Landslides
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Impact of event landslides on road networks: a statistical analysis of two Italian case studies

Abstract Despite abundant information on landslides, and on landslide hazard and risk, in Italy, little is known on the direct impact of event landslides on road networks and on the related economic costs. We investigated the physical and economic damage caused by two rainfall-induced landslide events in Central and Southern Italy, to obtain road restoration cost statistics. Using a GIS-based method, we exploited road maps and landslide event inventory maps to compute different metrics that quantify the impact of the landslide events on the natural landscape and on the road networks, by road type. The maps were used with cost data obtained from multiple sources, including local authorities, and specific legislation, to evaluate statistically the unit cost per metre of damaged road and the unit cost per square metre of damaging landslide, separately for main and secondary roads. The obtained unit costs showed large variations which we attribute to the different road types in the two study areas and to the different abundance of landslides. Our work confirms the long-standing conundrum of obtaining accurate landslide damage data and outlines the need for reliable, standardized methods to evaluate landslide damage and associated restoration costs that regional and local administrations can use rapidly in the aftermath of a landslide event. We conclude recommending that common standardized procedures to collect landslide cost data following each landslide event are established, in Italy and elsewhere. This will allow for more accurate and reliable evaluations of the economic costs of landslide events.

Keywords Landslide · Landslide event · Landslide damage · Road network · Cost estimation · Economic impact · Italy

Variables and acronyms

Variables and acronyms used in text.

Variable	Description	Unit
A_S	Area of study area	km^2
A_L	Area of an event landslide	m^2
A_{LT}	Total area of the event landslides	m^2
$A_{L\cap R}$	Area of event landslides intersecting a road	m^2
$A_{L\cap RT}$	Total area of event landslides intersecting roads	m^2
C	Total road cost	€
$\overline{C}$	Average road cost	€
$\overline{C}_L$	Average unit cost per square metre of damaging landslide	€/m^2
$\overline{C}_R$	Average unit cost per metre of damaged road	€/m
d_L	Landslide density, N_{LT}/A_S	#/km^2
D_L	Density of landslide area, A_{LT}/A_S	–
D_{MR}	Density of main roads (MR), L_{MR}/A_S	km/km^2
D_{ODR}	Density of official damaged roads (ODR), L_{ODR}/A_S	km/km^2
D_{RT}	Density of roads, L_{RT}/A_S	km/km^2
D_{SR}	Density of secondary roads (SR), L_{SR}/A_S	km/km^2
N_{ODR}	Number of official damaged roads (ODR) intersected by event landslides	#
L_{MR}	Total length of MR	km
L_{ODR}	Total length of ODR	km
L_{RD}	Length of a road damaged by an event landslide	m
L_{RDT}	Total length of roads damaged by the event landslides	m
L_{RT}	Total road length	km
L_{SR}	Total length of SR	km
M_L	Magnitude of landslide event, log (N_{LT})	m
N_{CPX}	Number of complex landslides	#
N_{DF}	Number of debris flows	#
N_{EF}	Number of earth flows	#
N_{GE}	Number of gully erosions	#
N_{LT}	Total number of event landslides	#
$N_{L\cap R}$	Number of event landslides intersecting roads	#
$N_{R\cap L}$	Number of roads intersected by event landslides	#
N_{RF}	Number of rock falss	#
N_{ES}	Number of earth slides	#
N_{SEF}	Number of slide–earth flows	#
N_{SS}	Number of soil slides	#
N_{ODR}	Number of ODR	#
N_{UL}	Number of undetermined landslides	#
V_L	Volume of an event landslide	m^3
V_{LT}	Total volume of the event landslides	m^3
Acronym	Description	
ANCE	Associazione Nazionale Costruttori Edili (Italian National Association of Construction Contractors)	
AVI	Aree Vulnerate Italiane (areas affected by landslides or floods in Italy)	
CRESME	Centro Ricerche Economiche, Sociologiche e di Mercato (Centre for Economic, Sociological and Market Research)	

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CTR	Carta Tecnica Regionale (Regional Technical Map)
DPCM	Decreto del Presidente del Consiglio dei Ministri (Prime Minister Decree)
GIS	Geographical information system
IFFI	Inventario dei Fenomeni Franosi in Italia (Inventory of Landslides in Italy)
MR	Main road
ODR	Officially damaged road
OPCM	Ordinanza del Presidente del Consiglio dei Ministri (Prime Minister Order)
SR	Secondary road
TRN	Total road network map

Introduction

In Italy, geohydrological hazards, including landslides, cause serious economic damage and represent a severe threat to the population (Salvati et al. 2014). In this country, rich information exists on landslides, their physical characteristics and consequences, while little is known on their economic impact.

The damage caused by landslides (and other natural hazards) in Italy has been and is currently being fixed primarily using public resources, often following specific legislation. As a result, the few available landslide cost estimates are given in reports and documents produced by local, regional and national government administrations and authorities. Lack of a rigorous strategy and of a single and accurate method to collect damage and cost information, combined with a complex network of agencies involved in reconstruction activities and cost reimbursement, make the collection of reliable landslide cost data challenging. In addition, the long periods required to complete restoration activities following a landslide event result in supplementary costs that are seldom accounted, making it even more difficult to obtain comprehensive landslide cost estimates. Lack of a single method to collect damage costs also hampers the efforts of regional and local administrations that immediately after a landslide event have to obtain reasonably accurate damage estimates to request the declaration of the state of emergency in their territory and emergency funding to reimburse the incurred and the foreseen restoration costs.

Here, we investigate the economic impact of landslides triggered by two rainfall events in Central and in Southern Italy. We focus on the damage caused by landslides to the road network, and we use the case studies to test a general methodology to assess statistically the direct economic impact of landslides on the road networks. In the first case, we analyse the impact of landslides caused by an intense rainfall event that hit the coastal area of the Messina province, Sicily, Southern Italy, on 1 October 2009. In the second case, we study the impact of landslides occurred as a result of prolonged rainfall in two mountainous municipalities, Acquasanta Terme and Roccafluvione, in the Marche region, Central Italy, in November and December 2013. For both events, we first evaluate the physical impact of the event landslides on the road networks. Next, we quantify the cost per unit length of damaged road and per unit area of damaging landslide. To evaluate the landslide impact on the road network, we use accurate event landslide inventory maps prepared shortly after the events, road network maps and cost data obtained from multiple sources available from local authorities and national administration offices. The proposed methodology allowed us to estimate the average cost per unit length of damaged road and per unit area of damaging landslide, after intense and prolonged rainfall events that triggered more than a thousand landslides. The obtained average costs can be used by local administrations and authorities for a preliminary assessment of the costs of the damage caused by landslides.

