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Predicting Extreme-Precipitation Effects on the Geomorphology of Small Mountain Catchments: Towards an Improved Understanding of the Consequences for Freshwater Biodiversity and Ecosystems

Stefano Segadelli [1,*], Federico Grazzini [2], Michele Adorni [3], Maria Teresa De Nardo [1], Anna Fornasiero [2], Alessandro Chelli [4] and Marco Cantonati [5]

[1] Servizio Geologico, Sismico e dei Suoli, Regione Emilia-Romagna, Viale della Fiera 8, 40127 Bologna, Italy; mariateresa.denardo@regione.emilia-romagna.it
[2] Agenzia Prevenzione Ambiente Energia Emilia-Romagna, Servizio Idro-Meteo-Clima (ARPAE-SIMC), Regione Emilia-Romagna, Viale Silvani 6, 40122 Bologna, Italy; fgrazzini@arpae.it (F.G.); afornasiero@arpae.it (A.F.)
[3] Biologist freelance, Via degli Alpini 7, 43037 Lesignano de' Bagni, Parma, Italy; akaros@libero.it
[4] Department of Chemistry, Life Sciences and Environmental Sustainability, University of Parma, 43100 Parma, Italy; alessandro.chelli@unipr.it
[5] MUSE—Museo delle Scienze, Limnology & Phycology Section, Corso del Lavoro e della Scienza 3, I-38123 Trento, Italy; marco.cantonati@muse.it
* Correspondence: stefano.segadelli@regione.emilia-romagna.it

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Abstract: In 2015 an intense rainfall event hit the Valleys of the Trebbia, Nure, and Aveto watercourses in the Northern Apennines. In about 6 h a mesoscale convective system deployed a stunning amount of precipitation of 340 mm, with an extreme hourly rainfall intensity of >100 mm/h. It triggered debris flows along slopes and stream channels, landslides and floods, which caused serious damages. Through the optimal combination of rainfall data and radar volumes, in this work we present a detailed rainfall analysis, which will serve as a basis to create a quantitative correlation with debris flows over elementary hydrological units. We aim at providing an objective basis for future predictions, starting from the recognition of the forcing meteorological events, and then arriving at the prediction of triggering phenomena and to the debris-flow type. We further provide seven observations/case studies on the effects of extreme-precipitation events on freshwater environments in small mountain catchments. Extreme-precipitation events are becoming more frequent and widespread globally but their ecological effects are still insufficiently understood. In general, the effects of extreme events on inland-waters' ecosystems are highly context-dependent, ranging from deleterious to beneficial. We therefore highlight the necessity of further studies to characterize these effects in more depth to be able to include appropriate mitigation measures in environmental planning and stewardship.

Keywords: inland waters' ecosystems; catchment; biodiversity; extreme rainfall events; ecological effects; northern Apennines; cloudburst

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1. Introduction

Meteorological events characterized by extreme rainfall intensity have recently struck the hilly and mountainous territory of the northern Apennines (Italy) [1,2] and the Emilia-Romagna region in particular [3–5], as well as many other geographic areas of the world [6–12].

These extreme rainfall events trigger fast flows of debris along the slopes, stream channels, landslides, and floods, which damage many man-made structures such as roads, houses, water-pipes, etc.

There is thus a strong practical interest in predicting the frequency and intensity of these effects for emergency management and to reduce the vulnerability of the territory.

On the contrary, the ecological effects of these intense precipitation effects seem to have been neglected so far. Under the pressure of the worsening consequences of climate change, several studies have tried to address the ecological effects of extreme events on running waters [13]. However, the extreme events generally include floods, wildfires, heat waves and droughts whilst cloudbursts are rarely included. Even more importantly, the ecological effects considered are almost always those on running waters, with some freshwater-ecosystem types, such as mires, mountain tarns, and, in particular, groundwater systems, being almost completely neglected.

In the present paper the analysis of an intense rainfall event has been performed, with the aim to investigate the height of the rain using several time spans (1 h, 2 h, 3 h, . . .) that has caused the triggering of the geomorphological effects on the ground. Rainfall analysis, recorded by the Emilia-Romagna network of weather stations and managed by ARPAE-SIMC, showed that the map of the spatial distribution of rainfall (in mm) in the 3 h time span from 23:00 on 13 September to 02:00 on 14 September, fits well with the area of the highest concentration of geomorphological effects caused by the precipitations themselves. Moreover, in particular, in consideration of the paucity of information on this specific topic available in the literature, we also aim at documenting the effects of extreme precipitation events on the biodiversity, structure, and function of freshwater ecosystems in small mountain catchments.

1.1. General Setting

In the study area, formations belonging to the Ligurian, Subligurian and Tuscan domains of the Northern Apennines [14] crop out. In general, limestones, marls and argillites are very common, like in the Canetolo Formation of the Subligurian domain or in the Flysch sequences both in the Ligurian (Ottone, Orocco, Cassio, Bettola, and Farini formations) and Subligurian (Vico and Penice Units) domains. They are often associated with the so-called "Basal Complexes", geological units characterized by a large variety though mainly-shaly lithologies. To the Ligurian domain also pertain several huge rock masses made up by ophiolites. Turbidites are made up by conglomerates, sandstones and pelites, which mainly crop out in the Valley of Trebbia River.

From the geomorphological standpoint, the general features of the area are determined by landslides, mainly related to the lithological characteristics of the outcropping shaly or pelitic rocks. Large-scale, complex landslides (rock and earth slides; earth flows) are very common to be found and sometimes may reach the bottom of the valleys, causing the narrowing of river beds. The river valleys show in general a classic V-shaped profile, sometimes characterized by very steep slopes with slope breaks, often symmetric on both sides. Alluvial terraced deposits are present also in the mountain sector of river valleys, and alluvial cones are very common at the confluence between streams and the main watercourse.

Landforms and deposits due to glaciers are advised in some tracts of the main divide of the mountain chain. In the highest portion of the Nure river valley, glacial cirques and landforms due to glacier erosion are reported [15].

The climatology of the study area can be considered as belonging to the Alpine type, with important differences in regards to precipitation, which has a strong Mediterranean influence. The Northern Apennines are one of the most rainy areas in Italy, along with the Maggiore Lake area and the Alpine Carnia Plateau. The Northern Apennines are characterized by a high percentage of annual precipitation deriving from intense rainfalls, rather than by frequent, low intensity rainy days, as is the case in the Alps, especially in the most inland sectors and in its northern side [16]. This effect, typical of the Mediterranean climate, is most evident in the transition and cold seasons. The more intense rainfall has a marked annual cycle, presenting the highest frequency and intensity from September to November [16]. The tendency to have a significant contribution to total amounts from heavy precipitation events is increasing in recent years. In the Emilia-Romagna Region, [17] an amplification of the seasonal precipitation cycle has been detected, with a marked precipitation decrease, especially in winter and spring, and a precipitation increase in autumn, mainly attributable to more intense events. This has been also confirmed in the recently published Climate Atlas of Emilia-Romagna [18].

Finally, in the study area there are numerous Natura 2000 network sites [19].

1.2. The Case Study

In the night between 13–14 September 2015, an intense mesoscale convective system (MCS) formed in the Tigullio Gulf, moved inland over the area between the Valleys of the Trebbia river, Nure, and Aveto streams, nearby the boundary between Emilia-Romagna and Liguria Regions (Figure 1a,b). This system, which remained in place for about 6 h, deployed a stunning amount of precipitation (300 mm/6 h) with extremely high hourly intensity (>100 mm/h) recorded in several meteorological stations of the ARPAE-SIMC regional network (Figure 1c).

