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MODELLING EFFECTS OF FOREST FIRE AND POST-FIRE MANAGEMENT IN A CATCHMENT PRONE TO EROSION: Impacts on sediment yield

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Abstract

The present paper contributes to bridging the gaps in modelling post-fire impact and mitigation measures on soil erosion. The specific aims were to predict the effects of forest fires and post-fire mitigation measures on runoff and specific sediment yield (SSY) in a river basin (Celone, S-E Italy). The Soil and Water Assessment Tool model, calibrated with field observations, was used to evaluate runoff and SSY for the current land use (baseline) and six post-fire scenarios. From 1990 to 2011, at the basin scale, the average annual SSY was 5.60 t $ha^{-1} yr^{-1}$ (SD = 3.47 t $ha^{-1} yr^{-1}$). 20% of the total drainage area showed a critical value of SSY (>10 t ha^{-1} yr^{-1}). The effects of different fire-severity levels were predicted for one year after the fire, acting on a limited area (2.3% of the total basin area). At the basin scale, the post-fire effect on surface runoff was negligible for all scenarios (< 0.4%), and the impact on SSY increased from 5.86 t ha^{-1} yr^{-1} up to 12.05 t ha^{-1} yr^{-1}. At the subbasin scale, the post-fire logging scenario showed the highest increase of soil loss (SSY increased from 9.48 t ha^{-1} yr^{-1} to 57.40 t ha^{-1} yr^{-1}). Post-fire mitigation treatments like straw mulching and erosion barriers effectively reduced soil erosion in high- and moderate-severity fires (19.12 t $ha^{-1} yr^{-1}$ and 20.93 t ha^{-1} yr^{-1}, respectively). At the hydrological response unit level, the SSY estimated for the forest in the baseline ranged from 1.18 t $ha^{-1} yr^{-1}$ to 2.04 t ha^{-1} yr^{-1}. SSY increased more than one order of magnitude for the high-severity fire scenarios and ranged from 4.33 to 6.74 t ha^{-1} yr^{-1} in the very low-severity fire scenario, underlining the scale effect from the HRU to the basin scale.

Keywords*: forest fires, sediment yield, runoff, SWAT model, fire severity, post-fire mitigation measures, model parametrisation*

1. Introduction

The Mediterranean European Region is a high fire risk area due to a combination of several factors. The high number of buildings has increased the probability of fire ignition by human causes (Ganteaume et al., 2013) and, the abandonment of some rural areas has led to an accumulation of fuel loads that have contributed to fire ignition and spread, especially in summer (San-Miguel-Ayanz et al., 2012). In addition to natural causes, negligent and deliberate behaviors have contributed to increasing wildfires. Consequently, many fire events are recorded every year in this region (Fernandéz-Anez et al., 2021). San-Miguel-Ayanz et al. (2012) estimated that, in Europe, around 65000 fire events occur every year, burning about half a million hectares of forest. The European Environmental Agency (European Commission, 2019) pointed out that the meteorological fire hazard has increased due to climate change. The last report on forest fires (European Commission, 2021; San-Miguel-Ayanz et al., 2021) highlighted in the recent years (2019, 2020, 2021) a positive trend of higher levels of fire danger in EU countries, despite the increased level of preparedness. About 340000 ha in 2020 and 0.5 million of ha in 2021 were burnt in the EU. About 25% of the burnt areas were inside the "Natura 2000" sites. Several researchers pointed out that droughts and high temperatures promote large fires in southern Europe (Camia and Amatulli, 2009; Lasaponara et al., 2018; Urbieta et al., 2015) that are also related to antecedent climate variables (Ruffault et al., 2016). Turco et al. (2017) highlighted that rising temperatures and droughts, which greatly influence summer fires, could make all fire prevention efforts useless in the next decades.

Wildfires may result in serious economic, cultural, and ecological damages in the Mediterranean Region (Ganteaume et al., 2021). A forest fire is a disturbance for the ecosystem; it may alter soil properties (Mataix-Solera et al., 2011; Lucas-Borja et al., 2018), reduce infiltration capacity and increase the peak of streamflow (Cerdà, 1998; Neary et al., 2005; Shakesby and Doerr 2006), ultimately changing the catchments hydrological and sedimentary processes (García-Comendador et al., 2017; Ice et al., 2004; Zema, 2021). In addition, in light of current climate change, it is expected that extreme rainfall events may accelerate soil erosion in burnt areas.

Wildfires seriously increase soil erosion (Fernández and Vega, 2018; Viera et al., 2015) and impair surface water quality by delivering fire-related contaminants to rivers with (Nunes et al., 2017; Verkaik et al., 2013; Campos et al., 2012; Chessman, 1986; Olivella et al., 2006). Fire severity (amount and duration of subsurface heating), nature of vegetation cover, physical and chemical characteristics of burnt areas (i.e. climate, soil, topography), and the time interval between the fire and rainfall determine the degree of impact on soil erosion and water quality (Viera et al., 2015; Tecle and Neary, 2015). Post-rehabilitation measures are needed to mitigate the effects of fire on hydro-sedimentary response and protect soil from erosion (Lucas-Borja, 2021). An accurate prediction of post-fire runoff and sediment yield is required to guide post-fire risk management and plan soil and water restoration measures (Argentiero et al., 2021; Fernández et al., 2010).

Hydrological and soil erosion models can provide valid support (Kampf et al., 2020) for quantifying the catchment hydro-sedimentary response to forest fire events and planning adequate restoration measures. Several modelling applications conducted to support management agencies are reported in the literature (Lopes et al., 2021). The Revised Universal Soil Loss Equation (RUSLE) was applied to sites affected by fire in the Mediterranean Region to estimate the impact on runoff and soil erosion (Coschignano et al., 2019; Efthimiou et al., 2020; Fernández et al., 2010; Lanorte et al., 2019; Rulli et al., 2013). Analogously, the Pan-European Soil Erosion Risk Assessment model (PESERA, Kirkby et al., 2004) was applied in central Portugal (Esteves et al., 2012), Spain (Fernández and Vega, 2016), and Greece (Karamesouti et al., 2016). The Water Erosion Prediction Project model (WEPP; Flanagan and Nearing, 1995) was used in Spain (Fernández and Vega, 2018). Rulli and Rossi (2005; 2007) developed a distributed hydro-geomorphological model to estimate the dynamics of fire-disturbed conditions at the basin scale. Di Piazza et al. (2007) used the RUSLE model and a spatial disaggregation criterion for sediment delivery processes (SEDD model) to assess the effects of bushfires in Italy. The Soil and Water Assessment Tool model (SWAT, Arnold et al., 1998) was applied in two Portuguese sites to estimate the post-fire impacts on streamflow and sediment yield (Basso et al., 2020; Nunes et al., 2018). Grangeon et al. (2021) proposed the WaterSed model to simulate forest fire and firebreak scenarios and analyse their respective effects on sediment loads. Zema et al. (2020) adapted the Morgan-Morgan-Finney model after wildfires in Spain. However, Lopes et al. (2021) pointed out in their review that many of the published studies reported modelling applications without field validation and that mitigation measures were simulated in a limited number of cases. The authors concluded that further studies and tests were needed for adapting models to burnt conditions. Indeed, the model parametrisation is not specifically designed for post-fire conditions, it needs to be adapted to the post-fire conditions, and currently, it remains an open problem (Basso et al., 2020; Nunes et al., 2018).

In this context, the present paper contributes to bridging the gap in modelling post-fire impact and quantifying mitigation measures' effects. The general aim of the work is to test and adapt the SWAT model as a tool for rapid post-fire erosion risk assessment. The specific aims of this work are: (i) to simulate runoff and sediment yield for the current land use in a mountainous river basin, (ii) to predict the effects of forest fire on runoff, erosion, and sediment transport, and iii) to quantify the effects of post-fire mitigation measures on runoff and sediment yield at the basin, subbasin, and hydrologic response unit (HRU) scale.