Background

Different classifications of costs produced by natural hazards exist in the literature. The classifications are based on various types of information, including the type of the event, the category of the costs and the extent of the geographical area. Meyer et al. (2013), in a recent review of methods to assess the costs of natural hazards, classified the costs as direct, business interruption, indirect, intangible and risk mitigation costs. Cost assessments may be estimated after an event (*ex post*) or considering potential future events (*ex ante*). *Ex post* assessments are the most common type of evaluations in the literature and aim at quantifying incurred economic damage to inform local, regional or national governments, stakeholders and business and to provide quantitative information useful to determine compensations or to decide on the possible levels of economic support (Karunasena and Rameezdeen 2010; McCarty and Smith 2005; Sächsische Staatskanzlei 2003). *Ex ante* cost assessments are less frequent in the literature and are usually conducted to support governmental and administrative decision-making and to decide among risk mitigation options and adaptation strategies. Hilker et al. (2009), using the Swiss flood and landslide damage database that includes information on direct economic impact, estimated the total cost of natural geohydrological events in Switzerland, from 1972 to 2007. Boonyanuphap (2013), working in northern Thailand, used interviews with stakeholders involved in land rehabilitation, to execute a cost benefit analysis. The analysis was performed comparing the net welfare gain of different land rehabilitation measures after landslide events.

Exploiting a landslide inventory map, a susceptibility model and information obtained through interviews, Vranken et al. (2013) proposed a methodology to estimate the direct and indirect damage caused by landslides at the regional scale in the Flanders, Belgium. Estimates were calculated differently for private properties and public infrastructures. For private properties, losses to land, buildings and production were considered, whereas for public infrastructures, the costs of prevention measures and restoration actions were estimated. Heam et al. (2008) used a landslide inventory map to estimate damage restoration costs along the national road network in the People's Democratic Republic of Lao. The authors considered direct and indirect costs, including the cost due to road disruptions and their consequent temporary interruption, and the related environmental and social costs. Costs to improve slope stability in the design and construction phases were compared to potential benefits for ordinary and emergency maintenance. Klose et al. (2015) investigated direct costs of landslides along transportation routes in Lower Saxony, Germany, between 1980 and 2010, and proposed a methodology for an *ex post* assessment based on the compilation, modelling and extrapolation of the landslide losses at different spatial scales over time. Using a landslide database, a regional landslide susceptibility model and cost data, the average annual cost per kilometre of highway was ascertained, for two case studies.

In Italy, abundant information is available on landslide events and their consequences. The National Research Council's Aree Vulnerate Italiane (AVI—areas affected by landslides or floods in Italy) project, an archive inventory of historical landslide (and flood) events in Italy (Guzzetti et al. 1994), lists information on more than 32,000 landslides from 1918 to 2001 (Guzzetti and Tonelli 2004). Information on the type and magnitude of damage for a subset of the AVI inventory is available in SICI, the Information System on Hydrological and Geomorphological Catastrophes in Italy (http://sici.irpi.cnr.it/). The national inventory of landslides in Italy (Inventario dei Fenomeni Franosi in Italia (IFFI), Trigila et al. 2010, 2015) has mapped 528,903 landslides, covering a total area of 22,176 km^2 (7.3% of national territory). For about 8% of the mapped landslides, information on the type of damage is available. Analysis of the IFFI database revealed that roads are the single category of vulnerable elements most frequently affected by damaging landslides.

The first attempt to evaluate economic costs of geohydrological (i.e. landslide and flood) events in Italy was conducted by Catenacci (1992) for the period 1944–1990. When landslides occurred together with large flood events, the author reported a single economic figure, classifying the events as "geohydrological". This made it impossible to separate the cost due to landslides from the cost due to floods. Following Catenacci (1992), and based on official amounts of public money spent after natural disasters, a report prepared jointly by the Italian National Association of Construction Contractors (Associazione Nazionale Costruttori Edili (ANCE)) and the Centre for Economic, Sociological and Market Research (Centro Ricerche Economiche, Sociologiche e di Mercato (CRESME)) (ANCE-CRESME 2012) quantified the cost of geohydrological hazards in Italy at 61.5 billion € (2011), for the 69-year period 1944–2012. This is an average cost of 0.9 billion € per year.

Materials

To devise and test our new cost estimation method, we exploit two recent landslide events in two study areas in NE Sicily, Southern Italy, and in the Marche region, Central Italy (Fig. 1). The two study areas differ for their spatial extent, terrain elevation and morphology, geology, prevalent landslide types and distribution and abundance of the vulnerable elements (i.e. the roads). The two case studies were chosen because of the availability of landslide event inventory maps, the road network maps and the cost data. The latter in Italy are typically available in different ways: (1) as cost estimations produced by local authorities and (2) as money allocated by law. We used the first for the 2013 Marche case study and the second for NE Sicily event. For both the areas, official damage road (ODR) lists were also provided by official documents. All the information that were collected giving costs (estimated by local authorities or allocated by law) related to landslide damage were associated to a unique road and organized in a database.

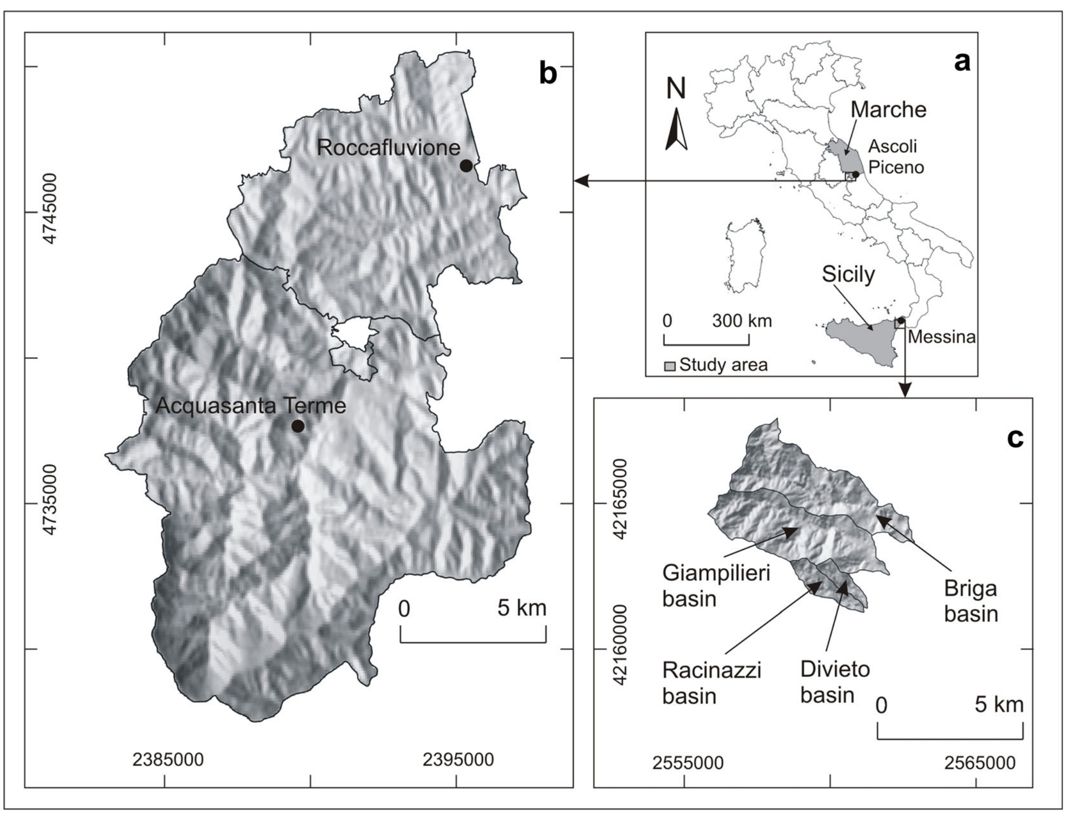

Fig. 1 Location and morphology of the study areas. **a** Index map. **b** Terrain morphology in the Acquasanta Terme and the Roccaluvione municipalities, Marche, Central Italy. **c** Terrain morphology in the Briga, Giampilieri and Divieto catchments, NE Sicily, Southern Italy. Maps are in the EPSG 3004 geographical reference system

