has serious off-site effects such as the increment of flooding hazards.

Most published scientific studies relating HC and wildfire corresponded to experimental approaches in field conditions by means of either rainfall simulations, plots, gauging stations, tracers or radionuclides (Martínez-Murillo *et al.*, 2016b). However, it is found a scientific gap in the literature focussed on modelling of HC in burned areas. Most available HC indices are based on Geographic Information Systems (GIS) and stream-power approaches, such as the “volume to breakthrough” of Bracken & Croke (2007), and the Connectivity of Runoff Model, 2D version, of Reaney *et al.* (2014). A few years ago, Borselli *et al.* (2008) developed the index of runoff and sediment connectivity (IC) testing successfully this approach in a large catchment in Central Italy against field observations. This qualitative index accounts the combined effect of the upslope topographic and land-use characteristics and those values of the same parameters throughout the flow path line that a soil particle has to travel to arrive at the nearest defined stream or sink. The ability of this index has been proved in different fields and catchments, such as in Austria (Heckmann & Schwanghart, 2013), France (Gay *et al.*, 2016) and Japan (Chartin *et al.*, 2013). In Spain, the studies of López-Vicente *et al.* (2013, 2016) and Foerster *et al.* (2014) proved its capacity to map runoff and sediment connectivity.

In this study, we simulate the evolution of HC in a WUI area affected by a wildfire and subsequent salvage post-fire management. Namely, the objectives are to: i) modelling the HC in pre-fire, burned, different post-fire management conditions and two potential future

scenarios by means of an updated version of the Borselli's index; ii) characterize and validate the simulated HC under field conditions; and iii) analyse the evolution of HC in the different types of sub-catchments (based on the human-induced changes) and geomorphic features.

STUDY AREA

The study area is located in South of Spain (Province of Malaga) and corresponds to eleven headwater sub-catchments (total area of 330 ha) that cover the entire burned area (Figure 1). The fire started in 2014, 27 June and lasted two days, affecting 223 ha in total and 213 ha within the study area (65% of the surface). The landscape is mainly mountainous, ranging from 630 to 1,102 m.a.s.l., with very steep slopes (>30%) and marbles as parent material. The climate is Mediterranean, with mean annual rainfall and temperature of 600 mm and 17°C during the latest 27 years (data source: Agencia Andaluza del Agua). The previous land use to the wildfire corresponded to shrublands (*Rosmarinus officinalis* L., *Stipa tenacissima* L., *Cistus clusii* L., *Lavandula stoechas* L., *Daphne gnidium* L.) and forests of *Pinus pinaster* L. Few olive and fruit groves appear at the bottom of the slopes, and abandoned olive groves are intersected between the disperse settlements in the lower part of the slopes. The dense urban area corresponds to Cmpeta village. Soils are normally shallow (less than 15 cm depth), with high content of rocks as well as sandy texture; these were mainly skeletal and calcaric Leptosols with inclusions of Regosols.

The burned area partly covers the WUI in its southern limit (Figure 1). Salvage logging started seven days after ending the fire and lasted four days. This consisted in cutting all trees, equally completely, partially and unburned trees, and taking them out by dragging upslope. Thus, new skid trails were built. Many erosive morphologies, as rills and gullies, were enhanced due to this post-fire management. The removal of burned trees was carried out by means of their dragging down-to-up the hillslopes using cables. This technique left some marks and incisions, which were taken advantage by the overland flow.

METHODS AND SCENARIOS

Wildfire images acquisition and processing

Two-Landsat 8 OLI/TIRS images were downloaded from the United States Geological Survey (USGS) Global Visualization Viewer (<http://glovis.usgs.gov/>) for the pre-fire (path: 201, row: 34; date: 18/Jun/2014) and post-fire scenario (path: 201, row: 34; date:

04/Jul/2014). Both images presented a spatial resolution of 30 x 30 m and 15 x 15 m for the multispectral and panchromatic bands, respectively. The atmospheric correction was performed using the dark object method (band-fixed transmissivity values; Chavez, 1996). Afterwards, the multispectral and panchromatic bands were merged by means of the local regression technique of pansharpening in TerrSet 1.0 © (Clark Labs, Clark University). This process let improve the spatial resolution of multispectral bands to 15 x 15 m. Secondly, images were geometrically rectified using a second-order polynomial model to minimize the loss of spatial accuracy of the data and included in ENVI 4.8 ©. Thus, image to map registration was performed using 154 commonly identified Ground Control Points (GCPs) between the different datasets. The nearest neighbour interpolation was employed to resample the image. This method better preserves the digital number (DN)/reflectance values in the original images. A mean Root Mean Square (RME) error registration below the OLI pixel was obtained in all cases that was considered satisfactory. Another image with major spatial resolution (1 x 1 m) from Google Earth (Digital Globe ©) was downloaded (Date: 27/Jul/2015) in order to photo-interpret the post-fire rill and gully network.