Field measurements were used to calibrate the hydro-sedimentary parameters of the model for the current land use in the Celone (S-E Italy) river basin that is characterised by an intermittent river network feeding the Capaccio reservoir. The post-fire scenarios were simulated by changing the appropriate parameters affecting hydrological processes and soil erosion by water. The work provides useful post-fire management information (i.e. quantification) to the river basin managers.

2. Materials and methods

2.1 Study area

The Celone River basin is located in northern Apulia (SE, Italy). The study area (72 km^2) is located upstream of the Capaccio reservoir (41° 25' 35''N; 15° 24' 52''E) (25.82 Million of m^3), of which the Celone river is the main inflow.

The elevation of the study area ranges from 1142 m a.s.l. to 218 m a.s.l. (mean value 386 m a.s.l.). Steep slopes characterise the upper part of the basin, making it prone to erosion. The main channel is incised in the mountainous area. Consequently, many check dams have been built to reduce bank erosion. Most of the coarse material is deposited in the first alluvial plain, resulting in a braided river. Downstream, it continues with a meandering pattern.

The lithology consists of flyschoidal units (flysch della Daunia), grey-blue clays in the mountain, and alluvial deposits in the valley. The soils show a variable texture (clay, clay-loam, and sandy-clay-loam) and are classified as typic-haploxerroll, vertic-haploxeroll, and typic-calcixeroll, according to the US Department of Agriculture classification.

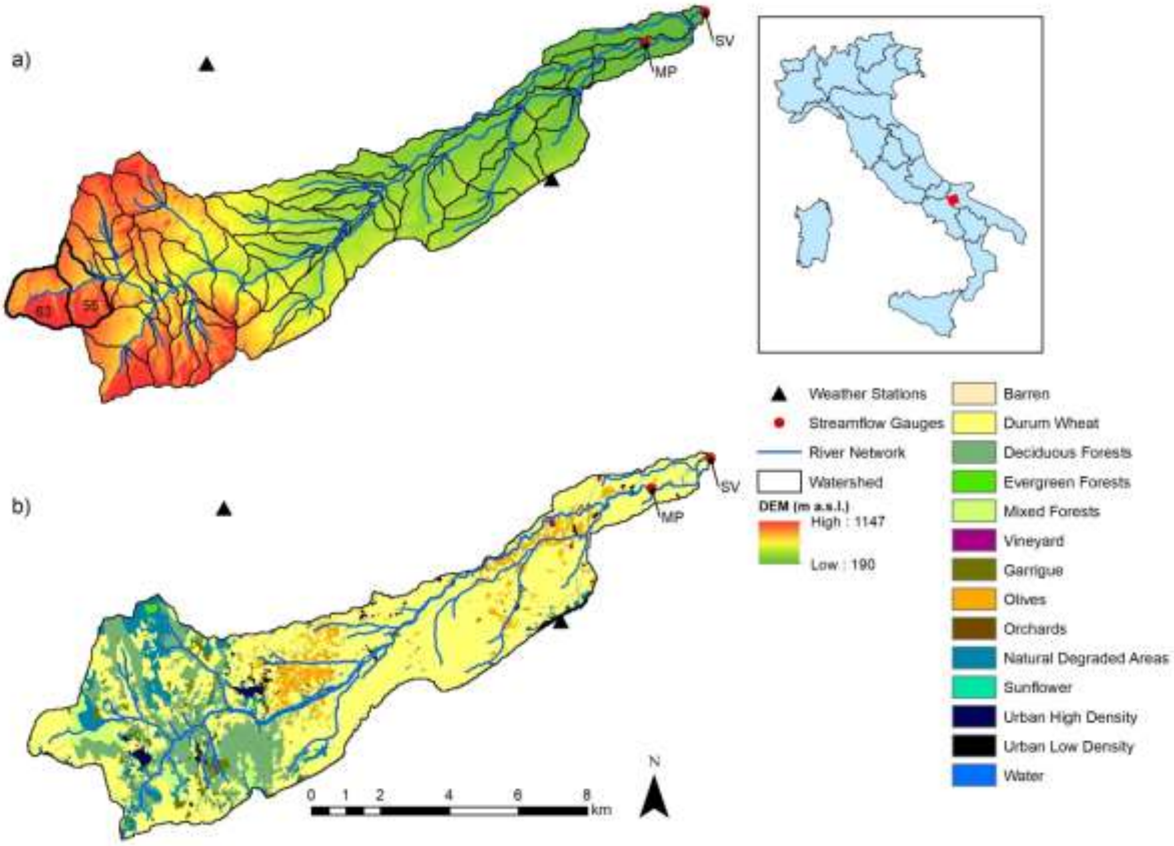

Figure 1. Study area: Celone river basin (Apulia Region, Italy). a) DEM and subbasins distribution, subbasins affected by forest fire are delineated with continuous black lines (55, 63); b) Land use, gauging stations: MP (discharge and suspended sediment during the period 2010-2011), SV (discharge during the period 1994-1996).

Mean annual rainfall is 770 mm (1990-2011), and mean temperature varies between 3.4°C (January) and 20.3°C (August) in the mountain, and between 7.2°C (January) and 25.5°C (August) in the valley (De Girolamo et al., 2017a).

The soil erosion by water in the basin is both distributed (sheet erosion) and localised (rill erosion) (De Girolamo et al., 2015). It is favoured by agricultural practices such as conventional tillage (multiple operations with chisel plough and disks). The prevalent land use is for cereal growth (mostly winter and durum wheat; 45% of the catchment area). Other land use includes sunflowers (9%), natural degraded areas (6%), olive groves (8%), vineyards and vegetables (2%), and urban areas (1%). Forests, primarily oaks and conifers (29%), cover the mountainous part of the basin.

The study area was monitored in 2010-2011 at the Celone Masseria Pirro gauge (41°23’41’’N; 15°20’02’’E) (MP in Figure 1), with continuous measurements of streamflow (Q) and discrete suspended sediment concentration (SSC) samples (De Girolamo et al., 2015; De Girolamo et al., 2018). Daily streamflow was computed starting from measurements taken on 15-min of the time step, and suspended sediment load at the monthly time scale was estimated using the sediment rating curve developed based on measured streamflow and suspended sediment concentrations (Eq. R3 in De Girolamo et al., 2018).

2.2 Conceptual model

The SWAT model with ArcGIS interface (Arnold et al., 1998) was used in the present work to simulate streamflow and sediment yield and predict the potential impact of forest fire and post-fire measures on sediment and hydrology. SWAT is a semi-distributed model able to predict hydrological processes, water quality, and the environmental impact of land use and management practices on water bodies and soils in agricultural basins (D’Ambrosio et al., 2020a; De Girolamo and Lo Porto, 2020). The SWAT model is widely used for assessing the effects of anthropogenic pressures on water quality (Cakir et al., 2020; D’Ambrosio et al., 2020b; Pulighe et al., 2019) for estimating climate change impact on water resources and flow regimes (Brouziyne et al., 2020; Glavan et al., 2015; Perra et al., 2018), and for simulating soil erosion (Gamvroudis et al., 2015; Vigiak et al., 2017) and the impact of best management practices (BMPs) on water resources (Ricci et al., 2020).

In SWAT, the basin is divided into subbasins that are further subdivided into HRUs, which are characterised by homogeneous land use, soil, and slope. The water cycle is divided into the land phase and routing phase. The components of the land phase (i.e. runoff, evapotranspiration, crop growth, soil erosion, nutrient and pesticides loads entering into the main channel) and the methods used for their computation are described in Neitsch et al. (2011). The routing phase through the river network includes transmission losses and degradation of nutrients, pesticides, and bacteria. Similarly, the sediment budget is divided into two components, landscape phase and channel routing. The soil erosion phase includes the detachment, transport, and deposition of soil particles by the erosive force of raindrops and the surface flow of water. The channel sediment routing phase considers deposition and degradation that occurs in the channel. The landscape sediment phase is computed with the modified universal soil loss equation (MUSLE), and the channel sediment routing is computed using the Bagnold equation (Neitsch et al., 2011). The SWAT model provided outputs at the basin, subbasin, and reach scale.