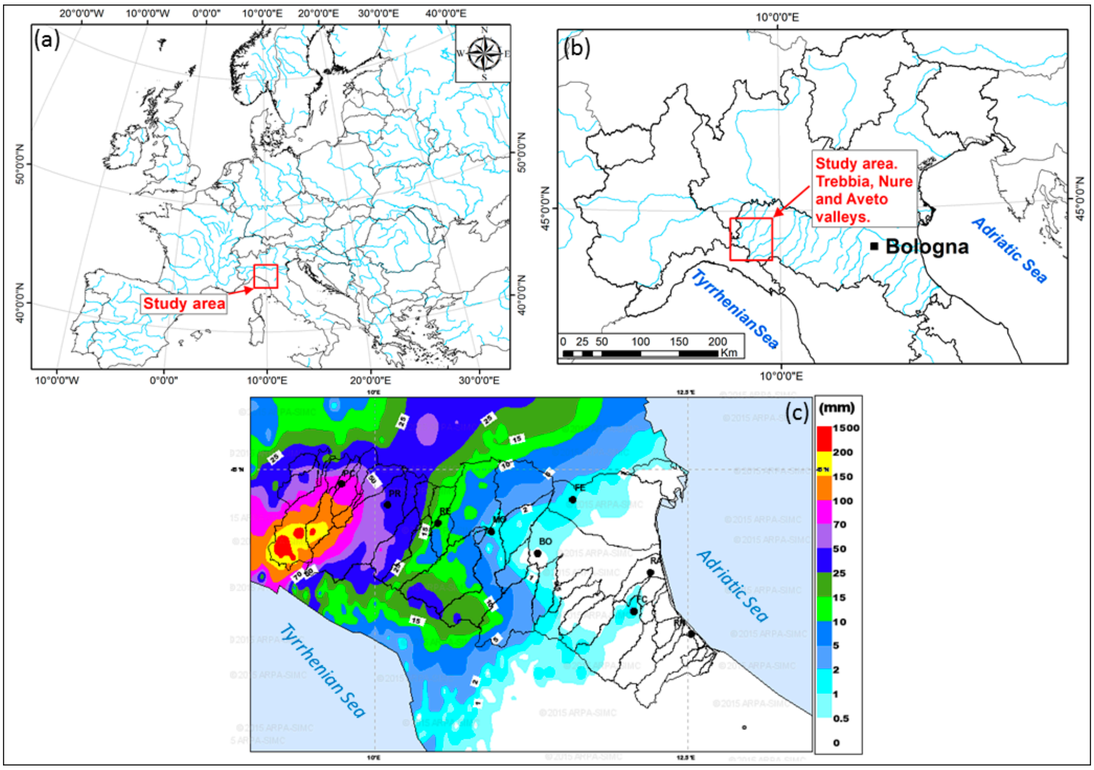


Figure 1. Location map of the study area (**a**,**b**) and the cumulative rainfall (**c**) from 23:00 local time on 13 September to 05:00 on 14 September, on the major catchment areas of the Emilia-Romagna Region. According to the rainfall data recorded in the meteorological stations of the ARPAE-SIMC regional network.

The threshold of 30 mm/h, fixed as discriminating for heavy rainfall (see the new Alert System established recently by the Administration of Emilia-Romagna Region [20]) in the Emilia-Romagna region was exceeded 47 times in all, summing the contributions of the different stations. An unprecedented number for a single extreme rainfall recorded in the Emilia-Romagna region.

During this event, several types of widespread effects on the ground developed i.e., fast flows of debris along the slopes and stream channels (a total number of 305 occurrences), shallow landslides (342) and overbank flooding occurred. These processes have struck many of the man-made structures like roads, houses, waterpipes etc., highlighting the vulnerability of this territory.

2. Materials and Methods

Since the Law 183/1989, river basins are the reference territorial units for land-use planning in Italy. In the Emilia-Romagna Region, within river basins the so-called Hydrogeomorphologic Elementary Units, (HEUs) were mapped as elementary units for land-use planning in the mountain sectors of catchment areas. HEU was defined [21,22] as the elementary drainage basin containing watercourses belonging to the lowest hierarchical Strahler stream order [23] (generally, from first to third order) and characterized both by (i) a functionality from the hydrologic point of view, and (ii) a defined geomorphological processes dynamic. HEU is a basic drainage basin for land-use planning because it allows establishing the relationship between geomorphological processes and land-use. It was employed, thus, as an elementary territorial unit also to study hazard evaluation and land degradation risk management.

During the rainfall event, a great number of flow processes occurred along the slopes and stream channels, within small first to third order steep catchment areas. The geomorphological mapping of the landforms genetically related to an intense rainfall, performed at the same scale, thus represents a very powerful tool to study the effects of these phenomena.

Precipitation data were taken from the record derived by the Emilia-Romagna meteorological station network managed by ARPA-SIMC. Despite a high density of the pluviometric stations (about one rain gouge every 40 km^2), data were not sufficient to produce a detailed precipitation filed to relate with local ground effects. For this reason, we also made use of radar-derived precipitation fields, adjusted with pluviometric observations. This technique (described in the ARPA-SIMC Tech. Report from [24]) removes radar biases through observation nudging, producing a precipitation field with higher accuracy (the original radar data have a resolution of 1 km^2) than rain gouges alone.

In order to recognize, identify and classify all the surveyed geomorphological effects caused on the ground by the extreme rainfall event and their source areas, the approach of combining field work and remote sensing was chosen. Series of remote sensing images acquired at different times and available through the database of the Emilia-Romagna Region [25] were used.

An inspection of the hyetograph revealed that most of the rainfall occurred in a 3 h time-span, slightly variable from station to station, according to storm movement. As the basis of our analysis, we decided to take the 3 h precipitation interval (23-02 UTC), where most of the precipitation was observed on the higher Aveto and Nure Rivers drainage basins. Another very remarkable characteristic has been the largest extension of the area affected by high or very high precipitation. Given the large dimension-duration of the MCS, it was assumed that 3 h was the most significant time-span, suitable to be related with the widespread effects observed in the field.

Landforms and deposits, existing in the area before the investigated effects caused by rainfalls, were mapped using the black/white (B/W) aerial photographs at a scale of 1:15,000 taken in the period March–July 1973 and the so called AGEA orthophotographs in color with an average pixel size of 50 cm, taken in the period May–June 2011. The B/W aerial photographs have a good resolution, and allowed recognition with great accuracy the features of the territory investigated, thanks also to a less-than-today dense and widespread wood cover. They were very useful to recognize and map the deposits, classified by their origin (scree slopes, landslides, alluvial deposits, and colluvium), that represented the main sources of debris mobilized as an effect of heavy rainfall.

The field work was realized using the Technical Regional Map 1:5000 as a topographic base, integrated with remote sensing imagery. The latter was airborne and satellite imagery was acquired by the Emergency Management Service (EMS) [26] within the framework Copernicus of EU Commission, realized with the support of European Spatial Agency [27]. The use of these images was very helpful because the study took place in a mainly mountainous area with many parts not always directly accessible.

All database information was managed using GIS software, georeferenced in World Geodetic System 1984 (WGS 84) and Transverse Mercator projection system.

Within the Topographic Database of the Emilia-Romagna Region, the following layers were used: (i) contour line at 5 m and index contour at 25 m, (ii) spot elevation, (iii) buildings and main roads, (iv) raster digital images. For more information: [28].

The description of the extreme-precipitation effects on freshwater biodiversity and ecosystems in the study area (Section 3.3) is preceded by two (Sections 3.1 and 3.2) in which a time-efficient method for the identification of thresholds or rainfall-intensity classes applied to hydrogeomorphologic elementary unit (HEU) is proposed on the basis of the following main factors:

- main ground effects observed;
- meteorological information;
- principal geological and morphometric characteristics of the study area.

This time-efficient method allows identification and mapping of the areas most exposed to the main types of effects on the ground (high discharge and hillslope-debris flows) produced by extreme events of precipitation in the catchment areas.

In this way it is possible to identify which are the freshwater ecosystems potentially at risk. This allows guiding and, optimally, organizing of the future monitoring activities necessary to better quantify the possible impacts of extreme events on freshwater biodiversity and ecosystems in small catchments.

3. Results

3.1. Relationships between Extreme Rainfall Intensity and Spatial Distribution of the Main Ground Effects

This study highlighted the presence of several ground effects recognized in the whole area affected by the rainfall event (Figure 2). The territory investigated was subdivided in 286 HEUs characterized by stream networks that, generally, do not exceed the 3rd Strahler stream order with extent less than 3 km^2. Generally, the slopes are very steep, with an average inclination between 25° and 50° that strongly delimits the development of the stream network.