Burn severity assessment

Burn severity was mapped by means of the Normalized Burn Ratio (NBR). According to Key & Benson (2005), this index highlights burned areas indicating the severity of burn. NBR calculates the differing responses of Landsat bands 4 (Near Infrared, NIR, 0.64–0.67 mm) and 6 (Short-wave Infrared, SWIR, 1.57–1.65 mm), which are sensitive to changes in soil and vegetation moisture (Garcia & Caselles, 1991):

$$NBR = \frac{NIR - SWIR}{NIR + SWIR} \quad (1)$$

The NBR was calculated for both pre and post-fire scenarios what made possible to difference both pre-/post-fire ratios. Then, the scaled index of burn severity, named differenced Normalised Burn Ratio (dNBR) (Key & Benson, 2005), was assessed. This index has been used worldwide in many different environments (Van Wagendonk *et al.*, 2004; Cocke *et al.*, 2005; Epting *et al.*, 2005; Gitas *et al.*, 2012; Veraverbeke *et al.*, 2011), and using the following equation:

$$dNBR = NBR_{pre} - NBR_{post} \quad (2)$$

The dNBR values were classified from the USGS FIREMON program (USGS, 2004) shown in Table I. Generally, unburned areas (i.e. no change between pre and post-fire scenarios) have dNBR values near zero; whereas the higher positive values corresponded to the more

severely burned areas (i.e. fire changed them the most). As burned vegetation was quickly removed after the fire, validation of the burn severity levels at field conditions was not possible. We took pictures of the burned area as soon as the authorities allowed entrance, and used this data as an alternative supervised method of validation.

Modelling of hydrological connectivity

We used the index of runoff and sediment connectivity (*IC*) proposed by Borselli *et al.* (2008) as well as part of the modifications made on it by Cavalli *et al.* (2013, 2015). The D_{dn} factor (downslope module) considers the probability that runoff and sediment arrives at a sink along a flow line, whereas the D_{up} factor (upslope module) summarizes the potential for downward routing of the overland flow produced upslope and expands the same analysis to an area:

$$IC_K = \log_{10} \left(\frac{D_{up,K}}{D_{dn,K}} \right) = \log_{10} \left(\frac{\overline{W}_K \cdot \overline{S}_K \cdot \sqrt{A_K}}{\sum_{i=K,n_K} \frac{d_i}{W_i \cdot S_i}} \right) \quad (3)$$

where A is the upslope contributing area (m^2), $\overline{W}$ is the average weighting factor of A (dimensionless), $\overline{S}$ is the average slope gradient of A ($m \ m^{-1}$), d_i is the length of the i th cell along the downslope path (m), W_i is the weight of the i th cell (dimensionless), and S_i is the slope gradient of the i th cell ($m \ m^{-1}$). The W weighting factor is a proxy of the impedance to sediment fluxes that is based on land use properties. Values of S_i lower than 0.005 must be replaced by the value $S_i = 0.005$ and those higher than 1 must be set to a maximum value of 1. This index is defined in the range of $[-\infty, +\infty]$ and connectivity increases when IC grows towards $+\infty$.

In the original version as well as in other studies, the W factor was equal to the *C-RUSLE* factor. In this study, we chose the product between the *C-RUSLE* factor, and the maps of burn severity, salvage logging and the different levels of vegetation recovery after the fire. In *IC*, the role of the linear landscape elements (LLE) is added to the simulation by modifying the map of flow direction: a mask with two values, 0 for the LLE and 1 for the remaining area (Table II).