The model was run at a daily time step from 1990 to 2011. The Hargreaves-Samani equation was selected for estimating the potential evapotranspiration (PET), and the SCS Curve Number Method was adopted to calculate surface runoff (Neitsch et al., 2011). Table I summarises input data used in the present study, their source, and resolution.

Table I. Input data: variable, source, scale, information.

Variable	Source	Scale	Information
Precipitation	Civil Protection Service Apulia Reg. Agency	Daily	2 weather stations (1990-2009)
Temperature	Civil Protection Service Apulia Reg. Agency	Daily min, daily max	2 weather stations (1990-2009)
Land use map	Corine Land Cover 2000 EU Project	ArcInfo format (scale 1:100000)	Minimum area digitalized 25 ha
Soil map	ACLA 2 - FEOGA EU Project	ArcInfo format (scale 1:100000)	5 soil profiles
Management Practices	Consorzio per la Bonifica della Capitanata; farmers	Subbasin scale; Municiality	Tillage oper., irrigation amount, fertilizers (type, timing, amount)
Digital Elev. Model	Apulia River Basin Authority	Arc Info grid format (8x8m)	
Streamflow (SV gauge)	Civil Protection Service	Daily	1992-1996
Streamflow (MP gauge)	Water Research Institute-National Research Council (IRSA-CNR)	Sub-daily	2010-2011
Suspended sediment load (MP gauge)	Water Research Institute-National Research Council (IRSA-CNR)	Monthly	2010-2011

2.3 Model calibration

The analysis of sensitivity, reported in De Girolamo et al. (2017a), identified among the most sensitive parameters influencing hydrological processes the initial SCS curve number for moisture condition II (CN2), the threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN [mm]), the available water capacity of the soil layer (SOL_AWC [mmH_2O/mmsoil]), the soil evaporation compensation factor (ESCO), the surface runoff lag time (SURLAG [days]), revap coefficient (GWREVAP), the Baseflow alpha-factor (ALPHA_BF, [days]), and Groundwater delay time (GW_DELAY, [days]).

In the present study, the model SWAT2012 version was used. The basin was divided into 74 subbasins, further partitioned into 200 HRUs. Conservation practices were not adopted in the study area (Panagos et al., 2015a; Wischmeier and Smith, 1978). The conservation practice factor (USLE_P) was assumed to be equal to 1 for all land uses, except for forested areas where the P factor was set to 0.8. According to the crop systems, the crop management factor (USLE_C) was set within 0.0019 to 0.2, as suggested by Panagos et al. (2015b).

Daily streamflow data were available at two gauging stations (SV and MP in Figure 1) over different time periods (Table I). The model was calibrated for the daily streamflow at the SV gauge over 1994-1996 and at the MP gauge over 2010-2011 (Figure 1). The sediment load (sediment transported by the river; SSC×Q) was calibrated at the MP gauge at the monthly time scale (2010-2011), and the validation was carried out for daily streamflow at the SV gauge (1992). Manual calibration was performed, including the above-mentioned parameters for hydrology. For sediment load calibration, the following parameters were included: channel erodibility factor (CH_COV1), channel cover factor (CH_COV2), Manning's "n" value for the main channel (CH_N2), the maximum amount of sediment that can be transported from a river reach (SPCON), and the exponent for calculating sediment that can be transported in the channel (SPEXP). Table II shows the parameter values corresponding to the best fit for the most sensitive parameters and their range of variability. The model's performance was evaluated by using the coefficient of determination (R^2), the Nash-Sutcliffe efficiency (NSE), and the observation standard deviation ratio (RSR). The simulations were considered good if $0.65 < NSE < 0.75$, $0.5 < RSR < 0.6$ and $R^2 > 0.8$ and satisfactory if $0.5 < NSE < 0.65$, $0.65 < RSR < 0.7$ and $R^2 > 0.5$ (Moriasi et al., 2007).

Table II. Calibrated parameters (actual value used) and their range of variability.

Parameter	Description	Actual value used	Range
CN2	SCS Curve number for moisture condition II	70-85 [a]	35-98
GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur [mm H_2O]	800	0-5000
OV_N	Manning's "n" value for overland flow	0.1-0.4 [a]	
SOL_AWC	Available water capacity [mm H_2O/mm soil]	0.12-0.21 [a]	0-1
ESCO	Soil Evaporation compensation factor	0.95	0-1
SURLAG	Surface runoff lag coefficient [days]	2	0-10
GWREVAP	Revap coefficient	0.02	0.02-0.2
ALPHA_BF	Baseflow alpha factor [days]	0.95	0-1
GW_DELAY	Groundwater delay time [days]	3	
CH_N2	Manning's "n" value for main channel	0.11	0.05-0.5
CH_COV1	Channel erodibility factor	0-0.5[b]	0-1
CH_COV2	Channel cover factor	0-5[b]	0-1
SPCON	Maximum amount of sediment retrained during channel sediment routing	0.007	0.0001-0.01
SPEXP	Exponent for calculating sediment retrained in channel	1.8	1-2

[a] value varies according to input data (soil, land use)
[b] value = 0 was assumed for reaches in plain area; values > 0 was assumed in the mountainous and hilly reaches.

2.4 Analysis at the reach scale

After the fire events, the sediment-associated pollutants transported via surface runoff could accumulate on the riverbed with several implications on water quality and ecological status. In order to identify the river segments where the deposition of sediment occurs, an analysis at the reach scale was carried out for the period 1990-2011. Thus, the sediment transported with water into the reach (SED_IN) were combined with the sediment transported with water out of the reach (SED_OUT), and the sediment from the subbasin to the river reach during the time step to identify the river reach's under erosion and deposition.

2.5 Simulating post-fire scenarios

Post-fire scenarios were simulated assuming that fire burnt the forest areas in two selected subbasins [Figure 1, Numbers 55, 63] since fire events not really occurred in the study. The basins were selected to analyse the effect of fire severity and management in soil erosion-prone areas. Both subbasins were characterised by steep slopes, high rainfall, and soil erodibility. The drainage area of subbasin 55 was 2.09 km^2, 1.17 km^2 was covered by forests, and the drainage area of subbasin 63 was 2.47 km^2, including 0.47 km^2 covered by forests. The fire was modelled to occur in 2010 only in forested areas.

The post-fire scenarios and the effectiveness of selected mitigation measures in reducing soil erosion by water were simulated and results were analysed for one year after the fire (data on the post-fire measures did not exist in the basin). Mayor et al. (2007) and Pausas et al. (2008) pointed out that soil erosion might be two orders of magnitude higher five years after the fire. However, the highest hydrological and erosive events occur beyond the first year after the fire (García-Comendador et al., 2017). The following six scenarios were simulated to provide a wide range of potential impacts on hydro-sedimentary response to support post-fire management. The model parameters influencing runoff and soil erosion were properly modified for each scenario using literature values. Table III shows the parameters and their values for the baseline and post-fire scenarios and the most relevant references used as guides for their selection and values' attribution.

Scenario Fr1: high-severity fire and post-fire logging

It was assumed that "high-severity fire" was ground and canopy fire (all shrubs and herbaceous plants killed) with high soil heating and alteration of soil structure (decreased infiltration and increased water repellency). This scenario analysed the potential effect of removing fire-killed trees from burnt areas (logging) and the successive tillage operation (chisel plough) on those areas.

The fire effect on soil characteristics was simulated by modifying the USLE erodibility factor (USLE_K). The effect of fire on soil water repellency (Sol_K) was incorporated into the USLE_K by adopting the suggestions by Miller et al. (2003) (reported by Larsen and MacDonald, 2007). The reduction of soil protection due to the damage of vegetation cover was considered by modifying USLE_C. In literature, the post-fire USLE_C factor applied ranges from 0.01 (low severity) to 0.3 (high severity) (Borrelli et al., 2016). USLE_P was set equal to one, and the increase of runoff at the different spatial scales consequent to the fire events were estimated by modifying OV_N and the CN2 (Table III).