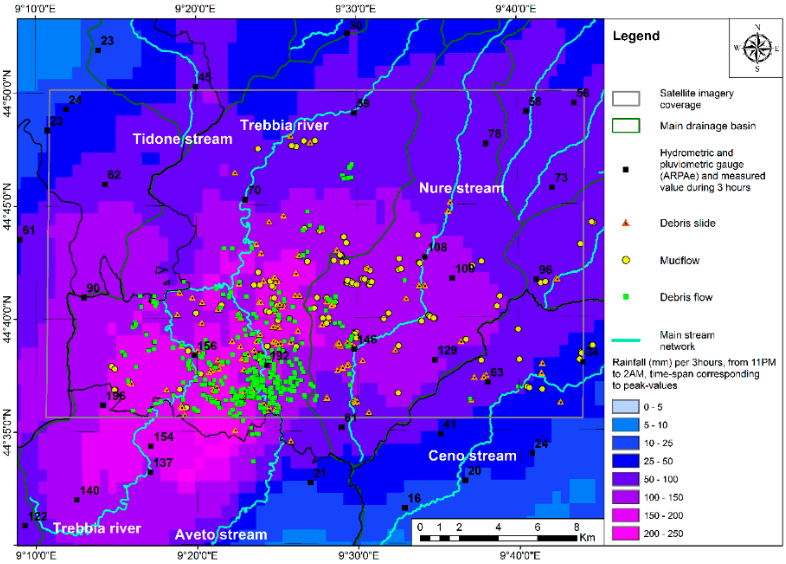


Figure 2. Rainfall estimates obtained from the combination of radar and surface rain gauge data. The time interval considered is from 11 p.m. 13th to 2 a.m. 14th September, it corresponds to the time period of rainfall maximum intensity. The main ground effects, that caused damages, are shown: 207 debris slides, 135 mud flows, and 286 hillslope-debris and hyperconcentrated flows.

Figure 2 shows a very good correlation between the distribution of newly generated landforms and the estimate of the maximum precipitation over the three hours. This is therefore a sufficiently long time interval for the development of forms that are genetically related to mass-transport mechanisms of a significant entity.

Among them, debris slides and soil slips were widespread but the most impressive landforms, both for their high number and destructive power were: (a) hillslope-debris flows (Figure 3a,b) high-discharge flows occurring along the torrent networks (Figure 3b). Ground effects not only damaged man-made structures but also affected freshwater environments heavily.

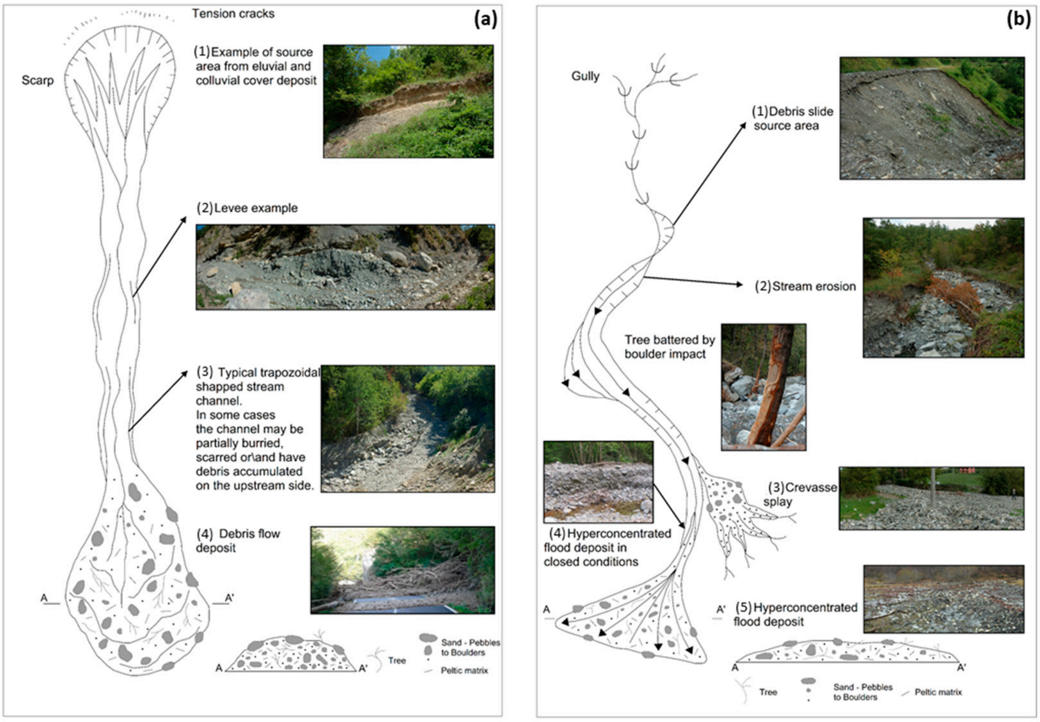


Figure 3. (**a**) Model of hillslope-debris flow derived from the geomorphological mapping where the typical landforms of source area (1), levees (2), channel (3) and deposit (4) are shown. (**b**) Field-work-based model of a hyperconcentrated flow in which the source area (1), stream erosion (2), crevasse splay (3), and deposits, both in open (4) and confined (5) condition, are shown.

The intensity and duration of the rainfall, associated with the high steepness of slopes, together with favorable geological-geomorphological conditions, has favored the trigger of numerous hillslope-debris flows and high-discharge flows (Figure 4) capable of producing sudden landscape changes. The heaviest damages were observed in correspondence of alluvial fans, a privileged site for human activity in mountain areas.

Source areas of hillslope-debris flows generally coincided with matrix-supported, poorly sorted deposits, characterized by coarse-grained pebbles and blocks of fine-grained matrix, like silt and clay. These kind of deposits are represented in the area by landslides, mainly mud-rich earth flows and earth slides, and different types of slope deposits, like eluvium and colluvium, and also regolith Figure 3a(1). The slope of the source areas usually exceeds 25°, and they were often covered by vegetation, trees, or shrubs that did not prevent the slope failure. The flowing path is characterized by lateral levees made by coarse, poorly sorted, and matrix-supported clasts Figure 3a(2),(3). In some circumstances, the levees clearly showed a reverse-graded structure of the material, due to the floating of larger clasts and boulders on the surface of the high density flow. The final deposition of the flowing debris mass occurs through an en-masse freezing of the flowing mass, due to the rapid loss of the water and the consequent fall of the interstitial pore-pressure. The flowing mass may stop in correspondence with slope breaks. The deposition gives origin to a deposit made by coarse, poorly sorted clasts, with abundant angular to sub-rounded gravel, cobbles, some boulder and large floating or protruding clasts, including large trees Figure 3a(4). These processes occurred, thus, as very fast movement along steep slopes, of flowing mixtures of material containing also a lot of trees and vegetal remains.

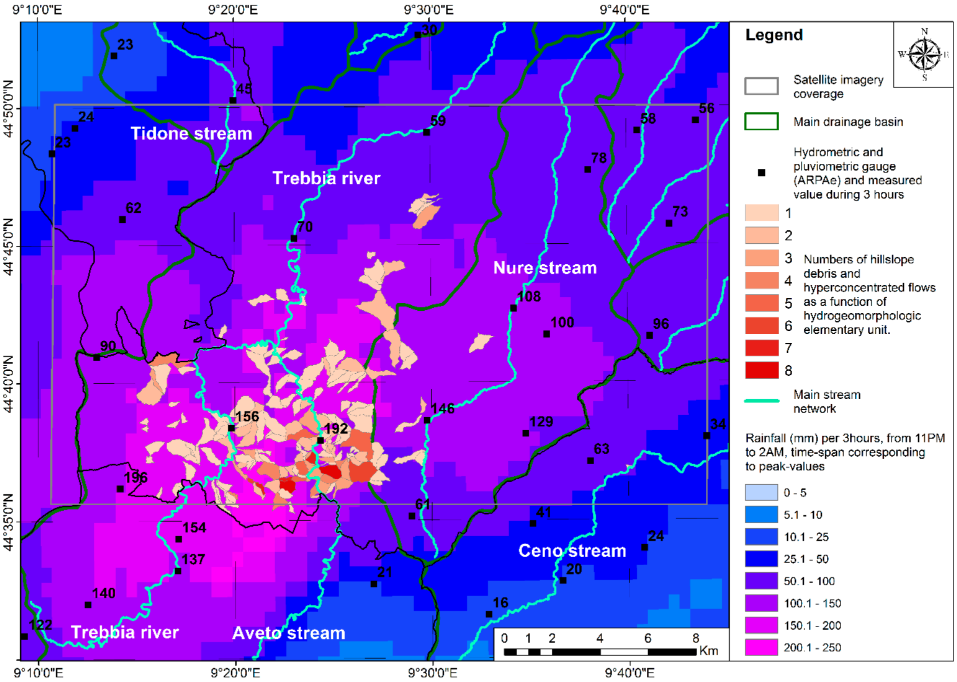


Figure 4. Distribution of hillslope debris and hyperconcentrated flows surveyed in the study area within hydrogeomorphologic elementary units and their classification.