NE Sicily case study

On 1 October 2009, a very intense rainfall event hit the Messina province, NE Sicily, producing inundations and triggering hundreds of landslides that caused 31 deaths, seven missing persons and hundreds of injured people (http://polaris.irpi.cnr.it). The intense rainfall event resulted in a maximum cumulated rainfall of 225 mm in 7 h, recorded at the Santo Stefano di Briga rain gauge (Fig. 2c) (Regione Siciliana, Centro Funzionale Regionale 2009). The rainfall caused inundations and a large number of soil slides and debris flows (Ardizzone et al. 2012) in an area of approximately 60 km^2 (Mondini et al. 2011). For our study, we focus on the area where landslides were most abundant and damaging, and specifically in the Briga, Giampilieri, Divieto and Racinazzo coastal catchments, covering a total study area A_S = 22 km^2 (Fig. 1c, Table 1). In this area, intense rainfall triggered a total of 1480 landslides (Table 1) (Ardizzone et al. 2012).

The event landslides affected roads, underpasses and the ground floors and basements of buildings in urban areas. The A18 Messina–Catania highway, the SS-114 state road 114 and the national railway connecting Messina to Catania were all disrupted by the landslides.

After the event, specific legislation was issued by the national government. First, the Prime Minister Order no. 3815/09 (*Ordinanza del Presidente del Consiglio dei Ministri*, OPCM 3815/09) of 2 October 2009 declared the "state of emergency" for the Messina Province and listed urgent civil protection works. Next, extra allocation was stated with OPCM 3865/10. The Work Plan included in the OPCM 3815/09 (updated on 12 September 2012) allocated a total amount of 193,688,223 € for risk mitigation, restoration of the hydraulic functionality of rivers and torrents, debris removal and restoration of roads, railways and public buildings (http://opcm3815.altervista.org/3815.html).

Event landslide inventory map

For the study area, an accurate event landslide inventory map was prepared by Ardizzone et al. (2012), at 1:10,000 scale, through field surveys and the visual interpretation of pre-event and post-event, stereoscopic and pseudo-stereoscopic aerial photographs. Figure 3a, modified from Ardizzone et al. (2012), shows 1480 event landslides (Table 1): 1071 were classified as debris flows, 30 as earth slides (Cruden and Varnes 1996; Hungr et al. 2014), 375 as gully erosion (areas with superficial and channelled erosion affecting the surface deposits) and 3 landslides remained unclassified. Figure 4 portrays examples of the mapped landslides.

Road network map

We obtained a map of the road network for the study area from a commercial provider, in vector format. We classified the single roads in two classes: (i) main public roads (MRs), including highways (toll roads), state and provincial roads, and (ii)

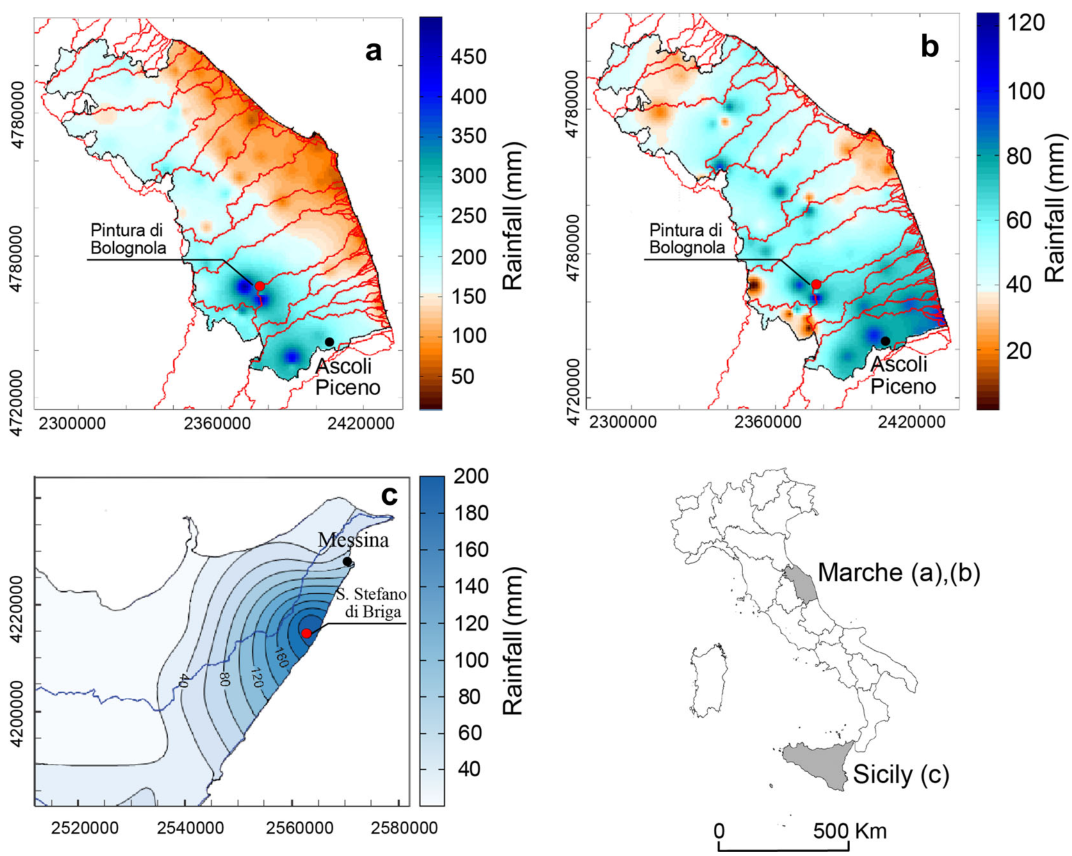

Fig. 2 Distribution of the cumulated rainfall for the NE Sicily and the Marche region test cases. **a** Cumulated rainfall in the Marche region from 12:00 (UTC+1) on 10 November 2013 to 24:00 (UTC+1) on 13 November 2013 (modified after Regione Marche, Centro Funzionale per la Meteorologia, l'Idrologia e la Sismologia 2013a). **b** Cumulated rainfall for the Marche region from 24:00 (UTC+1) on 25 November 2013 to 24:00 (UTC+1) on 1 December 2013 (modified after Regione Marche, Centro Funzionale per la Meteorologia, l'Idrologia e la Sismologia 2013b). **c** Twenty-four hour cumulated rainfall of 1 October 2009 in NE Sicily (modified after Regione Siciliana, Centro Funzionale Regionale 2009). Maps are in the EPSG 3004 geographical reference system