Scenario Fr2: high-severity fire and natural regeneration

High-severity fire impact on soil was simulated by increasing the USLE_K (Table III). For this scenario, USLE_P was set to 1, and USLE_C was fixed to 0.13 to mimic the effect of the regrowth of vegetation. CN2 was increased (+15) compared to the baseline scenario (Havel et al., 2018). Meanwhile, OV_N was assumed lower than the baseline (Table III).

Scenario Fr3: high-severity fire and emergency stabilisation (straw mulching and seeding)

Straw mulching was considered in this scenario to protect soil after the fire. The effect of straw mulching was simulated by modifying USLE_P, USLE_C, CN2, and OV_N. USLE_P was set to 0.343 and USLE_C to 0.13, considering the effect of seeding and regrowth of vegetation (Fernandez et al., 2010; and Rulli et al., 2013). In addition, mulch material on soil is a conservation practice that is generally simulated by modifying the CN2; here, it was reduced by 3 points compared to the value assigned in Fr2 (Waidler et al., 2009). Finally, OV_N was increased compared to Fr1 and Fr2, but lower than the one assumed in the baseline, as suggested by Neitsch et al., 2011.

Scenario Fr4: moderate-severity fire and erosion barriers

In this scenario, the moderate-severity fire was hypothesised, and erosion barriers were simulated as a post-fire mitigation measure to reduce surface runoff and soil losses. The assumption was ground fire and burning of lower tree limbs, moderate soil heating, increased water repellency and decreased infiltration. The baseline value of USLE_K was assumed to increase (Table III), and OV_N and CN2 were reduced and increased, respectively. USLE_P was modified by adopting the value of 0.85 (Myronidis et al., 2010).

Nevertheless, it is important to underline that literature reports a wide range of USLE_P values applied (from 0.2 to 0.85).

Scenario Fr5: low-severity fire and natural regeneration

Low-severity fire and natural regeneration were simulated in this scenario. It was assumed that leaf litter was completely consumed with small changes in soil properties. All the parameters mentioned above were modified as reported in Table III. OV_N was assumed to be 0.3, and the baseline value of CN2 was increased (+5), USLE_K was assumed to increase to a lesser extent than moderate-and high-severity fire.

Scenario Fr6: very low-severity fire and natural regeneration

In this scenario, it was assumed that fire had very lightly charred only fine fuel and litter on the ground and soil properties (i.e. hydraulic saturated conductivity, water repellency) were unchanged. The baseline value of CN2 was slightly increased (+3), and USLE_K was unchanged (Table III).

Table III. SWAT parameters used in the baseline simulation and fire scenarios.

Parameter	Description	Baseline	Fr1 High-severity fire, logging, tillage	Fr2 High-severity fire, natural regeneration	Fr3 High severity fire, straw mulching and seeding	Fr4 Moderate-severity fire and erosion barriers	Fr5 Low-severity fire and natural regeneration	Fr6 Very low-severity fire and natural regeneration	Reference
OV_N	Manning's roughness coefficient	(0.4)	0.09[a]	0.16[a,b]	0.22[a]	0.25[a]	0.3[a]	0.3[a]	[a]Neitsch et al., 2011; [b]Stoof et al., 2015
USLE_P	USLE eq. supporting practice factor	0.8[a,b]	1	1	0.343[c,d]	0.85[d,e]	0.9	0.9	[a]Panagos et al., 2015a; Wischmeier and Smith, 1978; [c]Fernandez et al., 2010; [d]Rulli et al., 2013; [e]Myronidis et al., 2010.
USLE_C (m^2/m^2)	USLE C factor for water erosion	0.0019[a]	0.23[b]	0.13[c,d]	0.13[c,d]	0.05[e,f]	0.01[e,f]	0.01[e,f]	[a]Panagos et al., 2015b; [b]Fernandez et al., 2016; [c]Fernández &Vega, 2018; [d]Rulli et al., 2015; [e]Larsen and MacDonald, 2007; [f]Terranova et al. 2009.
CN2	Initial SCS runoff curve number for soil moisture condition II	(70)	90[a]	85[b]	82[b,c]	80[b,d]	75[b,d]	73	[a]Neitsch et al., 2002; [b]Havel et al., 2018; [c]Waidler et al., 2009; [d]Basso et al., 2020.

USLE_K* (ton acre hour)/(hundred acre ft ton inch)	USLE eq. Soil erodibility factor	0.13-0.15	+0.016/0.1317[a,c,d]	+0.016/0.1317[a]	+0.016/0.1317[a]	+0.015/0.1317[b]	+0.014/0.1317[c]	0.13-0.15[e]	[a]Miller et al., 2003; [b]Fernandez et al., 2010; [c]Basso et al., 2019; [d]Coschignano et al., 2019; [e]Di Piazza et al., 2007.
Tillage	Plowing (chisel plow)		Deep						Nunes et al., 2018.

*0.1317 is the conversion factor for soil erodibility factor (USLE_K) from t h MJ^{-1} mm^{-1} to ton acre hour/ hundred acre ft ton inch

3. RESULTS

3.1 Modelling streamflow and sediment load

The statistics obtained for daily streamflow calibration showed a good model efficiency at the SV gauge (NSE = 0.70; RSR = 0.54; R^2 = 0.88) and at the MP gauge (2010-2011) (NSE = 0.73; RSR = 0.50; R^2 = 0.89). Similar results were obtained for the validation period of the streamflow at the SV gauge (NSE = 0.73; RSR = 0.63; R^2 = 0.90). Figure 2 shows the simulated and observed streamflow for the calibration period at the SV gauge. The performance for sediment calibration on the monthly time scale at the MP gauge was satisfactory (NSE = 0.73; RSR = 0.70; R^2 = 0.54). The results showed an underestimation of sediment load in March 2011, when a series of large floods occurred, and an overestimation in autumn. Figure 3 shows the observed and simulated daily streamflow at the MP gauge (Figure 3A) and monthly observed specific sediment load (SSL, t ha^{-1}) versus simulated values (Figure 3B).

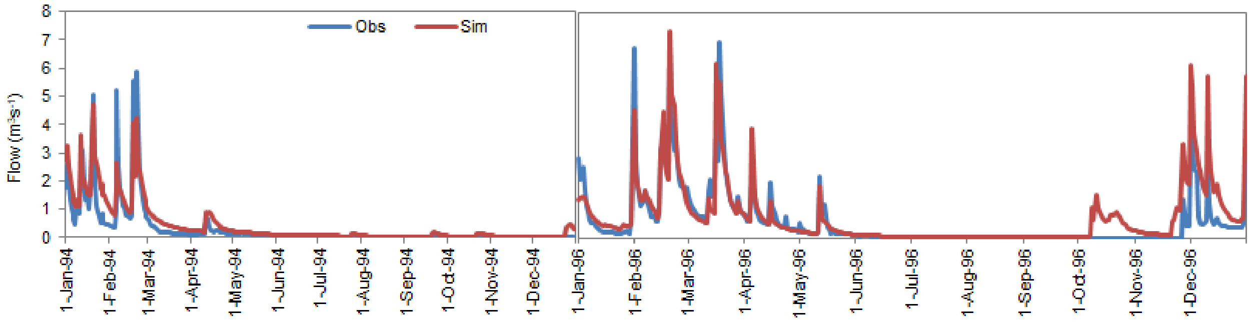

Figure 2. Simulated and observed streamflow for the calibration period at the SV gauge.