High-discharge (hyperconcentrated) flows occurred, generally, along gullies, and 1st to 3rd order streams according to Strahler's hierarchy. The source area usually coincided with the head, or higher portion, of the channels, and the material involved was mainly derived from alluvial and colluvial deposits Figure 3b(1). The flowing masses followed the path of the channels, generally steep (between 35° and 45–50°), sometimes filling their transversal sections completely. Along the path, the flowing masses continued to pick-up material from the stream banks, leaving scarps of variable height (from 1–1.5 to 2 m), completely modifying the channel morphology (Figure 3b(2)), both in depth and width. Locally, erosion caused the occurrence of landslides, mobilized downhill from the torrent valley slopes. The deposition of material (Figure 3b(3)–(5)) occurred at the first relevant diminishing of steepness of the channel, usually at the confluence between streams, due to the loss of the stream capacity to sustain the load in charge. The deposits are typically openwork or clast-supported, made by poorly sorted, abundant, angular to sub-rounded gravel, cobbles, sometimes boulders, and large floating material, including trunks and wood pieces. Where enough space existed, the deposits were fan-shaped (Figure 3b(4)). The material was deposited often in correspondence with the narrowing of river-bed sections caused by the intersection with man-made structures, like roads, bridges, and manufacts built up as a local protection against erosion effects. Poorly sorted deposits show crude down-current clast orientation, and crude inverse up-grading (Figure 3b(5)); they contain sand matrix, being locally matrix-supported, where the deposition occurred within the channel, caused by obstacles or breaks in steepness.

3.2. Relationship between Rainfall Intensity, Mass-Flow Distribution and HEU Incline

A time-efficient method for the identification of thresholds or classes of rainfall intensity, based on main ground effects data observed and meteorological information applied to HEU, is proposed.

Within each of the 286 HEUs mapped in the study area, the average rainfall recorded in the three hour time-span and the average acclivity of the microbasin, the latter playing a major role in driving mass flows [29], were calculated. The results were then matched with the number of high-discharge and hillslope-debris flows, recorded within each microbasin (Figure 5a).

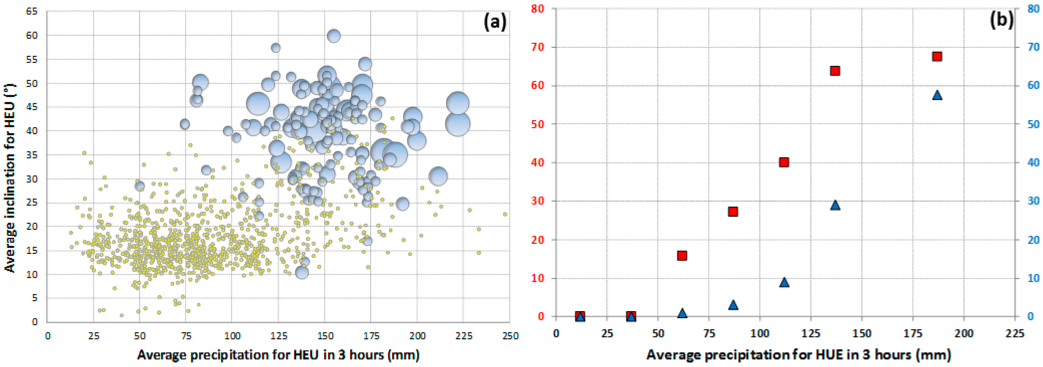


Figure 5. (**a**) Number of ground effects recognized in hydrogeomorphologic elementary units (HEUs), plotted with rainfall intensity (mm/3 h) and HEUs mean slope steepness. Yellow dots correspond to (HEUs) without flow processes, gray-shaded circles are the HEUs that were interested by flow processes, the size of circles is proportional to the number of processes, from a minimum of 1 (smallest circles) to a maximum of 8 (largest circles). (**b**) Only HEUs with average acclivity of more than 25° are reported. The figure shows the relationship between the percentage of mass flows triggered per HEU (red square), and the number of HEUs where mass-flows were recorded (blue triangle) in relation to average precipitation for HEU in 3 h.

A HEU mean slope steepness threshold could be identified. HEU with a mean steepness higher than 25° contain 97% of the total observed flows, while only 3% of these landforms developed in HEU with a mean steepness lower than 25°, though interested by intense rainfalls themselves (Figure 5a).

In detail:

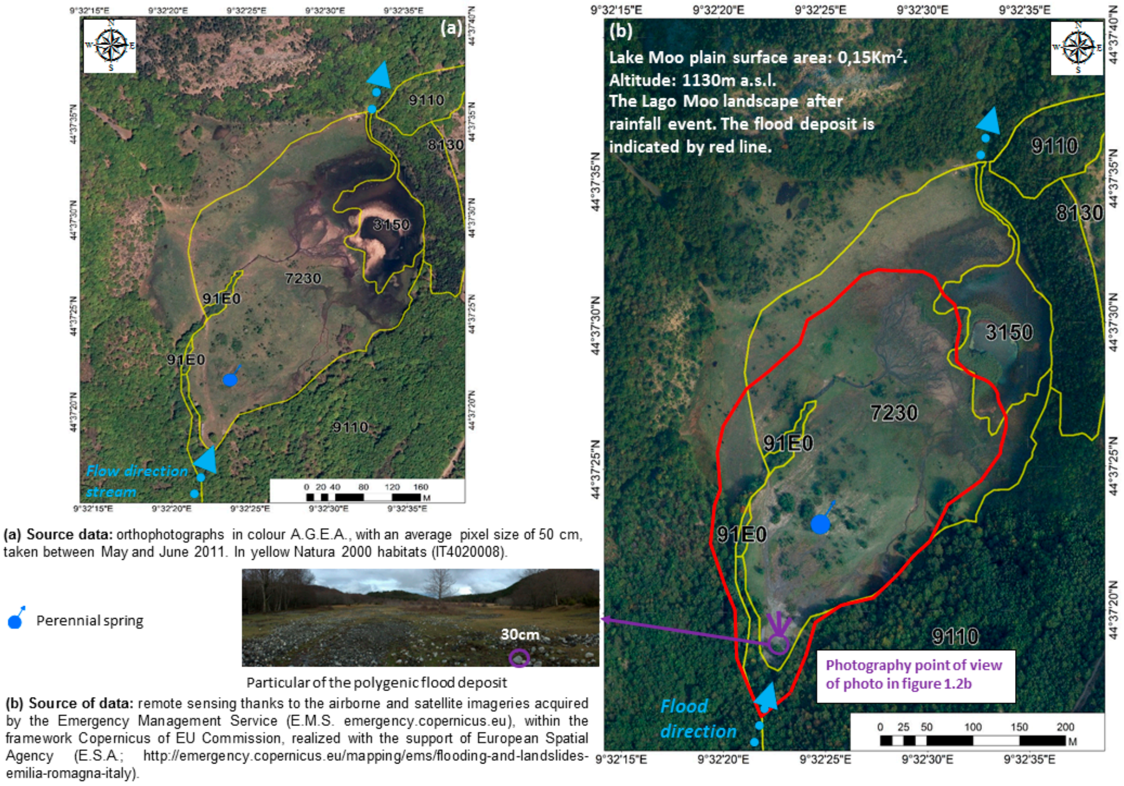
- HEUs with the highest density of high-discharge and hillslope debris-flows evidence (n° of observed landforms/km^2) are those with mean steepness comprised between 35° and 45° and rainfall intensity varying from 125 to 175 mm/3 h;
- 40.4% of HEUs that suffered flow processes have a mean steepness higher than 25° and less than 40°;
- 56.3% of HEUs that were widely affected by high-discharge and hillslope-debris flows development have a mean steepness higher than 40°;
- debris-flow occurrence in HEU with a mean steepness >60° is rare because of the lack of pre-existing slope deposits suitable to become source areas, both on slopes and within the stream channels.

Since in HEU with slope acclivity <25° the activation of hillslope debris and high-discharge flows is less likely, in Figure 5b the distribution of these landforms is plotted as a function of rainfall intensity (mm/3 h) within HEU characterized by average acclivity >25°. In HEUs with slopes steeper than 25° bearing geological and geomorphological preparing factors (i.e., availability of debris accumulations), four classes of rainfall thresholds can be identified: (i) Precipitations ≤50 mm/3 h: little or no ground effects. (ii) 50–100mm/3 h: rapid increase in the number of triggered ground effects and HEUs involved; 75 mm/3 h appeared to be the discriminatory threshold value beyond which the frequency of high-discharge and hillslope-debris flows became relevant with 15.8% of the HEUs concerned. (iii) 100–150 mm/3 h: the frequency of triggered mass-movements increased linearly, reaching over 60% of the HEU; this class can be defined as the one presenting the highest probability of debris mass-transport occurrence. (iv) >150 mm/3 h: high-discharge and hillslope-debris flows very likely to occur.