The weighted flow path length, the $\underline{W}$, $\underline{S}$ and A factors were calculated with the D-infinity flow accumulation algorithm (Tarboton, 1997) that is available in the software *SAGA*[®]-64 2.1.2. This approach is recommended for sediment transport studies in mountainous basins

(<http://www.sedalp.eu/index.shtml>; Cavalli *et al.*, 2015) as well as in the *TauDEM* 5.2 suite tools for the analysis of hydrologic information from topography (Tarboton, 2013). The D-infinity method captures the real flow paths especially on hillslopes where divergent flow predominates, and it better approximates channel width than the D8 single flow and the MD multiple flow direction methods. Finally, the *IC* model includes the “stream mask” layer that is associated with the presence of permanent and ephemeral streams. Different “stream mask” layers were associated with the pre-fire and post-fire gully networks as well as with the construction of the check-dams and their stage (non-silted, partially and completely silted).

Pre-fire and post-fire scenarios

Table II and figure 2 show the eight simulated scenarios. A pre-fire (*PreF*) scenario was modelled in order to compare the post-fire and future scenarios to the previous conditions. After the wildfire occurred, five scenarios were defined based on the observed vegetation and landscape changes, and on the different management done in the affected area. The first post-fire (*PostF-1*) scenario only considered the loss of vegetation due to the wildfire. The effect of salvage logging and construction of new check-dams and skid trails were included in the second (*PostF-2*) and subsequent scenarios. Two stages for the incipient and progressive vegetation recovery were considered in the fourth (*PostF-4*) and fifth (*PostF-5*) post-fire scenarios. Changes related to the stream network were included from *PostF-3* on, due to the growth of the gully system with new gullies and the clear lengthening of the previous gullies. The construction of the 23 new check-dams (12 made on wood and 11 with concrete) in the main streams were included in the stream maps, taking into account their evolution, from empty (*PostF-2*, -3 and -4 scenarios), to partially (*PostF-5* scenario) and completed silted (future scenarios) conditions. Additionally, two potential future scenarios were simulated in order to provide valuable information to the stakeholders and the local and regional authorities. These scenarios were associated with a poor and a good recovery of the natural vegetation within the burned area, and were linked to the expected vegetation recolonization at short- (ca. 5 years) and long- (more than 10 years) term. We did not include other potential future changes, such as vegetation mortality, new roads or the growth of the sub-urban areas in order to minimize the variability in the inputs of the simulated scenarios.

Model parameterization

A LiDAR-based DEM was free obtained from the Spanish National Center of Geographic Information (<http://centrodedescargas.cnig.es/CentroDescargas/>) at a spatial resolution of 5 x

5 m of grid cell size. This DEM was resampled at 2.5 x 2.5 m and all simulations were performed at this spatial resolution. Before running the *IC* model, the continuity of the flow path lines was ensured by removing the local depressions and artifacts of the DEM. We used the algorithm of Planchon & Darboux (2001) (*SAGA*[®]-64 2.1.2) that preserved a minimum slope gradient of 0.01 degree. Then, the boundaries of the eleven sub-catchments (SubC) were calculated upwards from the defined outlets (*ArcGIS*[®] 10.3).

Seven maps of vegetation cover (*W* factor) were generated using the maps of pre-fire land uses (*QGIS*[®]-64 2.14.0-Essen), burn severity and salvage logging, and the four levels of vegetation recovery. The pre-fire land cover information was taken from the “Red de Información Ambiental de Andalucía” Database (<http://www.juntadeandalucia.es/medioambiente/site/rediam>). The values of the *C-RUSLE* factor for the different pre-fire land uses were obtained from Gómez *et al.* (2003), Miller *et al.* (2003), López-Vicente & Navas (2009) and Panagos *et al.* (2015). The post-fire *C-RUSLE* parameterization (*PostF-1* scenario) was done by multiplying the pre-fire *C-RUSLE* map with the weighted map of burn severity classes, the field-identified wildfire limit and the weighting values proposed by Larsen & MacDonald (2007) and Yochum & Norman (2015): low burn = 1.10, moderate burn = 2.25 and high burn = 3.75. These authors didn't estimate extreme burn severity changes. Thus, we selected a new value (5.25) for this fire level using professional judgment. The consequence of salvage logging (*PostF-2* scenario) was simulated considering an average original canopy cover of 40% of the trees on the burned areas. On the basis of field observations and pictures, the effect of the incipient vegetation recovery was simulated in the scenarios *PostF-4* and -5 considering a 10 and 15% decrease in the values of the *W-PostF-2* map within the burned area. The poor and good vegetation recovery of the *Fut-1* and -2 scenarios corresponded to a 25 and 75% decrease in the values of the *W-PostF-2* map.