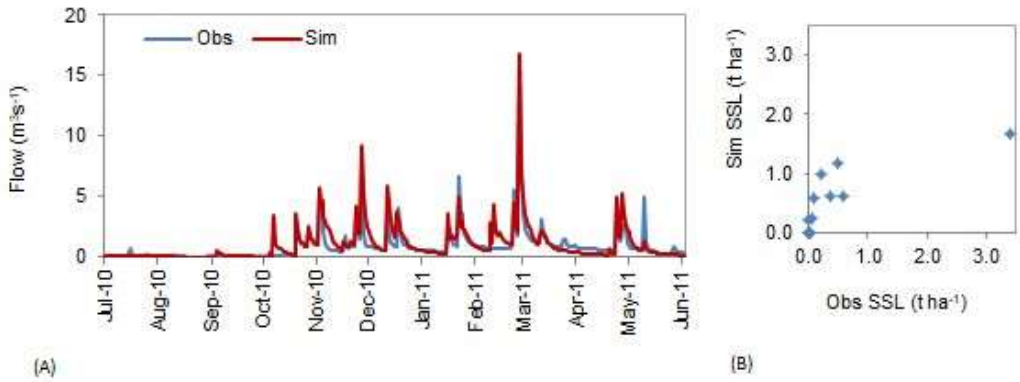

Figure 3. Observed and simulated daily streamflow at the MP gauge (A). Measured versus simulated specific sediment load SSL (t ha^{-1}) at monthly time scale for the calibration period (2010-2011) (B).

3.2 Streamflow and sediment load for the current land use (baseline)

At the basin scale, from 1990 to 2011, the average annual rainfall was 777 mm (SD = 179 mm), mainly concentrated from November to April (wet season), the surface runoff was 114 mm (SD = 66 mm), and the total water yield was 288 mm (SD = 140 mm). Most of the rainfall (61%) was lost via actual evapotranspiration (471 mm; SD = 41 mm), and the potential evapotranspiration was 954 mm (SD = 30 mm). The average annual SSY (sediment yield per unit of catchment area and unit of time; t ha^{-1}yr^{-1}) was 5.60 t ha^{-1} yr^{-1} (SD = 3.47 t ha^{-1} yr^{-1}). A high inter-annual variability characterised all the water balance components and the SSY due to differences in climate conditions. In the driest year (2000), the total annual rainfall was 471 mm, surface runoff (SR) was about 26 mm, and the SSY was 3.03 t ha^{1} yr^{-1}. In the wettest year (2009), the total annual rainfall was 1217 mm, SR was 300 mm, and SSY was 13.82 t ha^{-1} yr^{-1}.

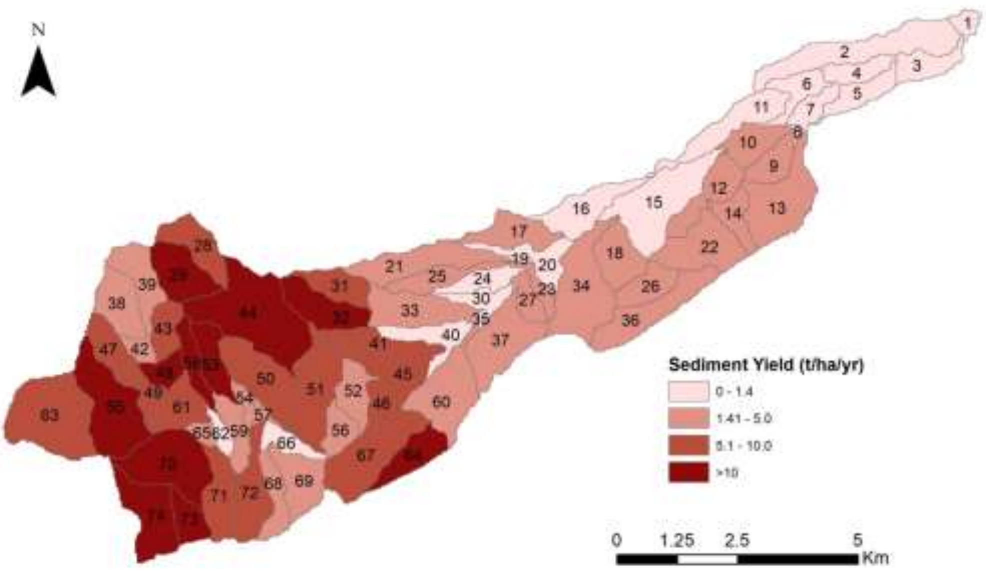

Figure 4. Average specific sediment yield (SSY, t ha^{-1} yr^{-1}) at the subbasin scale simulated from 1990 to 2011.

At the subbasin scale (Figure 4), over the period 1990-2011, the mean annual SSY was < 1.4 t ha^{-1} yr^{-1} in the subbasins located in the plain area (14% of total drainage area). Most of the subbasins showed values between 1.4 to 10 t ha^{-1} yr^{-1}, and some mountainous subbasins (20% of total drainage area)—characterised by steep slopes—showed severe soil erosion (SSY > 10 t ha^{-1} yr^{-1}). These results are consistent with the new assessment of soil loss by water erosion in Europe performed with the RUSLE2015 by Panagos et al., 2015c who reported soil loss rate in the range of 0 - 2 t ha^{-1} yr^{-1} in lowland, values from 2 t ha^{-1} yr^{-1} to 5 t ha^{-1} yr^{-1} in hilly areas, and values mostly in the range of 5 t ha^{-1} yr^{-1} to 10 t ha^{-1} yr^{-1} with several cells showing soil loss rate > 10 t ha^{-1} yr^{-1}in the mountainous part of the basin.

At the HRU level, natural degraded areas, predominant in the steep slopes areas, showed the highest values of SSY. Also, durum wheat fields, where up-and-down tillage was generally adopted, showed high values of SSY. Garrigue, deciduous, and mixed forests showed lower values of SSY. The box plot in Figure 5 shows the annual SSY estimated at the HRU level for each crop. Wide variability was found among the HRUs for each crop because of the different environmental factors (slope, soil, rainfall) that influence hydrology and soil erosion.

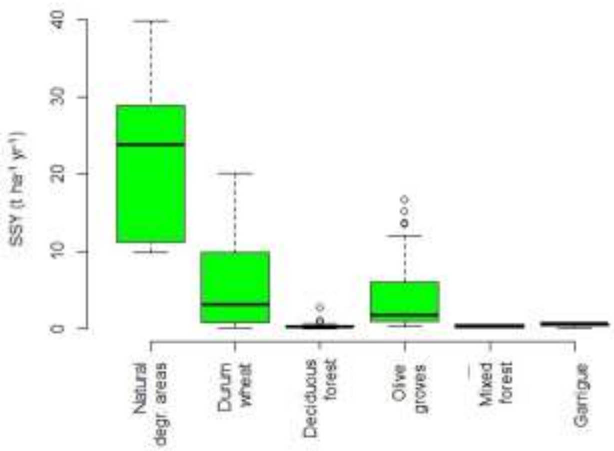

Figure 5. Box plot of the average specific sediment yield (SSY, tha^{-1}yr^{-1}) simulated at the HRU level from 1990 to 2011. The horizontal line within the box plot indicates the median, boundaries of the box indicate the 25th and 75th percentile, and whiskers indicate the minimum and maximum values.

The reach-scale analysis for identifying the river segments where sediment deposition occurs showed that most first-order river segments were under erosion. Meanwhile, sediment deposition was predicted in some intermediate reaches and those located in the alluvial plains (Figure 6). In the latter, if fire events occur in the upstream areas, pollutants such as Fe, Mn, As, Cr, Al, Ba, and Pb could be deposited along the river bed, and the water quality could be impaired (Smith et al., 2011).