3.3. Extreme-Precipitation Effects on Surface Water and Groundwater Ecosystems in Small Mountain Catchments

In the following, we provide seven observations/case studies on the effects of extreme-precipitation events on the biodiversity, structure, and function of freshwater ecosystems in small mountain catchments.

(i) Figure 6, referred to as the Lake-Moo area in the high Nure Valley, documents the consequences of the movement of a high-discharge flow into a peat bog. As a result of a break in the slope, the flow slowed down and deposited a large amount of its solid load, forming a large fan-shaped, coarse, polygenic deposit in the proximal part and a small delta. In the Lake-Moo mire depositional setting the following were observed.



(a) Source data: orthophotographs in colour A.G.E.A., with an average pixel size of 50 cm, taken between May and June 2011. In yellow Natura 2000 habitats (IT4020008).

Particular of the polygenic flood deposit

(b) Source of data: remote sensing thanks to the airborne and satellite imageries acquired by the Emergency Management Service (E.M.S. emergency.copernicus.eu), within the framework Copernicus of EU Commission, realized with the support of European Spatial Agency (E.S.A.; http://emergency.copernicus.eu/mapping/ems/flooding-and-landslides-emilia-romagna-italy).

Figure 6. Satellite imagery before (**a**) and after (**b**) the high-discharge flood in September 2015. The yellow line defines the habitats of the Natura 2000 network (IT4020008 site code).

First, the covering of the uppermost, subaerial deposits within the peat bog, characterized by the presence of springs due to the local emergence of the shallow water table (in Italian *risorgive*, Figure 6); these perennial springs are fed by the apical part of the alluvial fan ground sediments in the peat bog;

Second, the interference with habitats of the "Natura 2000" Network of Nature Preserves pertaining to the peat bog basin. 91E0*, "Alluvial forests with *Alnus glutinosa* and *Fraxinus excelsior* (*Alno-Padion, Alnion incanae, Salicion albae*)" and 7230, "Alkaline fens" (Figure 6) are the most affected habitats. The first, of primary conservation interest, consists of a strip of riparian forest vegetation dominated by *Alnus incana* that develops along the tributary of the lake. This is a habitat typically found along watercourses, able to cope with intense river dynamics, and that should therefore not be significantly affected by the alterations caused by the alluvial flood deposit. The habitat 7230 has an important phytogeographical value, because the mountain areas of the Nure Valley are one of the few sites where this habitat type has been found in the Emilia-Romagna Region. This habitat is characterized locally by peat bog vegetation, and is made up of a closed meadow with *Cyperaceae* (*Carex davalliana, Carex nigra, Blymus compressus*) and *Poaceae*, including *Sesleria uliginosa*. In the biotope two different aspects of this habitat type can be found. The first, developing in correspondence with springs and stagnant waters, is characterized by a substrate with high humidity on which numerous bryophytes and important hygrophilous vascular species develop. These include the rare *Menyanthes trifoliata* and *Drosera rotundifolia*, and the protected species *Dactylorhiza incarnata*, *Epipactis palustris*, *Gentiana pneumonanthe*, and *Eriophorum latifolium*. *Menyanthes trifoliata* is the dominant species in particularly wet stations. The second aspect is characterized by a drier substrate, and bryophytes are almost absent and the floral component is much poorer, often represented exclusively by *Carex nigra* and *Sesleria uliginosa*. The wettest aspect of the habitat, characterized by a greater naturalistic value, is also the most sensitive to the impact caused by the flood deposit. Figure 7 is an original contribution that shows lithological variations of the flood deposit due to down-slope-motion transformations, the areal importance of the deposit, and its interaction with the habitats of the Natura 2000 network.

(ii) Another observation was related to the pouring of a high-discharge flow into Lake Bino (nearby Lake Moo). A brown plume developed affecting the lake for its whole extension (Figure 8). During particularly important events, the plume plunges down and proceeds as a turbidity underflow, forming a clastic deposit on the bottom of the lake (Figure 9) [30]. Lake Bino is characterized by the presence of a rhizophytic vegetation dominated by *Nuphar lutea* that can be assigned to the Habitat of Community Interest 3150, "Natural eutrophic lakes with *Magnopotamium* or *Hydrocharition*-Type vegetation". The progressive sediment filling of the water body, worsened by frequent high-discharge flood events, constitutes a potential threat to the habitat, but only in the very long term.

(iii) Figure 10 describes an erosive effect particularly common in the catchment area that underwent the mass-movement phenomena. When channelized and flowing on an outcropping, hard-rock substrate, because of its high erosive capacity, the pre-existing alluvial deposits are often completely removed from the river bed, as well as the riparian vegetation.

(iv) In a few hours, the large rainfall amount resulted in concentrated runoff in small catchment areas. The inclinations and the related confinement of streams and rivers have contributed to producing and emphasizing this erosive phenomenon. Contrastingly, Figure 11 shows how the riparian vegetation was instead completely covered by the flooded sediment nearby the main inclination breaks in downhill segments of the stream network (Figure 3b(4)).

(v) The EBERs project (Exploring the Biodiversity of Emilia-Romagna Springs; 2011–2013) has allowed the identification of several limestone-precipitating springs (LPS) in the Emilia-Romagna Region [31]. Limestone-precipitating springs are generally found in the upper part of narrow stream valleys in the morphological facies of a 'pool terrace' or 'rapids and waterfalls', or distributed along slopes forming limestone clusters above the streams of nearby springs (Figure 12). Field surveying has shown that, due to a greater frequency and intensity of extreme rainfall, torrents erode alluvial deposits in their initial stretches. On the slopes this leads to landslides and to the destruction of existing LPS and their hygrophilous vegetation, often formed by *Molinia arundinacea* communities attributable to the Habitat of Community Interest 6410, "*Molinia* meadows on calcareous, peaty or clayey-silt-laden soils (*Molinion caerulaee*)". Locally, the habitat regularly includes several orchids (protected species) among which the most frequent are *Gymnadenia conopsea* and *Platanthera bifolia*.

(vi) Using aerial and satellite imagery, provided by the EMS service Copernicus, the extent of the removed ligneous vegetation areas (Table 1 [32]; Figure 13) was quantified along the riverbed of the Trebbia, Aveto and Nure Rivers, which are part of the regional ecological network. The age of the removed ligneous vegetation exceeded 20 years. The table does not include the removed vegetation areas produced by hillslope-debris flows, because of their limited extent. The consequences on the biodiversity of these erosive and depositional effects were manifested along the minor and main river network. The riparian woody vegetation that develops along the main Apennine watercourses is in most cases assignable to Habitats of Community Interest. In particular, the shrub-willow formations are attributable to the Habitat 3240, "Alpine rivers and their ligneous vegetation with *Salix eleagnos*", the *Alnus incana* woods to the priority Habitat 91E0*, "Alluvial forests with *Alnus glutinosa* and *Fraxinus excelsior* (*Alno-Padion, Alnion incanae, Salicion albae*)", and the *Salix alba*, *Populus alba* and *P. nigra* forests to the Habitat 92A0, "*Salix alba* and *Populus alba* galleries". All these riparian formations are frequently subjected to destruction by intense floods but they have a natural capability to rapidly recover.