The two maps of the LLE included the roads, trails, new skid trails and the main streets of the urban area (Table II). Five stream masks were mapped considering the temporal changes in the gullies (pre- and post-fire), the construction of the check-dams and their effectiveness (non-silted, partially and completely silted) to reduce runoff and sediment delivery. The location of the beginning and ending points of the buried pipes in the urban area of the SubC-4, -6 and -7 were identified by field survey and included in the stream maps. Along the pipes, the main streams flow underground, and thus these sections were removed from the gully network.

Validation of simulated scenarios

The HC from the different scenarios was validated by means of two procedures. Firstly, a photo-interpretation process was performed using high resolution Digital Globe images downloaded from Google Earth; its spatial resolution (1x1 m) was sufficient to draw the post-fire drainage network of rills and gullies and thus evaluate the actual connection between the top of hillslopes to the bottom and channels. And secondly, several field surveys were conducted in the study area in order to checking that photo-interpretation, the land use and scenario maps, and connectivity of hillslopes with channels as well as the effect of the new skid trails and check-dams.

RESULTS AND DISCUSSION

Mapping of burn severity

Figure 3 shows the burn severity map obtained from the dNBR calculation. The burn severity was spatially variable covering all the burn severity classes according to USGS (2007). Some unburned areas were observed within the wildfire limit but represented less than 6% of the total area (Table III). More than the 50% of the burned area was classified as low and low-moderate severity burn class, whereas less than 10% corresponded to high/extreme severity. The extreme burn severity was obtained for those pixels with major vegetation cover in the pre-fire scenario and in the SubC-1, -7, -8 and -9.

In Figure 3, the rill and gully network developed after the wildfire were also included. At a glance, no spatial relations were observed between burn severity class and the formation of rills and gullies. All of them were formed or crossed areas classified in all of the burn severity classes. This situation may be indicating the burn severity were not the most influential factor in the post-fire erosion processes. This is not the case of the salvage logging carried out after the wildfire, which enhanced the formation of many new rills and gullies as it will be presented later.

Evolution of the hydrological connectivity

The values and spatial patterns of HC clearly changed over the eight scenarios and throughout the study area (Figure 4). On the basis of the *PreF* scenario, the overall values of HC increased during the three initial post-fire scenarios, reaching the highest values of connectivity in *PostF-3* (Table IV). From *PostF-3* on, connectivity slightly decreased during the two most recent post-fire scenarios and more clearly during the two potential future

scenarios. These changes were greater within the burned area, reaching an increment of 26% of HC during *PostF-3*. This trend was constant in all sub-catchments except in the SubC-2, -4 and -5 due to the small burned area within these SubC, lower than 2%, and the high percentage of urban areas, higher than 47%, in SubC-4 and -5 (Figure 5a). In order to refine the analysis of the evolution in the values of HC, we distinguished four types of SubC: (I) forestry with check-dams and large burned area, (II) urban and small burned area, (III) urban and large burned area, and (IV) forestry without check-dams and small burned area (Table III). The two SubC-IV had the lowest impact of human activities, whereas the other three types of SubC presented different human-activity impact. The evolution in the values of HC was clearly different in each type of SubC. Wildfire (*PostF-1*) produced an increase of 11.4, -4.4, 3.0 and 2.5% in the values of HC in the SubC-I, II, III and IV, respectively, whereas salvage logging and the new skid trails (*PostF-2*) triggered an increase of 18.2, -4.3, 8.2 and 4.6%. The construction of check-dams in this scenario was not enough to stop the overall increase of HC. These changes were greater in SubC-1 and -7 where extreme burn severity affected the forest, and the increase of HC immediately after the fire was of 12.4% on average. These results agreed with those reported by Moody *et al.* (2008) after analysing the runoff response in mountainous watersheds affected by different burn severity levels.

The development of new gullies (*PostF-3*) explained the increment up to 22.9, -4.3, 9.1 and 6.3% in the values of connectivity in the SubC-I, II, III and IV related to the *PreF* scenario. The decrease of connectivity in the SubC-II was explained by their high density of LLE (roads and streets, see Figure 2) that acted as effective downslope and lateral route, and thus connecting the hillslopes of the different SubC between them. The incipient vegetation recovery in the burned areas (*PostF-4*) provided a 2.5, 0.05, 1.3 and 1.0% decrease of connectivity in the SubC-I, II, III and IV, respectively, related to the *PostF-3* scenario. The effectiveness of the small (*PostF-5*) and future (*Fut-1*, -2) vegetation recovery reducing the values of HC was greater than the role played by the partially and silted check-dams increasing the connectivity values. In *Fut-2*, lower values of HC than those obtained during *PreF* were predicted in SubC-II, III and IV, and still higher values in SubC-I. This fact was explained by the methodology used to modify the *W* factor, considering a homogeneous recovery of the vegetation in the burned areas. Following this approach, we obtained lower values of the *W* factor (higher vegetation density) in same patches of the hillslopes than those values assigned in the pre-fire scenario. In spite of the different evolution of connectivity obtained between the different types of SubC, we found the same evolution when the analyses was limited to the burned area (Figure 5b).