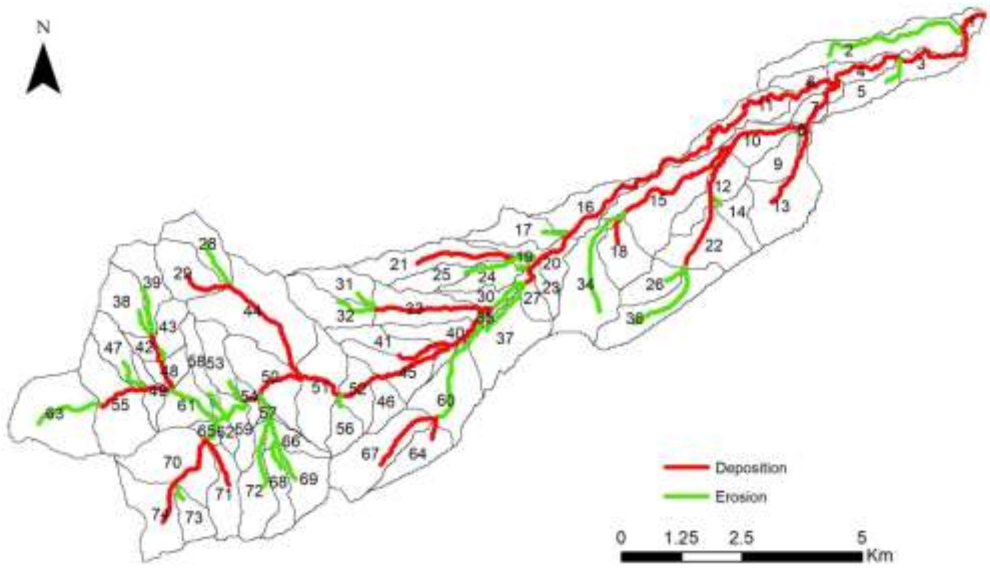

Figure 6. Segments of the Celone River under erosion and deposition.

3.3 Post-fire scenarios: potential impact on hydro-sedimentary response

At the basin scale, the integrated effect of the two burnt areas (1.64 km^2, 2.3% of the entire river basin) on surface runoff was negligible. Only the scenario Fr1 showed a slight increase in annual surface runoff (99.95 mm) compared to the baseline (99.53 mm). Similarly, the impact of wildfire on the total water yield (total streamflow at the outlet for the unit area; TWY, mm) was negligible for all the scenarios. The lateral flow and baseflow contributions to the streamflow showed a slight decrease only for Fr1 (194.56 mm) compared to the baseline (194.88 mm). It can be inferred that these results depend on the limited extension of the burnt area (2.3%). For all the fire scenarios, including post-fire mitigation measures, an increase in SSY was modelled, ranging from 5.86 t ha^{-1} yr^{-1} (baseline) to 12.05 t ha^{-1} yr^{-1} (Fr1) (Figure 7A). The severity of the fire played an essential role in SSY. A massive difference was predicted between high-severity fire (Fr1 and Fr2) and low-severity fire scenarios (Fr5, Fr6, Figure 7A). Fr5 and Fr6 showed limited increases in SSY (6.4 and 6.3 t ha^{-1} yr^{-1}) compared to the baseline. The post-fire management decreased SSY compared to Fr1 (8.9 t ha^{-}

[1] yr^{-1} and 7.7 t ha^{-1} yr^{-1} for Fr3 and Fr4, respectively), although it was still higher than the baseline (Figure 7A).

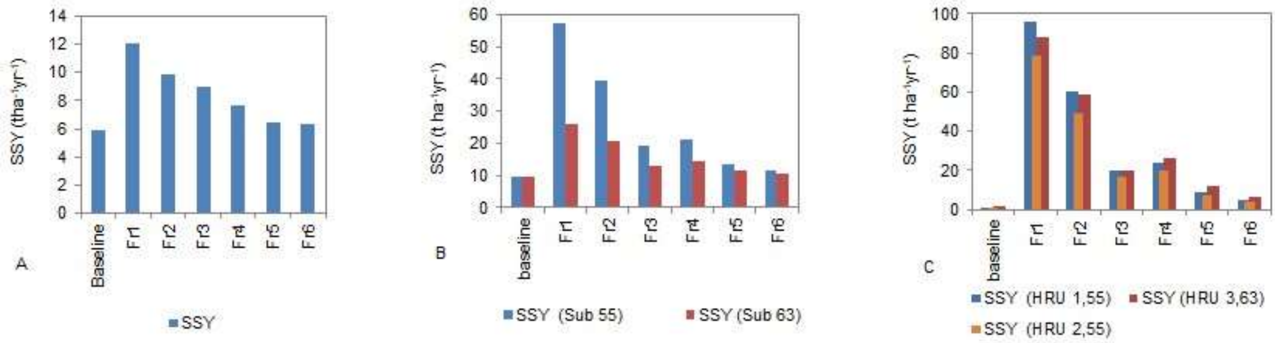

Figure 7. Specific sediment yield (SSY, t ha^{-1} yr^{-1}) simulated for the baseline and post-fire scenarios at the basin scale (A), subbasin scale (B), and at the hydrological response unit level (HRU) (C).

Results at the subbasin scale showed negligible variations in surface runoff (ranging from 129.01 mm to 129.17 mm) for all the analysed scenarios in the subbasin 55 compared with the baseline (129.00 mm). Similarly, the increase in surface runoff simulated for the subbasin 63 was negligible, ranging from 98.78 mm (baseline) to 98.83 mm (Fr1), and for low-severity fire simulated in the Fr5 and Fr6 scenarios, it was 98.79 mm. The SSY simulated for the baseline (9.5 t ha^{-1} yr^{-1} and 9.7 t ha^{-1} yr^{-1}, for sub 55 and sub 63, respectively) increased up to 57.4 t ha^{-1} yr^{-1} (sub 55, Fr1) and up to 26.1 t ha^{-1} yr^{-1} (sub 63, Fr1), confirming that the high severity of fire events and the post-fire logging may produce a dramatic increase in soil loss (Figure 7B). The extension of the burnt area within the basin played an essential role in SSY variations. Indeed, as a result of the larger burnt area in the subbasin 55 (56%), the SSY predicted in this subbasin was much more than SSY simulated in the subbasin 63 (burnt area 19% of subbasin area), especially in the high-severity fire scenarios with no measures to reduce soil erosion (Fr1, Fr2) (Figure 7B). Post-fire mitigation treatments (Fr3 and Fr4) effectively reduced soil erosion in high- and moderate-severity fires. In particular, straw mulching and seeding—as simulated in Fr3—protected ground cover better than erosion barriers (Fr4) (Figure 7B). Indeed, SSY was19.11 t ha^{-1} yr^{-1} and 13.13 t ha^{-1} yr^{-1} (subbasin 55 and 63, respectively) in Fr3 and 20.93 t ha^{-1} yr^{-1} and 14.35 t ha^{-1} yr^{-1} (sub 55 and 63, respectively) in Fr4, while fire severity was simulated to be high and moderate, respectively. As expected, due to the lower severity of fire represented by the Fr5 and Fr6, SSY increased to a lesser extent in these scenarios, ranging from 11.4 t ha^{-1} yr^{-1} (Fr6) to 13.3 t ha^{-1} yr^{-1} (Fr5) in the subbasin 55, and from 10.62 t ha^{-1} yr^{-1} (Fr6) to 11.57 t ha^{-1} yr^{-1} (Fr5) in the subbasin 63. The analysis of the potential impact of post-fire scenarios in terms of soil erosion was carried out also at the HRU level. Figure 7C shows the results for the three HRUs. The SSY estimated for the baseline ranged from 1.18 t ha^{-1} yr^{-1} to 2.04 t ha^{-1} yr^{-1}. It increased more than one order of magnitude for the high-severity fire scenarios, Fr1 ranged from 78.19 t ha^{-1} yr^{-1} to 95.77 t ha^{-1} yr^{-1} and Fr2 from 49.40 t ha^{-1} yr^{-1} to 59.91 t ha^{-1} yr^{-1}. As expected, the very low-severity fire scenario presented the lower increase of SSY, ranging from 4.33 (HRU 2,55) to 6.74 t ha^{-1} yr^{-1} (HRU 3,63) (Figure 7C).

4. Discussion

4.1 Simulating baseline

Soil erosion models are widely used around the world for estimating soil losses by water (Borrelli et al., 2021, Bezac et al., 2021), although some critical points have not been completely solved yet (i.e. parameterisation, lack of measurements to validate results, upscaling from local to larger scales). The implementation of a conceptual model is a complex activity that requires a broad knowledge of the river basin and the integration of various data and knowledge sources. In addition, conceptual models must be applied by experienced modellers who have deep knowledge of hydrological and sedimentary processes (i.e. equations, parameters). The present study shows that the SWAT model is a valuable tool to simulate both the hydrological processes and SSY under the Mediterranean climate, and it has great potential in watershed management.