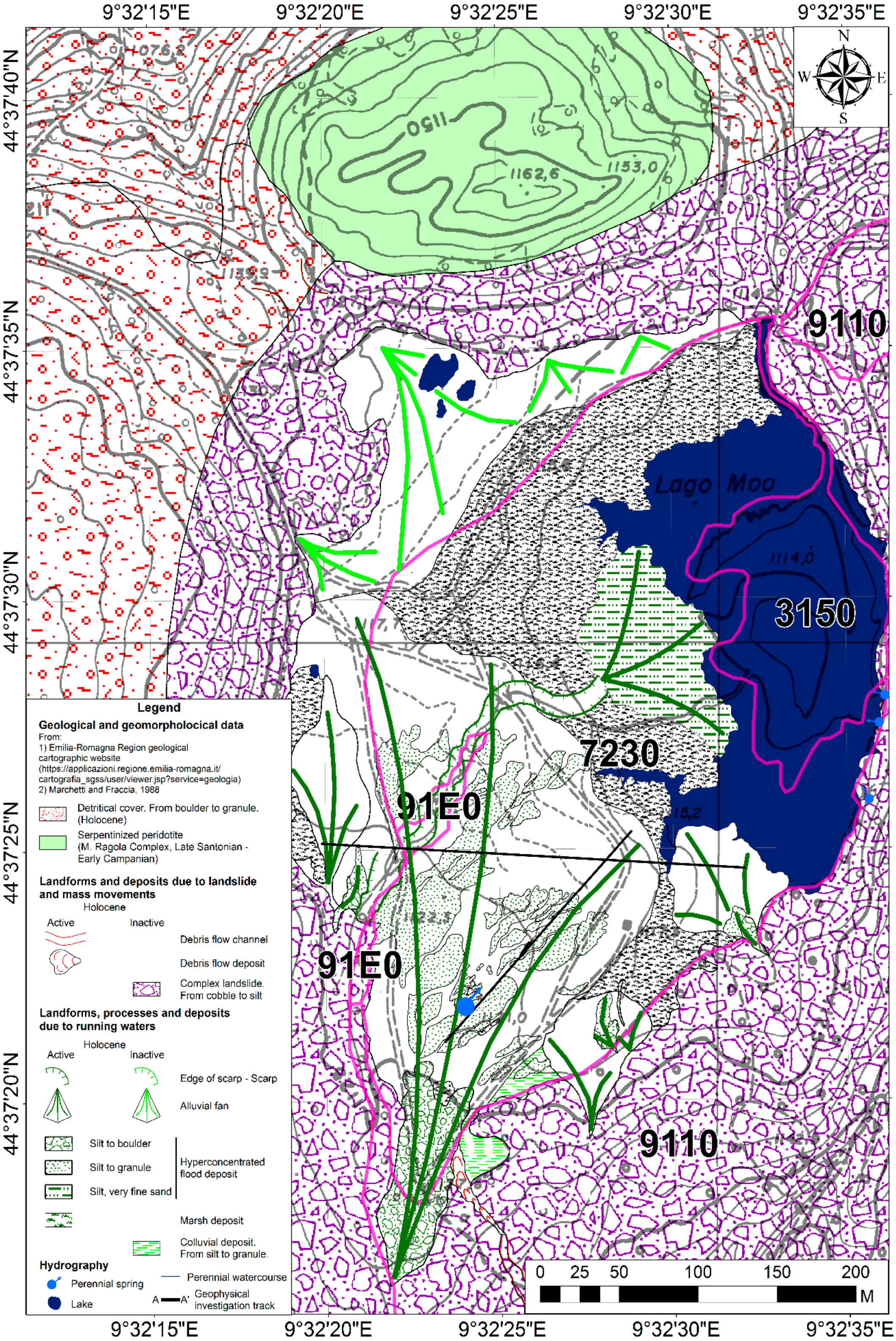


Figure 7. Original detailed geomorphological mapping of the flood deposits, related to the habitats of the Natura 2000 network (purple line), IT4020008 site code.

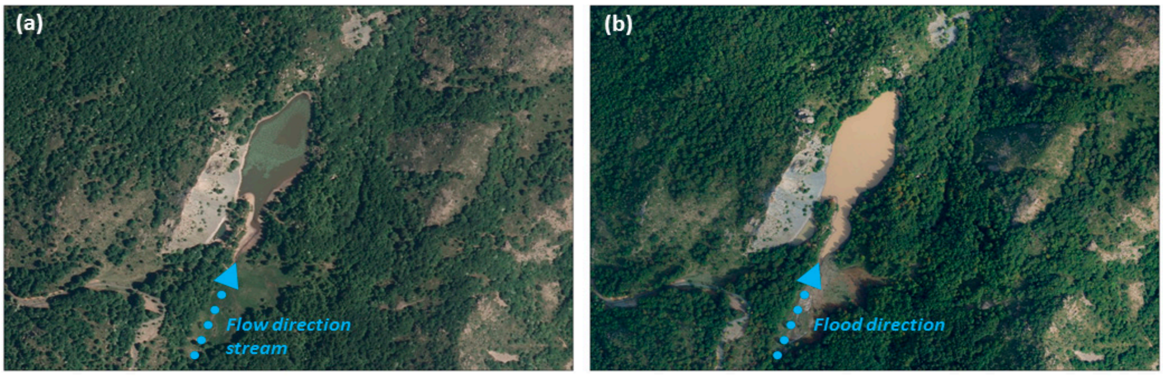


Figure 8. Satellite imagery before (**a**) and after (**b**) the high-discharge flood in September 2015. Note the solid transport that has long hit Lake Bino (IT 4020008 site code). Note the occurrence of *Nuphar lutea* during summer.

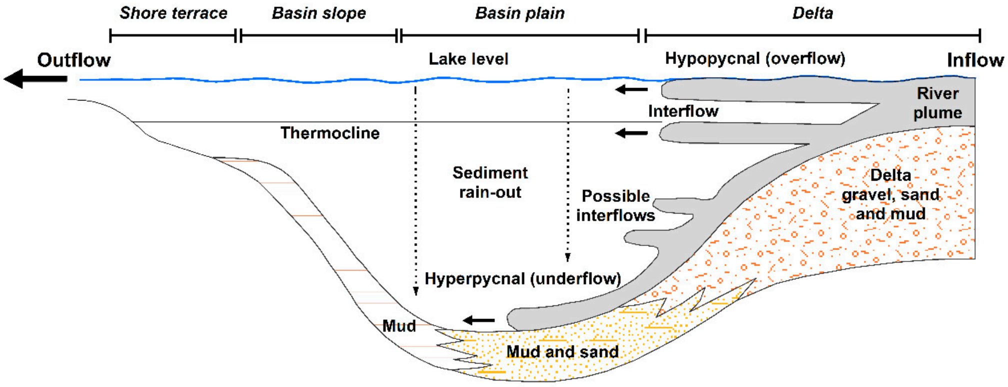


Figure 9. Conceptual model of sediment dispersal and associated deposits within a lake basin dominated by clastic sedimentation. Figure not to scale, modified from [30].

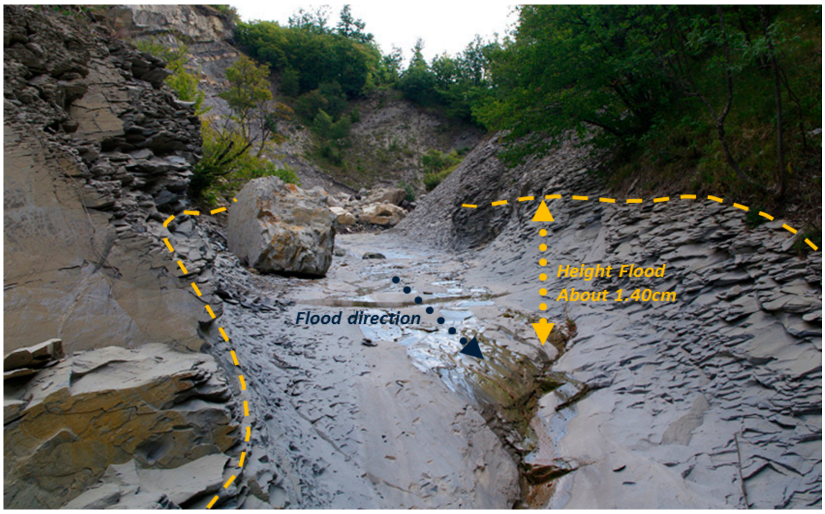


Figure 10. Example of erosive forms in the riverbed. The alluvial deposits that filled the channel before the event were completely removed, causing the exposure of the marly substrate (Late Cretaceous Helmintoid Flysch).

Figure 11. Examples of high-discharge flow deposits, emplaced in a narrow riverbed tract.