Effect of post-fire practices on hydrological connectivity

The effect of the different post-fire practices on connectivity was assessed by means of analysing the evolution of the values of HC in the different geomorphic features of each SubC and during the eight scenarios. Changes of HC in the LLE (Figure 5c) mirrored the general patterns described at SubC scale, although the skid trails construction (*PostF-2*) triggered an increase of HC of 43.2% in the LLE of the four affected SubC (# 1, 7, 8 and 9) whereas the average increase of HC in these SubCs was of 16.6%. Additionally, the expansion of the gully system (*PostF-3*) did not produce any effect on the values of HC in the LLE. Connectivity at the outlets of the SubC showed a different behaviour, decreasing significantly after the wildfire, increasing a little with the post-fire practices and remaining almost stable during the vegetation recovery, except in *Fut-2* when HC decreased. This evolution may be explained because the outlets are located far from the burned areas, by the short-distance effect of the changes in HC due to the wildfire, and by the creation of many new routes of connectivity within the hillslopes that are located upslope the outlets (Figure 5d).

The evolution of connectivity in the ephemeral streams (Figure 5e) and gullies (Figure 5f) showed the same patterns as those described in the burned areas in SubC-I, although the magnitude of the changes was greater in the gullies, especially during *PostF-3* with the emergence of new gullies. In SubC-II, III and IV, changes of HC in the gullies were similar to the general trend, reaching the highest values of connectivity in *PostF-3*, and decreasing from that scenario on. However, the changes of HC in the ephemeral streams in SubC-II, III and IV were contrary. These apparently contradictory results may be explained by the mean length of the effective flow path lines in the different SubC during the eight scenarios. The different characteristics of each type of SubC caused different changes in the values and patterns of HC. These results agree with those reported by Ferreira *et al.* (2008) who found that land use patterns play a crucial role in reducing or enhancing the hydrological and sediment yield processes.

Further research and suggested practices

In order to refine the proposal of the best scenario to reduce the values of runoff and sediment connectivity in the burned area, we will estimate in further research the alone effect of each change (burned forest, salvage logging, new skid trails, new gullies, new check-dams and vegetation recovery) that have lead the evolution of the HC in the study area since 2012 until

October 2016 (Figure 6). We will also refine the map of the vegetation recovery, accounting the actual potential regrowth in the different patches of the landscape, year by year after the wildfire.

Another remarkable consideration to take into account, maybe the most important in the study area, is the effect of salvage logging. This procedure is frequently conducted in some burned areas with the main purposes of inhibiting plagues and reducing the risk of falls. However, this task extremely disturbed the scarce soil of the study area, enhanced rilling and gullying. It has been widely investigated that salvage logging contribute to soil degradation and post-fire erosion processes (Wagenbrenner *et al.*, 2015; Fernández & Vega, 2016). Thus, the effects of post-fire management should be balanced before proceeding to carry it out.

To minimize the off-site effect of vegetation depletion, several check-dams were built in the main streams. Only with one rainwash event (60.0 mm in 6 hours) occurred three months after the wildfire (*PostF-3*), most of the check-dams were almost silted; many of them are now fully silted after 2.5 years and only the major one is partially silted. Both these field data and the simulation results of this study demonstrated that there is a very high connectivity along the burned sub-catchments, enhanced by the rills and gullies which easily connect hillslopes with channels. Check-dams played a remarkable but short effective role in slowing down delivery processes and off-site effects. The very low recovery of vegetation in this type of soils as well as consequence of the salvage logging is now producing a positive feedback of overland flow and sediment transport from headwaters to off-site. Thus, it is necessary to carry out some post-fire erosion management in hillslopes.