The model has already been successfully used in the Apulia Region (De Girolamo et al., 2017a,b) for analysing hydrological processes. However, the low flow was generally overestimated. Similarly, in the present work, the model did not simulate the zero-flow condition, which was recorded in the summer in several observed years. The minimum flow predicted by the model was about 20 l s^{-1}. In the previously mentioned studies, which were oriented to support ecological status evaluation, it was identified that a zero-flow threshold and time series of streamflow were appropriately modified. In the present study, taking into account that the extremely low flow is characterised by negligible sediment transport, the discrepancy between observed and simulated streamflow was considered insignificant for the research.

The model performance in simulating SSY was satisfactory. Nevertheless, SSY was underestimated in the extremely wet conditions and slightly overestimated in autumn, confirming the results obtained by Abdelwahab et al. (2018), who implemented the SWAT model in the Carapelle basin (Apulia Region). Data resolution and problems linked to the transferability of the Modified Universal Soil Loss Equation approach may have influenced model performances (Ricci et al., 2018; Williams & Berndt, 1977).

At the basin scale, over the period 1990 to 2011 that included both dry and wet years, SSY was 5.60 t ha^{-1} yr^{-1}. This estimate was comparable with the studies carried out in the same region by Ricci et al. (2018). At the subbasin scale, SSY varied in the range 0.2-17.6 t ha^{-1} yr^{-1}. 20% of the total drainage area presented SSY values higher than the critical value (10 t ha^{-1} yr^{-1}). These results agree with the soil losses estimated by water erosion in Europe. Indeed, the application of a modified version of the RUSLE model (RUSLE2015) (Panagos et al., 2015c; 2016) and the PESERA model (Kirkby et al., 2004; 2008) estimated soil losses rate in the range 0 - 2 t ha^{-1} yr^{-1} in lowland, values from 2 t ha^{-1} yr^{-1} to 5 t ha^{-1} yr^{-1} in hilly areas and values generally from 5 t ha^{-1} yr^{-1} to 10 t ha^{-1} yr^{-1} in the mountainous part of the basin where several cells showed soil loss rate $>$ 10 t ha^{-1} yr^{-1}.

At the HRU's level, land use and management practices played a key role in determining SSY variations. Natural degraded areas with a very low vegetation rate showed a very high SSY (median value 23.8 t ha^{-1} yr^{-1}), mainly due to their location on steep slopes. Agricultural lands predominated by the basin's prevalent crop—durum wheat—showed a median value of 3.2 t ha^{-1} yr^{-1}, comparable with the predicted soil loss rate from erosion plots in Europe (Cerdan et al., 2010). Deciduous and mixed forests showed low SSY (0.3 t ha^{-1} yr^{-1}). These results were expected since it is well known that human activities such as agriculture and land-use change have induced an important increase in erosion rates (Foucher et al., 2021; Poesen, 2018). In the study area, soil losses are favoured by up and down ploughing, which is common, especially in mountainous areas.

It is important to remember that the dataset used for sediment calibration was limited and that measurements taken at the outlet could be insufficient for optimal parameterisation. Hence, an uncertainty degree could affect the results at the subbasin and HRU levels. In the present study, parameters such as USLE_P and USLE_C were fixed on the literature basis and were not calibrated. A new monitoring plan with a nested approach could be very useful for improving model parameterisation and SSY estimation.

Despite its limitations, the model can predict the hydro-sedimentary response of the basin and may contribute to the management of the reservoir, providing both the inflow and sediment loads.

4.2 Simulating post-fire mitigation measures

The forest located in the upper Celone river basin is an important natural area, it has been recognised as a Site of Community Importance, and it is included in the network “Natura 2000” (IT9110003) that covers Europe’s valuable species and habitats. The Regional Plan 2018-2020 developed by the Civil Protection Agency classified this area as a “high risk of fire” site due to weather conditions and ignition sources (Civil Protection Agency, 2018). Future climate projections predict an increase in temperature and a reduction of rainfall (De Girolamo et al., 2017b) that could increase the probability of wildfires and the risk of short and long-term post-fire contamination for surface waters. Hence, studies on the effects of wildfire on hydrology and soil erosion (Zema, 2021) as well as the analysis of different post-fire scenarios (Rulli et al., 2013) are needed to support watershed managers in managing the post-fire risks.

The hydro-sedimentary response of a watershed to fire events is complex (Vieira et al., 2018). It is related to fire impact on soil properties and changes in the vegetation cover (Cerdà and Doerr, 2008; Neary et al., 1999; Neary et al., 2005; Shakesby et al., 2011). The difficulties in evaluating the hydrological and sediment regimes generally increase in the Mediterranean environment with intermittent river networks due to the high spatial variability of soil properties, land use, and climate (Forteza et al., 2021).

The SWAT model, indispensable in water and soil management, may be used for the scenario analysis in the context of wildfire, but it needs to be adapted. Indeed, SWAT and all other hydrological/soil erosion models have not been developed specifically to simulate post-fire conditions. The adaptation consists of changing hydrological, soil, and cover parameters in an attempt to mimic the effect of fire (Lopes et al., 2021). Then, the model predictions should be calibrated, comparing the results with measurements. This is a critical point; most studies have not been validated with field observations since the latter are rarely available, especially at the basin scale (Lopes et al., 2021).

After fire events, land degradation and soil properties changes are not easy to measure and model since the effect may change according to the severity of fire and characteristics of the soils (Neary et al., 1999). Literature reports severe impacts on soil properties, providing sometimes conflicting results. Ice et al. (2004)

reported that reduction in infiltration rate could be very high (i.e. one or two orders of magnitude). Stoof et al. (2015), in their study in Portugal, evaluated that despite the high fire intensity, bulk density, organic matter, porosity, and saturated hydraulic conductivity did not significantly change. Nevertheless, they concluded that even if the fire has a low impact on soil properties, it may have a high impact on runoff and erosion. Mataix-Solera et al. (2011), in their review, reported that the effect on soil aggregate stability may increase or decrease for similar fire-severity events according to the soil characteristics. Post-fire water repellency, which is a key factor in post-fire erosion since it reduces infiltration rate, especially after high-severity fires, is highly variable spatially (Doerr et al., 2009; Shakesby and Doerr, 2006) and difficult to accurately estimate.

This work assumes that wildfire increases the soil's water repellency and reduces the saturated hydraulic conductivity, except for the very-low fire (Fr6). A reduction of the soil protection consequent to damage of vegetation cover was assumed to vary according to the scenarios. Hence, the effect of fire and the post-fire mitigation measures on runoff and SSY was estimated by modifying parameters such as OV_N, CN2, USLE_K, USLE_C, and USLE_P after an accurate literature analysis. To take into account the change in water repellency (not explicitly considered in the models) and the consequent reduction of soil permeability, it was assumed an increase of USLE_K by 0.016 Mg ha^{-1} MJ^{-1} mm^{-1} ha h, considering a high rate of change in soil erodibility (60-80%) as suggested by Miller's et al. (2003).

Post-fire measurements were not available. Due to this, the model was not calibrated for the above-mentioned scenarios, and the parameters were fixed based on the literature. This is a limitation of the present study because the parameters adopted based on measurements made in other Mediterranean sites do not necessarily apply to the Celone river basin. The choice of the scenarios was performed keeping in mind the necessity of providing a wide range of realistic effects of wildfire and mitigation measures on soil loss and runoff. Consequently, the above-mentioned parameters changed dramatically too. Thus, USLE_K was assumed to vary from +80% for high-severity fire to no difference for the very low-severity fire. They were the highest and lowest values reported in the literature, respectively. Similarly, CN2 was assumed to change drastically (73 to 90 for Fr6 and Fr1, respectively).