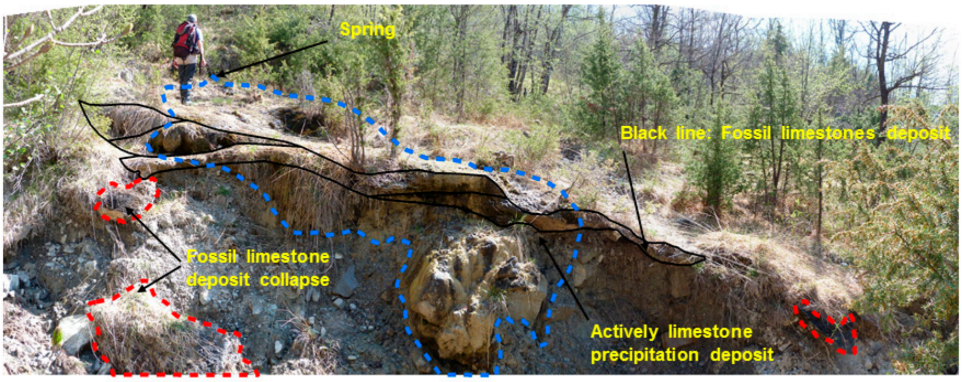


Figure 12. Example of limestone-precipitating springs (LPS) distributed along slopes to forming limestone clusters above the rivulets and streams of nearby springs.

Table 1. Areas with eroded vegetation along the Trebbia, Nure and Aveto Rivers (data source: [32]).

Streams	Eroded Vegetation Areas (Hectares)	% with Vegetation Older Than 20 Years (Hectares)
Trebbia–Aveto	84	78
Nure	77	80

(vii) [33] shows a possible effect of extreme-rainfall events on organisms living in selected spring habitats in the Northern Apennines, in particular as far as the occurrence of *Niphargus* species (amphipod crustaceans) is concerned. Figure 14 refers to a case study in the Parma Apennines (western sector of the northern Apennines), where the Fontanarezza-spring discharge was measured from 1 May 2016 to December 2017. During this period, a severe drought affected the Emilia-Romagna Region, with peak effects occurring in the westernmost provinces. Discharge-rates monitoring revealed an absolute minimum value, corresponding to the beginning of the drought in October 2016. Since then, discharge never recovered the peak values recorded before the drought, in spite of the occurrence of some intense rainfalls. Moreover, the Fontanarezza monitoring pointed out water-supply criticalities at least four months earlier than in lowland areas of the Emilia-Romagna Region, where a drought emergency was declared in June 2017. This points to spring discharge monitoring as a powerful tool applied to early-warning systems of regional droughts. The correspondence between main precipitation peaks, flow-rate increases, and occurrences of depigmented, stygobiontic living species of niphargid amphipods, identified as *Niphargus* sp. aff. *puteanus* [34], is clearly recognizable in Figure 14.

According to the conceptual hydrogeological model described in [35,36] we hypothesize that the increased *Niphargus* sp. aff. *puteanus* occurrences in the springhead are due to enhanced flow rates, mainly caused by the sudden increase in hydraulic load due to the massive input of newly-infiltrated waters in the parent aquifer. This abrupt increment and the subsequent pressure wave likely favor the mobilization of large volumes of deeper and more mineralized waters, along with the displacement of the hypogean organisms (Figure 15).

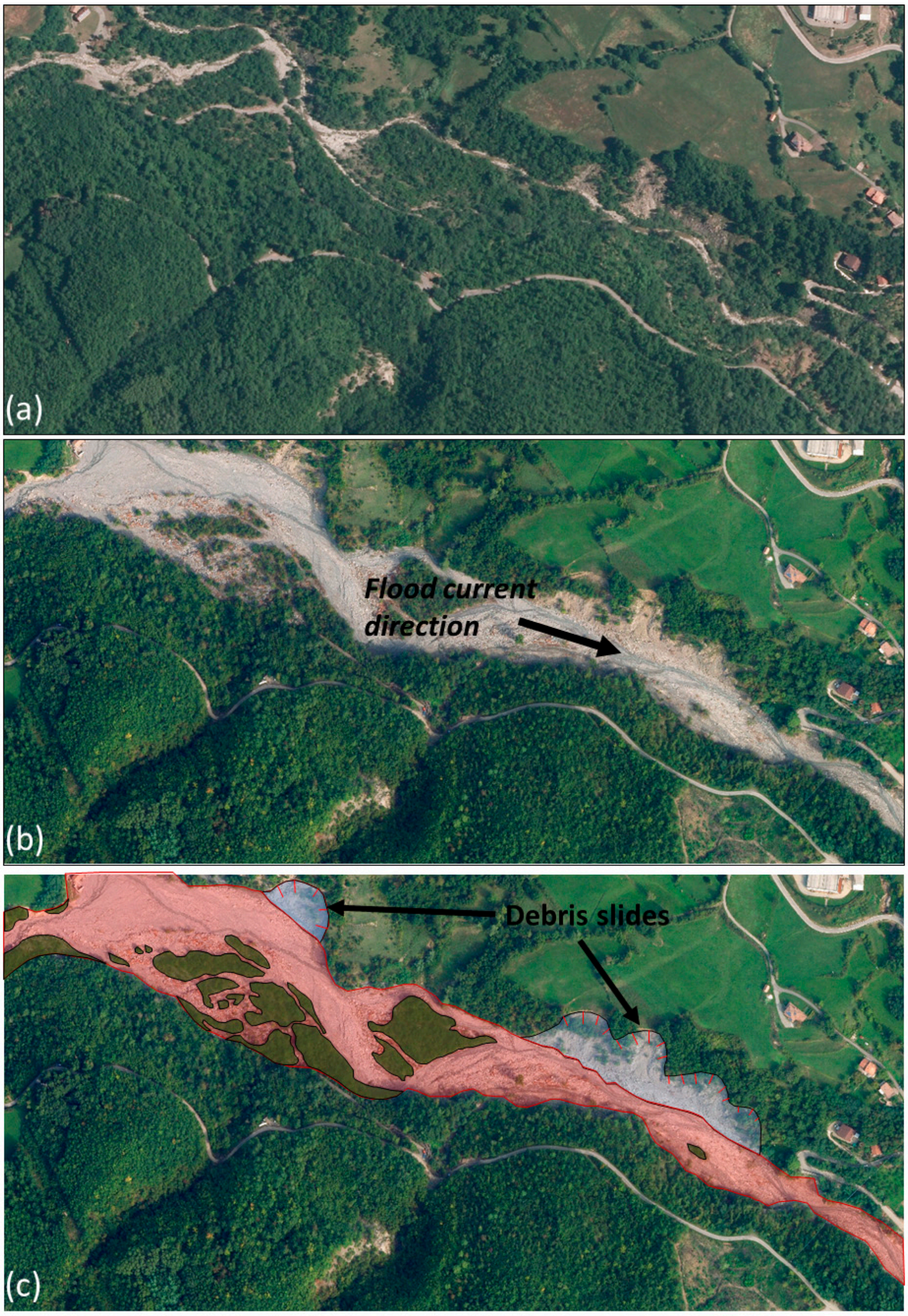


Figure 13. Satellite imagery of the Nure River before (**a**) and after (**b**) the high-discharge flood in September 2015. (**c**) Example of removal of the ligneous vegetation cover in the streambed of the Nure River, eroded areas are in red.

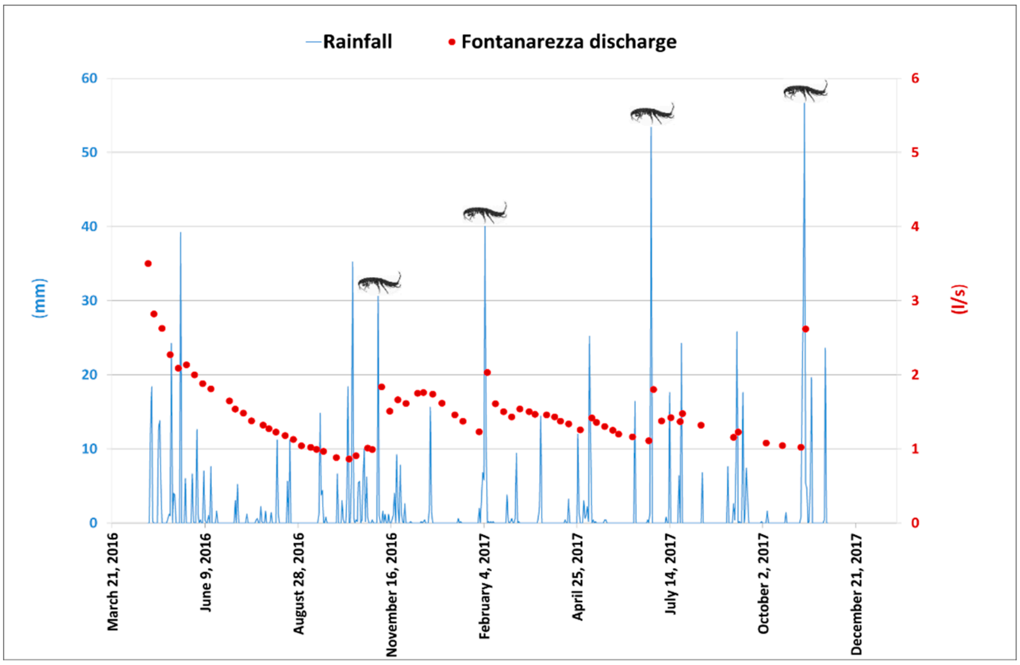


Figure 14. Flow rate (red dotted line), *Niphargus* occurrences, and precipitation data (blue bar histogram) obtained from perennial springs, monitored in the Northern Apennines, modified from [33].