CONCLUSIONS

This study revealed salvage logging after a wildfire might be considered as a more influential factor than, for instance, burn severity enhancing the hydrological connectivity in the hillslope-catchment system. Namely, the conclusions are the following:

- i) Considering different pre- and post-fire scenarios, the modelling of hydrological connectivity at high spatial resolution using the D-Infinity algorithm as well as modifying the values of C-RUSLE by the burn severity was satisfactory.
- ii) In the modelled scenarios, the hydrological connectivity increased after the wildfire, independently of burn severity, and, especially, when skid trails as well as salvage logging were carried out, triggering new rills and gullies in the most burned sub-catchments, despite check-dams reduced that connectivity at short-distance. Only the hydrological connectivity

was reduced when a certain recovery of vegetation cover was considered in two future scenarios. These changes were especially observed within the gully system but not always in the ephemeral streams and outlets.

iii) The modelling was satisfactorily validated with aerial and field observations of concentrated (rills, gullies and ephemeral streams), dispersed (hillslopes) and blocked (check-dams) overland flow. The linear landscape elements, such as trails, skid trails, roads and streets connected the hillslopes of the different sub-catchments between them. This process explained either the small decrease of hydrological connectivity in the three subcatchments with large urban area and small burned area or the increase in sub-catchments with major burned areas.

iv) Salvage logging implied the removal of burned vegetation and the opening of new skid trails without considering mitigation techniques to be performed in hillslopes and not only in channels (building of check-dams). In further researches, monitoring of check-dam siltation and of the actual vegetation regrowth following a patched design is necessary and recommended to minimize the current and future off-site consequences of high hydrological connectivity, especially, in those sub-catchments containing burned wildland-urban interface.

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565

566 Table I. The scaled index of burn severity based on values derived from the USGS
 567 FIREMON program (USGS, 2007).

dNBR	Burn Severity class
<-0.25	High post-fire regrowth
-0.25 to -0.10	Low post-fire regrowth
-0.10 to +0.10	Unburned
0.10 to 0.27	Low severity
0.27 to 0.44	Moderate-low severity
0.44 to 0.66	Moderate-high severity
>0.66	High severity

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569

570 Table II. Date and characteristics of the eight simulated scenarios. LLE: linear landscape elements; T: trails; R:
571 roads; St: streets; S-T: skid trails; EpS: ephemeral streams; Gu: gullies; BP: buried pipes; and C-D: check-dams.

Scenario			Vegetation maps	Flow direction map features	
Date	Name	Description		LLE	Stream mask
2012	<i>PreF</i>	Before the fire	C-2012	T, R, St	EpS, Gu and BP
28-Jun-2014	<i>PostF-1</i>	Immediately after the fire	C-2012 + Burn severity	T, R, St	EpS, Gu and BP
Sep-2014	<i>PostF-2</i>	First management practices	C-2012 + Burn severity + Salvage logging	T, R, St and new S-T	EpS, Gu, BP and C-D
Oct-2014	<i>PostF-3</i>	Development of new rills and gullies	C-2012 + Burn severity + Salvage logging	T, R, St and new S-T	EpS, Gu, BP, new Gu and C-D
2015	<i>PostF-4</i>	Incipient vegetation recovery	C-2012 + Burn severity + Veg. recov. 10%	T, R, St and new S-T	EpS, Gu, BP, new Gu and C-D
Oct-2016	<i>PostF-5</i>	Check-dams partially silted	C-2012 + Burn severity + Veg. recov. 15%	T, R, St and new S-T	EpS, Gu, BP, new Gu and C-D partially silted
Future: Short-term	<i>Fut-1</i>	All check-dams silted and poor vegetation recovery	C-2012 + Burn severity + Veg. recov. 25%	T, R, St and new S-T	EpS, Gu, BP, new Gu and all C-D silted
Future: Long-term	<i>Fut-2</i>	All check-dams silted and good vegetation recovery	C-2012 + Burn severity + Veg. recov. 75%	T, R, St and new S-T	EpS, Gu, BP, new Gu and all C-D silted

574 Table III. Surface percentage occupied by each burn severity class according to the satellite
575 images (see Figure 3); and percentage of burned (BA) and urban areas within each sub-
576 catchment. Type I: forest with check-dams and large BA; Type II: urban and small BA; Type
577 III: urban and large BA; Type IV: forest without check-dams and small BA.