Table 1 Descriptive statistics of event landslides for the NE Sicily and the Marche case studies

Metric	Unit	NE Sicily	Marche
A_S	km^2	22	198
N_{ES}	#	30	289
N_{SS}	#	0	424
N_{SEF}	#	0	328
N_{EF}	#	0	371
N_{DF}	#	1071	0
N_{GE}	#	375	0
N_{RF}	#	0	17
N_{CPX}	#	0	9
N_{UL}	#	3	0
N_{LT}	#	1479	1438
M_L	–	3.17	3.16
A_{Lmin}	m^2	1.9×10^0	1.6×10^0
A_{Lmax}	m^2	4.5×10^4	2.2×10^4
A_{Lavg}	m^2	1.0×10^3	4.8×10^2
A_{LT}	m^2	1.5×10^6	7.7×10^5
V_{Lmin}	m^3	8.0×10^{-2}	2.1×10^{-1}
V_{Lmax}	m^3	1.3×10^5	1.5×10^5
V_{Lavg}	m^3	1.1×10^3	1.3×10^3
V_{LT}	m^3	1.2×10^6	1.8×10^6
D_L	–	0.068	0.004
d_L	#/km^2	67.3	7.3

A_S (km^2) is the size of the study area. N_{ES} (#), N_{SS} (#), N_{SEF} (#), N_{EF} (#), N_{DF} (#), N_{GE} (#), N_{RF} (#), N_{CPX} (#) and N_{UL} (#) are, respectively, the number of earth slides, soil slides, slides-earth flows, earth flows, debris flows, gully erosions, rock falls, complex slides and undetermined landslides. N_{LT} (#) is the total number of landslides. M_L (–) is the landslide event magnitude estimated as log (N_{LT}) following Malamud et al. (2004). A_{Lmin} (m^2), A_{Lmax} (m^2), A_{Lavg} (m^2) and A_{LT} (m^2) are the minimum, maximum, average and total event landslide areas, respectively. V_{Lmin} (m^3), V_{Lmax} (m^3), V_{Lavg} (m^3) and V_{LT} (m^3) are the minimum, maximum, average and total event landslide areas, respectively. D_L (–) is the density of landslide area, calculated dividing A_{LT} (in km^2) by A_S (in km^2). d_L (#/km^2) is landslide density, calculated dividing N_{LT} (#) by A_S (in km^2)

secondary public roads (SRs), encompassing municipal roads and country roads. We calculated a total road length of 128.45 km, including 23.72 km (18%) of MR and 104.73 km (82%) of SR (Table 2).

Cost data

We obtained cost data from the mentioned Work Plan included in the OPCM 3815/09, (updated on 12 September 2012). The Work Plan provides economic information for five MRs (Table 3) corresponding to the ODR. The Work Plan does not provide information on SR. In some cases, the cost data were aggregated (e.g. by including in a single item the restoration costs of a damaged road together with the restoration cost of a neighbouring damaged public building). For this reason, we manually selected only data that unambiguously referred to a single MR, but it was impossible to associate to each main road the single damage and the exact description of the restoration works. We acknowledge that this has resulted in an underestimation of the economic resources allocated for the restoration of the damaged MR in our study area. Figure 3b shows the ODR and all the other public roads (MR and SR) in the Briga, Giampilieri, Divieto and Racinazzo coastal catchments. The 12.79 km of ODR represents 53.92% of the total length of the MR in the study area (Table 2). The cost for fixing the five ODRs totalled 26,140,736 €, corresponding to an average cost per road of 5,228,147 € and per kilometre of 2,043,841 €.

Marche case study

In November and December 2013, prolonged and intense regional rainfall events caused abundant and widespread landslides throughout the Marche region, Central Italy, with more abundant landslides in the southern part of the region. For our experiment, we focus on two mountain municipalities, Roccafluvione and Acquasanta Terme, in the Ascoli Piceno Province, Southern Marche, covering collectively 198 km^2 (Fig. 1a, Table 1).

In the 4-day period from 10 to 13 November 2013, heavy rainfall occurred in the area, with a maximum cumulated rainfall of 499 mm recorded at Pintura di Bolognola (Fig. 2a). A few days later, between 25 November and 1 December 2013, the area was affected by heavy snowfall followed by rapid snowmelt (Fig. 2b). Finally, in the 24-h period from 24:00 (UTC+1) on 2 December to 24:00 (UTC+1) on 3 December 2013, a heavy rainfall event struck the southern part of region, with a maximum cumulated rainfall of 129 mm recorded at Pintura di Bolognola. As a result, floods and flash floods occurred along rivers and torrents, and a large number of landslides were triggered, mainly in the region's hilly and mountainous terrain. Most of the landslides affected secondary roads that connect numerous small rural settlements. The landslides caused road interruptions at multiple sites; around 100 people were isolated (Regione Marche, Centro Funzionale per la Meteorologia, l'Idrologia e la Sismologia 2013a, 2013b) and few hundreds were evacuated. The Marche regional government estimated at 398,010,736 € the total amount required to overcome the state of emergency (Dipartimento della Protezione Civile 2014).

Event landslide inventory map

In January and February 2014, we executed reconnaissance field surveys in the municipalities of Acquasanta Terme and Roccafluvione. Each landslide was mapped in the field as a polygon using Google Earth™. Single or pseudo-stereoscopic photographs were taken in the field for each landslide or group of landslides. The preliminary mapping (position, shape, size) of the individual landslides was transferred in a geographical information system (GIS), in vector format, and was checked and enhanced using the field photographs. Overall, we mapped 1438 landslides in the municipalities of Acquasanta Terme and Roccafluvione (Fig. 5a, Table 1), including 289 earth slides, 424 soil slides, 328 slide–earth flows, 371 earth flows, 17 rock falls and 9 complex landslides (Cruden and Varnes 1996; Hungr et al. 2014) (Fig. 6).

During the field surveys, the damage caused by landslides found along roads was mapped and assessed. Adopting a heuristic (qualitative) approach, the different types of damage were organized in three classes (Cardinali et al. 2002; Galli and Guzzetti 2007; Reichenbach et al. 2005): (i) aesthetic (minor),