Figure 15. Example of high concentration of *Niphargus* sp. aff. *puteanus* observed at the springhead. This abundant presence of *Niphargus* was related to the pressure wave induced by the extreme event of 5 November 2016. The observation was made only three days later. The spring had been visited also shortly before the extreme rainfall (31 October 2016), and these organisms were not present. The size of this depigmented species ranges from a minimum of 3 mm to a maximum of 8 mm.

4. Discussion

The detailed meteorological analysis of the storm led us to consider the 3 h accumulation rain field as the most relevant for high-discharge and hillslope-debris flow triggering. This time interval is short enough to describe the intensity peak of macro precipitating structures (avoiding excessive smoothing), and at the same time it is long enough to allow the development of the debris and stream-flow processes described. With this type of soil cover (mostly wood and grassland), a shorter time interval (say 1 h) might possibly not be sufficient to get the degree of saturation into the soil and to start the debris/mud flow. The very good match between the 3 h peak intensity and the distribution of high-discharge and hillslope-debris flow support the hypothesis. The 3 h interval further emphasizes the meteorological event with respect to its overall duration of 6 h.

We consider this quick and easy approach a foundation for further, more in-depth studies, because there are other factors besides acclivity that control the activation of high-discharge and hillslope-debris flow (e.g., vegetation cover, fires, type and amount of debris).

The ecological impact of extreme precipitations is almost always overlooked. Hillslope-debris flows and high-discharge flows induced by extreme precipitation affecting forested mountain watersheds will increasingly be an important issue for their impacts on aquatic ecosystems, since these are high energy flows that can cause drastic changes in a short time, and are capable of mobilizing and entraining large amounts of sediment and coarse woody debris in the catchment areas that are consequently fed into the river drainage.

Instrumental as well as historical [2] data clearly suggest that extreme rainfall events are increasing in the northern Apennines, in good agreement with the international literature [6–12]. This trend will, unfortunately, most likely be confirmed, and our case studies/observations suggest that there might be consequences also for the biodiversity, structure, and function of mountain freshwater ecosystems.

The effects on the typical riparian vegetation, and in particular on shrub formations and riparian woods (habitats 3240, 91E0 * and 92A0) are well-known and do not involve particular problems as regards to the loss of biodiversity. In fact, these formations are intrinsically linked to river dynamics, and in most cases can cope also with intense flood phenomena that involve erosion or debris accumulation. In the case of extreme events, which involve the destruction of vast areas occupied by these formations, they are in any case able to recover in a short time when the conditions are favorable. The existence of the 3240 habitat is, moreover, conditioned precisely by active river dynamics that prevent the evolution of riparian shrubs and woods towards the formation of a more mature hygrophilous forest [37]. Extreme alluvial events entail a rejuvenation of riparian ecosystems, bringing succession back to the most precocious evolutionary stages. The portions of the riverbed modified by erosion and debris accumulation can be colonized by pioneer herbaceous formations. At higher elevations the development of assemblages of herbaceous or suffrutescent pioneering-plants colonizing gravel beds of streams is favored. These vegetation types are attributable to the habitat 3220, "Alpine rivers and the herbaceous vegetation along their banks", locally represented by the association *Epilobio dodonaei-Schrophularietum caninae*. At lower altitudes the gravel beds can be colonized by amphibious short annual vegetation with *Cyperus* spp. (habitat 3130, "Oligotrophic to mesotrophic standing waters with vegetation of *Littorelletea uniflorae* and/or *Isoeto-Nanojuncetea*), or annual pioneer nitrophilous vegetation with *Xanthium italicum* and *Bidens* spp. (habitat 3270, "Rivers with muddy banks with *Chenopodium rubri* p.p and *Bidention* p.p. vegetation" [38]). Extreme flood events can thus alter or destruct important river ecosystems such as riparian forests and shrubbery. However, these negative effects are compensated by the increase in phytocenotic diversity and by the number of habitats that can colonize the riverbed. Obviously, this compensation is possible only in the long term.

As previously stated, high-discharge flood events can pose a threat to the rhizophytic vegetation of mountain tarns (e.g., Lago Bino), but only in the very long term. The gradual deposition of inorganic sediment can instead favor the colonization by helophytes (*Typha* spp., *Sparganium* spp., *Schoenoplectus* spp., *Phragmites australis*) in the shallow areas, and therefore trigger the dynamic processes of autogenous succession that precede bog formation.

The most negative impacts on biodiversity are on LPS sources and on peat bogs. In the first case, the erosion of the slopes leads to landslides and to the destruction of existing LPS and of their hygrophilous vegetation (habitat 6410), with rare plants such as orchids. In the second case, the alluvial flood deposit due to the movement of a high-discharge flow into a peat bog (habitat 7230) leads to a strong alteration of the ecosystem. In particular, the wettest aspect of the habitat, characterized by rare hygrophilous vascular species, and in general by a greater naturalistic value, is the most sensitive to the impact caused by the flood deposit. These alterations are hardly reversible, also in the long term, due to the widespread drying of peatlands caused by climate change [39].

In general, the effects of extreme events on inland-waters' ecosystems are highly context-dependent, ranging from deleterious to beneficial, and are strongly conditioned by event magnitude, extent, and timing relative to life cycles of the main species involved (e.g., [13]). Hydrologic extremes can even be beneficial to ecosystems. It was, for example, shown that they play a major structuring role in river ecology across Australia [40]. Extreme events can aggravate the effect of multiple stressors, with potentially dire effects on freshwater environments. For example, high flows can mobilize nutrients, sediment and toxic chemicals, and favor invasive-species dispersal [40,41]. Great care must be applied also in the realization of mitigation and restoration infrastructures because some adopted measures can, at times, worsen the situation. For instance, land-use change and channelization compromise flood refugia and constrain recolonization pathways [41]. Therefore, it is important that extreme-precipitation effects recovery management strives to minimize additional damage to habitat availability and connectivity [42]. The presence and persistence of habitats (e.g., springs) and microhabitats (e.g., surficial sediments overlying karstic bedrock in temporary-drying streams [43]) capable of functioning as effective refugia is of pivotal importance in allowing biota resilience after extreme hydrologic events.

We therefore highlight the necessity of further studies to understand in more depth and characterize these effects to be able to include appropriate mitigation measures in environmental planning and stewardship.

5. Conclusions

Here we provide relevant indications on where extreme-precipitation events are most likely to strike, on the main ground effects and on possible impacts on mountain freshwater ecosystems. We showed that it is possible to identify the most critical points of a geographic or administrative area through the combination of meteorological and geological-geomorphological data.

In particular, the meteorological data allow the identification of geographical areas that have a strategic position with respect to the dominant atmospheric flow associated with heavy-precipitation events. In addition, relevant and appropriate geological, geomorphological, vegetation characteristics and basin size (<2 km^2) allowed us to clearly identify high-intensity-precipitation thresholds triggering hillslope-debris flows/high-discharge flows.

As documented in the results, it is of great importance to safeguard the integrity and naturalness of the ecological dynamics of the surface and groundwater systems of mountain environments, which are increasingly exposed to the effects produced by extreme events that could compromise their functionality.

Furthermore, changes in the hydrological cycle of the Alps and Apennines are not only due to extreme events that increase in frequency and intensity [2–12], but also to heat waves and droughts, which are increasingly intense and prolonged, respectively. The combined action of these two factors can and will have important effects on the biodiversity of mountain surface and groundwater environments.

This ongoing trend requires the activation and reinvigoration of studies, environmental monitoring, management measures, and popularization and outreach actions for an improved understanding on how to reduce and mitigate the effects of extreme climatic events.

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