Burn severity class	Burned area (%)	Sub-catchment number and type, and burned area (%)										
		1	2	3	4	5	6	7	8	9	10	11
		I	II	III	II	II	III	I	III	I	IV	IV
Urban areas	-	1.0	10.4	28.2	47.3	86.9	32.1	12.5	31.2	4.4	1.6	0.4
Unburned	5.7	11.9	99.1	77.5	98.1	100*	50.5	30.0	58.2	24.3	71.2	63.4
Low / Very low	28.8	18.7	0.9	10.1	1.0	-	25.9	22.7	24.7	21.0	14.6	23.5
Moderate-low / Low	40.1	43.9	-	11.5	0.9	-	22.2	28.8	15.0	38.8	10.8	12.7
Moderate-high / Moderate	18.6	23.4	-	0.9	-	-	1.5	10.3	1.6	15.4	3.4	0.4
High / Extreme	6.8	2.0	-	-	-	-	-	8.2	0.4	0.4	-	-
Total burned area	100.0	88.1	0.9	22.5	1.9	0*	49.5	70.0	41.8	75.7	28.8	36.6

578 *: a small burned area was identified in the field survey, smaller than the pixel resolution of the satellite images.

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581 Table IV. Values and changes (δ) of hydrological connectivity (HC) obtained at the eight simulated scenarios.
582 LLE: linear landscape elements; TL: total length; *: related to the pre-fire scenario; **: related to the previous
583 scenario.

Scenario	C-RUSLE	LLE	Stream	HC - all study area				HC - burned área			
name	mean	TL (m)	TL (m)	mean	sd	δ^*	δ^{**}	mean	sd	δ^*	δ^{**}
<i>PreF</i>	0.1499	31024	16058	-3.488	1.188	----	----	-4.046	1.170	----	----
<i>PostF-1</i>	0.1890	31024	16058	-3.212	1.072	7.9	7.9	-3.534	1.104	12.7	12.7
<i>PostF-2</i>	0.2146	36612	15844	-3.027	1.026	13.2	5.7	-3.212	1.049	20.6	9.1
<i>PostF-3</i>	0.2146	36612	47135	-2.869	1.067	17.7	5.2	-2.980	1.062	26.3	7.2
<i>PostF-4</i>	0.2030	36612	47135	-2.926	1.066	16.1	-2.0	-3.068	1.060	24.2	-2.9
<i>PostF-5</i>	0.1974	36612	47323	-2.956	1.066	15.3	-1.0	-3.114	1.059	23.0	-1.5
<i>Fut-1</i>	0.1861	36612	47349	-3.023	1.068	13.3	-2.3	-3.218	1.057	20.5	-3.3
<i>Fut-2</i>	0.1380	36612	47349	-3.536	1.179	-1.4	-17.0	-3.994	1.078	1.3	-24.1

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Figure 1. Location of the study site (top, left) and pre- (middle, left) and post-fire view (bottom, left). General views of the burned area (right, from top to bottom): wildland urban interphase area affected by the wildfire, burned trees partially affected by the fire, hillslopes after removing vegetation, and hillslopes with accumulated burned and cut trees and a new skid trail.

Figure 2. Maps of land uses of the eight simulated scenarios before and after the wildfire.

Burned area & Burn severity

- C6mpeta village
- Outlets
- ▭ Forest fire limit: Field survey
- Sub-catchment boundary
- Post-fire rill & Gully network
 - Gully
 - Ephemeral stream
- Burn severity (level): Satellite images
 - Unburned (<100)
 - Very low (100 - 270)
 - Low (270 - 440)
 - Moderate (440 - 660)
 - Extreme (>660)
- Hillshade
 - 64.0932
 - 250.583

Figure 3. Map of burn severity obtained with the dNBR index and postfire network of rills and gullies.

Figure 4. Maps of simulated hydrological connectivity in the pre-fire and seven post-fire scenarios.

Figure 5. Mean values of hydrological connectivity (HC) at the outlets, ephemeral streams, gullies, linear landscape elements (LLE), burned and total sub-catchment area, in the eleven SubC and during the eight simulated scenarios. *: Considering the maximum extension of the feature.

611

612 Figure 6. Top left: view of SubC-7 with a new skid trail, accumulated cut burned trees and partially silted check-

613 dams along the channel; top right: new gully formed after wildfire (width: 2.45 m) in the outlet of SubC-10;

614 bottom left: headwater located in SubC-9 with rills in hillslopes and fully silted wooden check-dam at the

615 bottom; bottom right: fully silted wooden check-dam and new deposits of sediments with incisions ahead

616 located near the outlet of SubC-9.

617