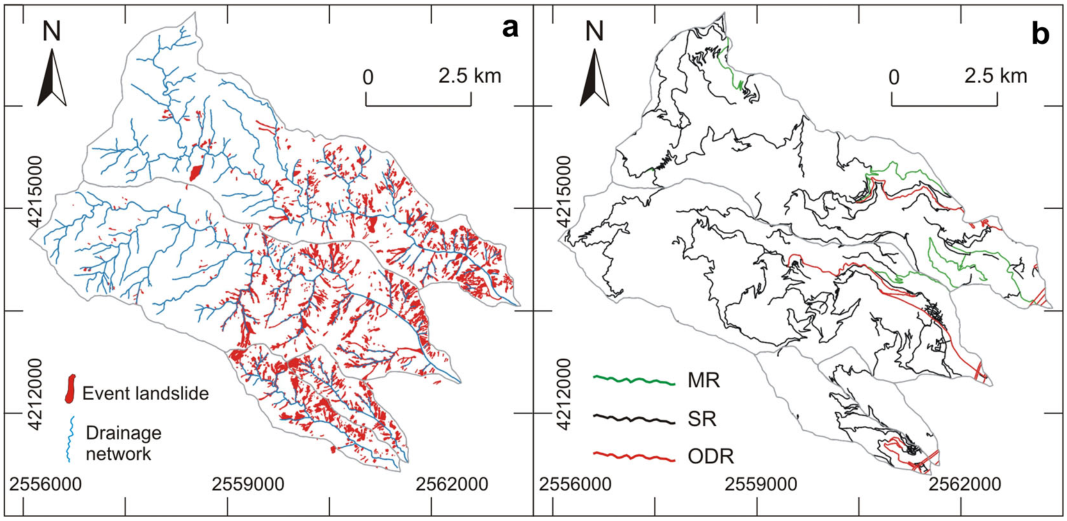

Fig. 3 NE Sicily case study, encompassing the Briga, Giampilieri and Divieto catchments. **a** Landslide event inventory map, modified after Ardizzone et al. (2012). **b** Road network map. *MR* main road (*green*), *SR* secondary road (*black*), *ODR* official damage road (*red*). See text for explanation. Maps are in the EPSG 3004 geographical reference system

where the road functionality was not compromised; (ii) functional (medium), where the road functionality was compromised; and (iii) structural (severe) where the road was severely damaged or destroyed completely. Overall, the damage was assessed as aesthetic at 140 sites, functional at 154 sites and structural at 64 sites.

Road network map

We prepared a digital map, in vector format, of the road network in the Acquasanta Terme and Roccafluvione municipalities. We started from the road information available in CAD format from regional technical maps (CTR), at 1:10,000 scale. For our scopes, the original dataset had a number of limits, including the lack of road classification attributes. To overcome these limitations, we first moved the road geographical information in a GIS environment to produce an ESRI® shapefile of the entire road network. We then updated the road information using 1-m resolution orthophotographs taken in 2012 (http://www.pcn.minambiente.it) and Bing© images taken in July 2011 and August 2012 (http://www.bing.com). Table 2 shows, for the Marche case study, a total road length of 428.14 km, including 99.93 km (23%) of MR and 328.21 km (77%) of SR.

Cost data

A few days after the 2 December rainfall event, the Acquasanta Terme and Roccafluvione administrations restored partially the functionality of their SR to guarantee access to villages, hamlets and rural homes. The two municipalities compiled mandatory reports providing cost information for 110 ODRs, shown in Fig. 5b. The reports gave for each road the restoration cost without associating them information on the type of damage and on the type of restoration works. In terms of road length, the 271.98 km of ODR represents 82.87% of the total length of SR in the two municipalities (Table 2). Restoration costs for the 110 ODRs totalled 11,837,409 €, corresponding to an average cost per road of 107,613 € and an average cost per kilometre of 43,523 €. Costs estimated for restoring a single ODR ranged from 2000 € to 1,230,000 € (average 107,792 €). Figure 7b shows the distribution of the estimated costs and reveals a clear (and expected) bias towards less expensive works, with 60 works (54%) in the lowest cost class (<60,000 €). The box plot in Fig. 7a portrays the distribution of the costs, with 75% of the cost for restoring the SR below 130,000 € and 50% of the costs below 43,000 €. We attribute the relatively low cost of the single restoration works to the type of the damaged roads. The most expensive work

Fig. 4 NE Sicily case study. Examples of rainfall-induced landslides triggered by the intesnse rainfall event. **a** Debris flow. **b** Slide

Table 2 Descriptive statistics for the road networks in NE Sicily and in Marche area

Road metric	Unit	NE Sicily	Marche
L_{RT}	km	128.45	428.14
D_{RT}	km^{-1}	5.8	2.2
L_{MR}	km	23.72	99.93
D_{MR}	km^{-1}	1.1	0.5
L_{SR}	km	104.73	328.21
D_{SR}	km^{-1}	4.8	1.7
L_{ODR}	km	12.79	271.98
D_{ODR}	km^{-1}	0.58	1.37
$ODR_{\#}$	#	5	110
$ODR_{\%}$	%	53.9	82.9

L_{RT} and D_{LT} is, respectively, the length and the density of the total road network map. L_{MR} and D_{MR} is, respectively, the length and the density of the main roads. L_{SR} and D_{SR} is, respectively, the length and the density of the secondary roads. L_{ODR} and D_{ODR} is, respectively, the length and the density of the official damaged roads. $ODR_{\#}$ is the number of official damaged roads. $ODR_{\%}$ is the percentage of official damage roads, in terms of kilometres of roads, estimated with respect to secondary roads for the Marche case study and to main roads for the NE Sicily case study

(estimated at 1,230,000 €) consisted in the restoration of a road hit by nine different landslides.

Landslide and road statistics

A preliminary analysis of the event landslide inventory maps (Figs. 3a and 5a) allowed for general considerations on the impact of the event landslides in the study areas, in terms of size, density and number of damaging landslides.

The size and the cumulated area of the event landslides triggered by the two rainfall events (A_{LT}) were different in the two case studies (Table 1). In NE Sicily, landslides ranged in size 1.9×10^0 m^2 < A_L < 4.5×10^4 m^2 (average = 1.0×10^3 m^2), for a total landslide area $A_{LT} = 1.5 \times 10^6$ m^2, and in the Marche case study, landslides were 1.6×10^0 m^2 < A_L < 2.2×10^4 m^2 (average = 4.8×10^2 m^2), with $A_{LT} = 7.7 \times 10^5$ m^2. In terms of total landslide area A_{LT}, the event in NE Sicily had twice the impact of the Marche event.

Determining the volume of a landslide is known to be a challenging task that requires information on the surface and subsurface geometry of the slope failure, an information difficult and expensive to collect. The volume estimation of a large population of landslides (hundreds to several thousand failures) can be estimated only by applying empirical relationships that link the surface area to the volume of the individual landslides (Guzzetti et al. 2009). Table 1 shows landslide volumes (V_L) that were estimated applying the empirical power law equation proposed (i) by Guzzetti et al. (2009) for landslides of the slide type and (ii) by Innes et al. (1983) for landslide of the flow type (debris flow, earth flow). For the other failure types, we did not estimate the volume of the single failures because no empirical relationship linking V_L to A_L was available to us. Table 1 shows that, in NE Sicily, landslide volume was in the range 8.0×10^{-2} m^3 < V_L < 1.3×10^5 m^3 (average = 1.1×10^3 m^3), corresponding to a total landslide volume $V_{LT} = 1.2 \times 10^6$ m^3, whereas in the Marche area landslide volume ranged 2.1×10^{-1} m^3 < V_L < 1.5×10^5 m^3 (average = 1.3×10^3 m^3), for a total landslide volume $V_{LT} = 1.8 \times 10^6$ m^3. We note here that an accurate comparison of the total landslide volume V_{LT} mobilized by the two events was not possible, because—as explained before—the volume of some of the failures was not estimated.