According to the assumptions, wildfires have an important effect on the sedimentary response. The increment related to the runoff was negligible in all the analysed scenarios. Lucas-Borja et al. (2019)

highlighted that the type of treatment (i.e. mulching or logging) did not influence the runoff generation in their plots. Fr1 and Fr2 showed a dramatic increase in SSY for the three HRUs analysed, increasing in the worst case (HRU 1, Sub. 55) from 1.26 t ha^{-1} yr^{-1} (baseline) to 95.8 t ha^{-1} yr^{-1} and to 59.9 t ha^{-1} yr^{-1}, respectively (Figure 7). Malvar et al. (2017) and Wagenbrenner et al. (2015) evidenced that logging operations may increase SSY mainly because of the trail generated by the passage of heavy machinery.

Fr5 and Fr6 showed a moderate increase of SSY that was quantified in 8.6 and 5 t ha^{-1} yr^{-1} (HRU 1, Sub. 55), respectively. These results agree with the Shakesby (2011) studies, which pointed out that from high to low-severity fire, the effect on erosion may vary from more than two orders of magnitude or may not show differences at all. From the modelling point of view, the difference in SSY between Fr5 and Fr6 was mainly attributable to the USLE_K factor and, to a very small extent, to CN2 (-2 in Fr6) since all the other parameters were unchanged. This result confirmed the USLE_K factor as a very sensitive parameter in soil loss modelling. The difference in SSY between the Fr1 and Fr2 resulted from the integrated effect of several parameters (USLE_C, CN2, and OV-N) that were differentiated in the two scenarios (Table III).

The post-fire mitigation measures have been widely implemented, but the assessment of their efficiency has been limited to local studies mainly conducted at the hillslope scale (Girona-García et al., 2021). The authors highlighted the need for studies on post-fire erosion mitigation measures, especially in high soil erosion areas. In the present study, the mulching treatment (Fr3) reduced SSY (20.2 t ha^{-1} yr^{-1}) compared with the high-severity fire Fr2 producing a reduction of SSY (66%). This result confirmed the study by Fernandez et al. (2011) carried out in Galicia, where the authors concluded that straw mulch application with 80% soil cover reduced soil loss by 66%. Fr3 resulted in more effective mitigation than the moderate-severity fire and erosion barriers. From the modelling point of view, this result is mainly attributable to the parameter USLE_P, which was assumed equal to 0.343 for straw mulching (Fernandez et al., 2010). When moderate-severity fire and erosion barriers were modelled (Fr4), SSY ranged from 19.8 to 26.2 t ha^{-1} yr^{-1} in the three analysed HRUs showing a reduction (56-61%) compared with Fr3. These results agree with the study by Rulli et al. (2013), who determined a value of 24.1 t ha^{-1} yr^{-1}, and with Fernandez et al. (2011), who observed a mean efficiency of barriers in retaining sediment of 58%.

4.3 Future perspectives

Despite the limits of the present study, the results clearly indicate that the rate of soil loss for the current land use and management practices is much higher than the soil rate formation that was estimated for European soils in 140 t km^{-2} y^{-1} (0.056 mm y^{-1}) by Verheijen et al. (2009). This study confirms that it is urgent to reverse this trend by promoting soil loss mitigation measures (Montanarella and Panagos, 2021).

Ricci et al. (2020) analysed the efficiency and economic implications of some best management practices (BMPs) like contour farming, no-tillage, and reforestation, for the public and private sectors. They concluded that those BMPs, which the Apulia Region Rural Development Programme currently supports, effectively reduce soil losses but have not yet been adopted at a large scale. Several barriers still exist that limit their adoption (e.g., farmers' education, lack of awareness of soil erosion). Numerous actions are needed to favour the adoption of BMPs, and important public economic resources are needed to support a plan for soil protection.

In order to address these challenges, the EU's common agricultural policy may have an important role in ensuring that agriculture is in line with the soil protection principles. The new European Green Deal (EGD) with the "Farm to Fork" and the "zero pollution action plan" strategies will be central in preserving soil systems and biodiversity (Montanarella and Panagos, 2021). Research and monitoring may play an important role in reaching the EGD's goals.

In the next decades, increased fire risk is expected in the Mediterranean. Watershed management will need fire prevention efforts and specific actions to protect and restore the river basins before disturbance occurs. 95% of fires are due to human activities (i.e. agricultural practices) or negligent behaviour and arson (Vilar del Hoyo et al., 2009). It is, therefore, necessary to increase public perception and awareness of the risks of wildfires and their impact on soil and water resources. Fire impact on soil is significant (Cerdà and Robichaud, 2009), leading to an increase in soil erosion (Shakesby and Doerr, 2006). Hence, implementing mitigation measures to reduce soil erosion is imperative and should be a part of every forest and soil recovery strategy (Bento-Gonçalves et al., 2012). This study has shown the effectiveness of straw mulching, seeding, and soil erosion barriers in reducing soil erosion. However, further studies and new monitoring programs are needed to assess additional mitigation measures and adequately analyse their cost-effectiveness.

5. Conclusions

Through a case study, the present work contributes to bridging the gaps in modelling post-fire impact and mitigation measures on soil erosion and the hydrological response of a Mediterranean watershed with an intermittent river network.

The SWAT model, calibrated with field measurements, was applied for the current land use and land management practices for hydrology and sediment yield, then it was applied to simulate post-fire mitigation options. The model adequately reproduced the measured discharge for two monitoring periods: 1994-1996 and 2010-2011. It also satisfactorily reproduced suspended sediment dynamics over the period 2010-2011, indicating that it may be used to analyse the hydro-sedimentary response of the basin. At the basin scale, results showed that the average soil loss estimated over a long period (1990-2011) is much higher than the soil formation rate. About 20% of the drainage area showed critical values of soil losses. At the subbasin scale and HRU level, the results showed that steep slopes areas and natural degraded areas are under severe soil erosion. However, results could be affected by a large uncertainty since the dataset used for sediment calibration was limited and the measurements of sediment taken only in a river section located in lowland could be insufficient for optimal parameterization.

The results reveal the need of implementing mitigation measures to reduce soil losses. Water resources managers are called to take action to increase the awareness of farmers on soil erosion-related problems and to develop strategies to promote the adoption of BMPs such as contour farming, no-tillage, and reforestation. On the other hand, programs of soil conservation must be implemented over long time frames with important investments with strong actions of the policymakers at the European, national and regional levels.

Due to weather conditions and ignition sources, the basin is classified as a “high risk of fire” site. The probability of wildfires and the risk of short and long-term post-fire contamination of surface water could increase due to climate change in the near future. The results of the present study clearly showed that watershed management may have an important role in reducing the effects of wildfire on soil and water by implementing post-fire risk mitigation and restoration measures. SWAT—a hydrological and water quality model—may contribute to selecting the mitigation options to reduce soil erosion after a fire. In addition, the SWAT model is also a useful tool for the post-fire risk assessment in terms of water quality since it identifies the river segments where sediment-associated pollutants transported via surface runoff could accumulate on the riverbed after fire events.

The choice of the post-fire scenarios was performed keeping in mind the necessity of providing a wide range of realistic effects of wildfire and mitigation measures on soil loss and runoff. According to the assumption, high-severity fire vastly increases SSY at the basin and subbasin scales and HRU levels. This study shows that a dramatic increase in soil erosion occurs in areas sensitive to erosion, demonstrating that major efforts are needed to prevent forest fires and better manage the post-fire. The results showed that a small part (2%) of the catchment is enough to cause a dramatic increase in soil loss quantified at the basin scale by up to 12 t ha^{-1} yr^{-1}. Post-fire management is effective at mitigating fire impact on soil erosion. In particular, post-fire mitigation measures such as emergency stabilisation (straw mulching and seeding) and soil erosion barriers are better at reducing soil erosion than natural regeneration or logging operations. However, post-fire measurements were not available and the model parameters were fixed based on literature. This is a limitation of the present work. Further studies and field campaigns are needed to validate modelling results and for adequately analysing the cost-effectiveness of these measures.

Credit Authors Statement

All co-authors conceptualized the study. AMDG designed the model simulations and wrote the initial draft. AMDG, RV, GFR, and TG collected input data. AMDG finalized the writing. All co-authors reviewed the paper. AMDG wrote the revised manuscript. RV, OC, AMDG and ALP secure funding and were involved in project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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