Table 3 NE Sicily case study

Road	km	Cost (€)
A18		3,218,770
SS-114		9,027,000
SP32		7,199,966
SP33		2,670,000
SP35		4,025,000
Total		26,140,736

Damaged roads and associated restoration costs from the Prime Minister Order OPCM 3815/09 Work Plan, revised on 12 September 2012. Highway (Austostrada (*A*)), state road (*SS*), provincial road (*SP*)

The density of the event landslide area D_L, derived dividing A_{LT} by the size of the study area A_S, was 0.069 in NE Sicily and 0.004 in the Marche area (Table 1). This means that D_L, an alternative measure of the impact of the landslide events on the landscape, in the Marche areas was only 5.6% of the corresponding density in Sicily and that the event in NE Sicily had a much higher impact on the landscape than the event in the Marche study area.

Significant differences in the two study areas (Table 2) emerged from the comparison of the statistics of the road networks (Figs. 3b and 5b). In NE Sicily, the total length of the roads was L_{RT} = 128.45 km, corresponding to a road density D_{RT} = 5.8 km/km^2, whereas in the Marche area, the total length of the roads was L_{RT} = 428.14 km, a density D_{RT} = 2.2 km/km^2, 37% of the road density in NE Sicily. Since roads were classified as MR and SR, we calculated the road density separately for the two road categories. The density of the MR was D_{MR} = 1.1 km/km^2 in NE Sicily and D_{MR} = 0.5 km/km^2 in the Marche area, corresponding to 46.3% of the density of MR in NE Sicily. The density of the SR was D_{SR} = 4.8 km/km^2 in NE Sicily and D_{SR} = 1.7 km/km^2 in the Marche area, corresponding to 35% of the density of MR in NE Sicily.

Method

Since it is difficult for each landslide affecting roads to obtain information on the type of damage and cost, we devised a general (i.e. not site or area specific) method to assess the impact of landslides on the road network and to evaluate the related direct unit costs. The method exploits a GIS approach, which is exemplified in Fig. 8. The aim of the method is to quantify (i) the geographical impact of landslides on the road network, (ii) the unit cost per metre of damaged road (€/m) and (iii) the unit cost per square metre of damaging landslide (€/m^2). The approach exploits the geometric intersection of a road network map, where the roads are shown by lines, with an event landslide inventory map for the same area, where landslides are shown by polygons. To account for the width of the roads, we considered a fixed 12-m buffer zone centred on the road centreline, represented by a line in the road network maps (Fig. 3b for NE Sicily and Fig. 5b for Marche).

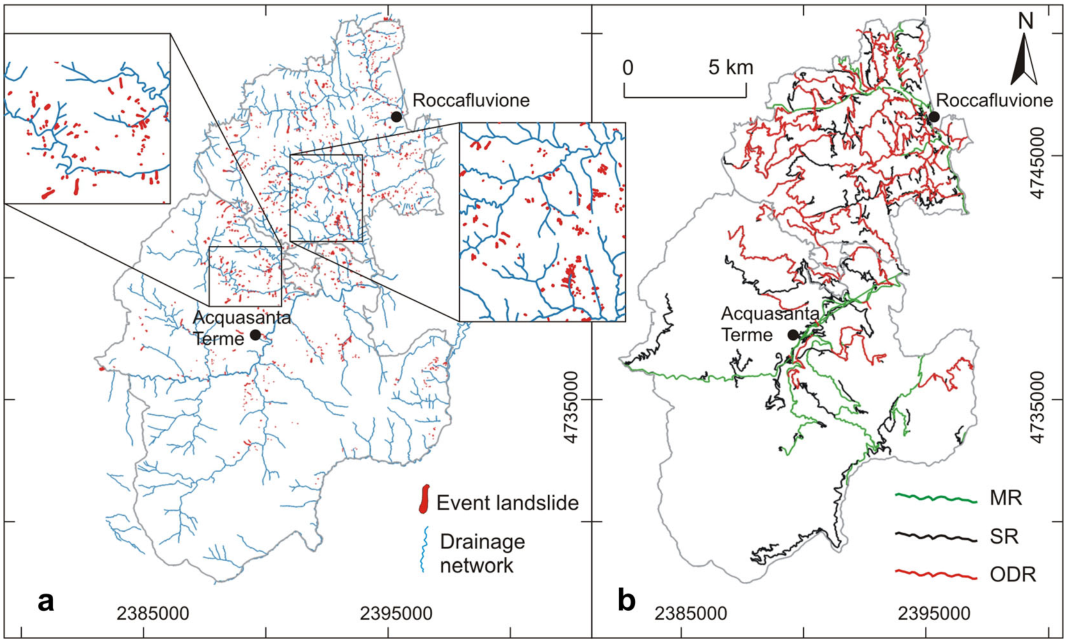

Fig. 5 Marche case study, encompassing the Acquasanta Terme and Roccaluvione municipalities. **a** Landslide event inventory map, modified after Ardizzone et al. (2012). **b** Road network map. *MR* main road (*green*), *SR* secondary road (*black*), *ODR* official damaged road (*red*). See text for explanation. Maps are in the EPSG 3004 geographical reference system

To account for possible mapping errors during the landslide reconnaissance field survey (Santangelo et al. 2010), and in the visual interpretation of the aerial photographs (Santangelo et al. 2015), we considered a 5-m buffer drawn around the landslides shown in the NE Sicily (Fig. 3a) and in the Marche (Fig. 5a) event landslide inventory maps. We selected these two buffer sizes based on field observations. Application of the 5-m buffer resulted in an increase in the size (area) of the single landslides (Fig. 8b). The relationship between the original landslide area and the buffered landslide area was estimated using a dependency between the two areas obtained though linear regression (least square method) (Fig. 8c). For the purpose, we intersected, in the same geographical area, the buffered road network map with the buffered landslide event inventory map (Fig. 8e).

The geometric intersection allowed us to outline the sections of the roads that were (potentially) damaged by landslides (the yellow areas in Fig. 8e). This area depends on the size of the two buffers that we applied to the landslides (5 m) and to the roads (12 m). Therefore, a direct computation of the total length of roads intersected (i.e. potentially damaged, blue line in Fig. 8e) by landslides would have resulted in an overestimation of the actual (real) length (length of damaged road (L_{RD})), biasing the subsequent analyses. To avoid the bias, we scaled the intersection polygons based on the linear regression between the original landslide area and the buffered landslide area. Specifically, we applied a 0.625 scaling factor, which corresponds to the inverse of the angular coefficient of the regression line shown in Fig. 8c.

To calculate L_{DR}, we considered the downscaled intersection polygon to be equivalent to a 12-m-large rectangle aligned along the road (green rectangle in Fig. 8f), with the L_{DR} representing the base of the rectangle (red line in Fig. 8f). We excluded from the analysis the intersection polygons with a downscaled area of less than 12 m^2, which corresponds to less than 1 m of damaged road. For each intersection polygon, we then linked the corresponding landslide area in the GIS database.

The procedure was applied to (i) all the roads in the road maps, to evaluate the geographical impact of landslides on the entire road networks, and (ii) the subset of the ODR (roads with associated restoration costs), to ascertain the unit cost per metre of damaged road (€/m) and per square metre of damaging landslide (€/m^2).

The intersection between the event landslide inventory maps and the ODR highlighted that the former did not intersect all of the latter. This occurred because the cost data associated to the roads did not differentiate between landslides and other types of rainfall-induced damaging events, including, e.g. fallen trees, damaged drainage systems, debris or mud along the roads. For this reason, some of the damaged roads were not associated to any specific landslide.

The estimation of the unit cost per metre of damaged road (€/m) and per square metre of damaging landslide (€/m^2) was performed applying the following procedure. First, we calculated the total road cost C, as the sum of the cost to restore each single road,

$$C = \sum_{i=1}^{i=n} c_i, \quad [€] \tag{1}$$

where c is the cost to restore road i and n is the total number of damaged roads. We then divided C by the number of roads in the ODR subset N_{ODR}, to obtain the average road cost $\overline{C}$, in euro.

Finally, we computed the average unit cost per 1 m of damaged road $\overline{C}_R$, as

$$\overline{C}_R = \frac{\overline{C} \times N_{ODR}}{L_{RDT}}, [€/m] \tag{2}$$

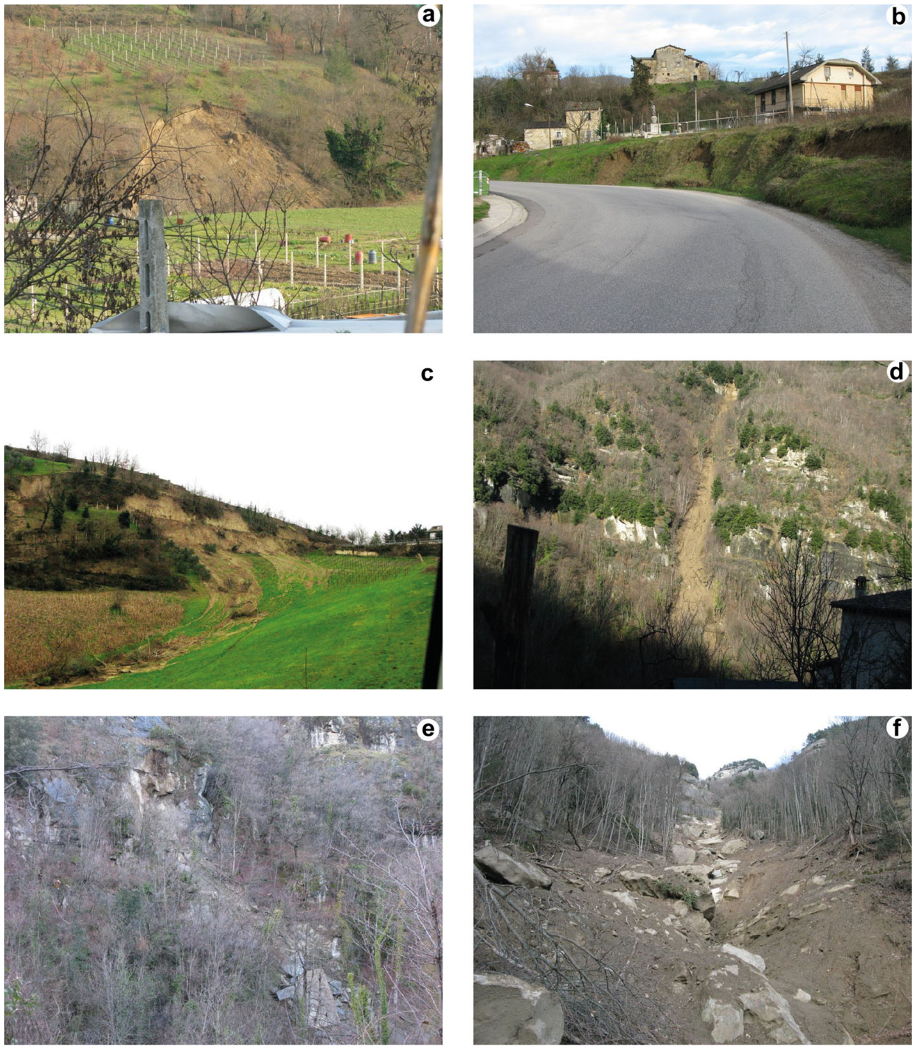

Fig. 6 Marche case study. Examples of rainfall-induced landslides triggered by the rainfall events. **a** Earth slide. **b** Soil slide. **c** Slide-earth flow. **d** Earth flow. **e** Rock fall. **f** Complex landslide

where N_{ODR} is the number of ODR intersected by the event landslides in the inventory and L_{RDT} is the total length of roads damaged by the event landslides (in m).

The average unit cost per square metre of damaging event landslide area $\overline{C}_L$, was estimated as

$$\overline{C}_L = \frac{\overline{C} \times N_{ODR}}{\mathrm{A}_{\mathrm{L}\cap\mathrm{RT}}}, \ [€/m^2] \quad (3)$$

where N_{ODR} is the number of ODR intersected by event landslides and $A_{\mathrm{L}\cap\mathrm{RT}}$ is the total area of the event landslides that intersected the damaged roads (in m^2).

Results

To quantify the impact of the event landslides on the road network, and the related restoration costs, we applied in the Marche and NE Sicily case studies our proposed method (and the GIS approach that implements the method) shown in "Method" section, using (i) the event landslide inventory maps (Figs. 3a and 5a), (ii) the available road network maps (Figs. 3b and 5b) and (iii) the official cost data available to us (Table 3 for NE Sicily). The event landslide inventory maps were intersected with (i) all the roads in the road network maps (total road network map (TRN)) and with (ii) roads for which restoration costs are known (ODRs).

The GIS intersections of the event landslide inventory maps with the ODR highlighted that in Marche case study, about 60% of the ODR were intersected by more than one landslide type, and in NE Sicily case study, all the ODRs were intersected by two landslide types.

To verify if a relationship exists between the type of landslide and the type of damage, we compared, for Marche case study, (i) the types of mapped landsides and (ii) the type of qualitative damage estimations (aesthetical, functional and structural) made during the field surveys. The results (Table 4) shows that more than 50% of the landslides caused aesthetical and functional damage and that no significant differences exist among the landslide type, in terms of damage to the road network.

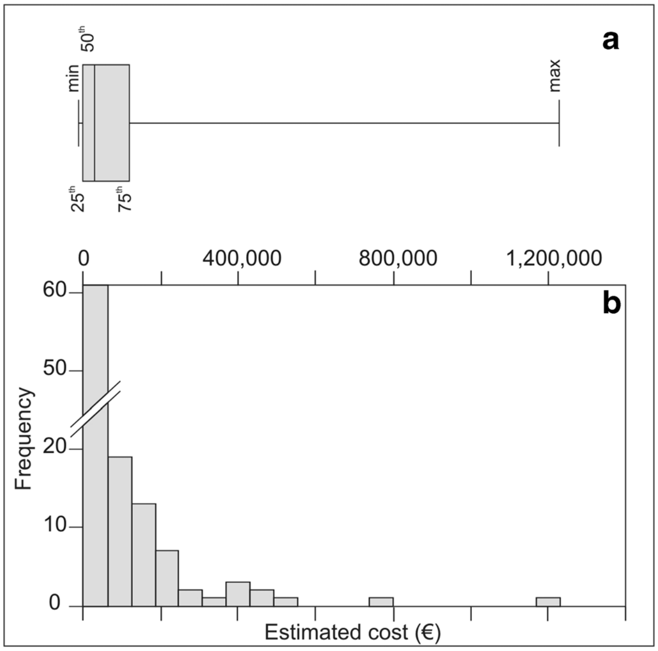

Fig. 7 Marche case study. Cost estimates for restoring official damage roads (ODRs) in the Acquasanta Terme and Roccaluvione municipalities. **a** Box plot. **b** Frequency histogram. Plots prepared using PAST software (Hammer et al. 2001)

Table 5 shows the results of the GIS intersections of the event landslide inventory maps with (i) the TRN and (ii) the ODR. In NE Sicily, a total of 520 landslides intersected the road network ($N_{\mathrm{L}\cap\mathrm{R}}$), including $N_{\mathrm{L}\cap\mathrm{R}}$ = 95 (18.3%) intersecting MR and $N_{\mathrm{L}\cap R}$ = 425 (81.7%) intersecting SR. In the Marche area, $N_{\mathrm{L}\cap R}$ = 681 landslides intersected roads, including $N_{\mathrm{L}\cap R}$ = 167 (24.5%) affecting MR and $N_{\mathrm{L}\cap R}$ = 514 (75.5%) affecting SR. Interestingly, the relative proportions of damaged (intersected) roads in the two road categories (MR, SR) are similar in the two study areas. The size of the event landslides that have intersected the road networks ($A_{\mathrm{L}\cap\mathrm{R}}$) in the two study areas is listed in Table 6. The table shows that the size of landslides in NE Sicily was one order of magnitude larger than in Marche area. We used the method exemplified in Fig. 8 to obtain measures of each damaged road segment intersected by an event landslide L_{RD}, in metres, and we reported the results for the two case studies in Table 6. The total length of the damaged roads (L_{RDT}) in NE Sicily was twice than in the Marche area. Compared to L_{RT}, the percentages of damaged roads were 13.3% (MR) and 8.58% (SR) in NE Sicily and 1.37% (MR) and 1.53% (SR) in the Marche area. We conclude that the event landslides in NE Sicily impacted the MR more than twice and the SR 1.8 times than in the Marche area.

A goal of our work was to assess the restoration unit cost for the different road categories: MR and SR. To obtain this result, we applied the method described in "Method" section using the ODRs, i.e. the subset of the roads in each study area for which (i) information exists that they were damaged and (ii) official estimates of the restoration costs are available. The descriptive statistics of the road networks (Table 2) revealed that the ODRs were 5 MRs in NE Sicily and 110 SRs in the Marche area.

Table 2 also shows that the total length of the ODR was L_{ODR} = 12.8 km in NE Sicily (53.92% of all MR in the area) and L_{ODR} = 272 km (82.87% of all SR in the area) in the Marche area. Differences exist also in the density of the official damaged road D_{ODR}, calculated as $L_{\mathrm{ODR}}/A_{\mathrm{S}}$. D_{ODR} is 0.58 in NE Sicily and 1.37 in the Marche area. The two figures are difficult to compare, but they confirm a different impact of event landslides on the road networks in the two study areas.

Analysis of the intersection between the event landslides and the ODR, shown in Table 5, reveals that in NE Sicily, four of the five ODRs (80%) were intersected (anywhere) by event landslides shown in the inventory map (Fig. 3b), representing 96.6% of the total length of the ODR, L_{ODR}. We checked the missing intersection along the SS-114 and found that it was located outside our study area, which is smaller than the entire area affected by the 1 October 2009 rainfall event (Mondini et al. 2011). In the Marche area, 71 of the 110 ODRs (64.5%) were intersected (anywhere) by event landslides shown in the inventory map (Fig. 5b). The proportion represents 79.9% of L_{ODR}.

In NE Sicily, event landslides affected 53.92% of the MR, whereas in the Marche area, the percentage was an outstanding 82.87% for SR (Table 2). This is despite the fact that the landslide event in the Marche area was significantly less severe than in NE Sicily. The landslide density was D_{L} = 67.27 landslide per square kilometre in NE Sicily, significantly higher than D_{L} = 7.36 for the Marche area. We hypothesize that the figures measure a higher vulnerability of the SR, compared to the MR.

For the ODR, Table 6 summarizes statistics (a) for the size of landslides intersecting roads ($A_{\mathrm{L}\cap\mathrm{R}}$) and (b) for the length of the damaged roads (L_{RD}) estimated through the GIS analysis, for the two case studies. In NE Sicily, the size of landslides intersecting ODR was on average = 2.3×10^3 m, for a total landslide area intersecting ODR $A_{\mathrm{L}\cap\mathrm{RT}}$ = 1.9×10^5 m^2. In the Marche area, the size of landslides intersecting ODR was on average = 3.9×10^2 m^2 and $A_{\mathrm{L}\cap\mathrm{RT}}$ = 1.6×10^5 m^2. In terms of average $A_{\mathrm{L}\cap\mathrm{R}}$, the size of the landslides in NE Sicily was one order of magnitude larger than in the Marche area. Focusing on the damaged road length L_{DR} estimated through the GIS analysis, inspection of Table 6 reveals that in NE Sicily, the landslide–road intersections was on average = 1.6×10^1 m, for a total landslide–road intersection length L_{RDT} = 1.3×10^3 m. In the Marche area, L_{DR} was on average = 7.7×10^0 m and L_{DRT} = 3.9×10^3 m. In conclusion, the L_{RDT} for ODR the in the Marche area was three times the corresponding L_{RDT} in NE Sicily.

Finally, we estimated the average unit cost per metre of damaged road (using Eq. (2)) and per square metre of damaging landslide area (using Eq. (3)). The total road cost C was 26,140,736 € in NE Sicily and 11,837,409 € in the Marche area. The number of ODR intersected by landslides I was 4 in NE Sicily and 71 in the Marche area ($N_{\mathrm{L}\cap\mathrm{R}}$ in Table 5). The total length of damaged roads L_{RDT} was 1.3×10^3 m in NE Sicily and 3.9×10^3 m in the Marche area (Table 6), and the total area of event landslides that have intersected a road $A_{\mathrm{L}\cap\mathrm{RT}}$ was 1.9×10^5 m^2 in NE Sicily and 1.6×10^5 m^2 in the Marche area (Table 6). Using these figures, we calculate $\overline{C}_R$ = 16,287 €/m and $\overline{C}_L$ = 110 €/m^2 for NE Sicily and $\overline{C}_R$ = 1958 €/m and $\overline{C}_L$ = 49 €/m^2 for the Marche area.

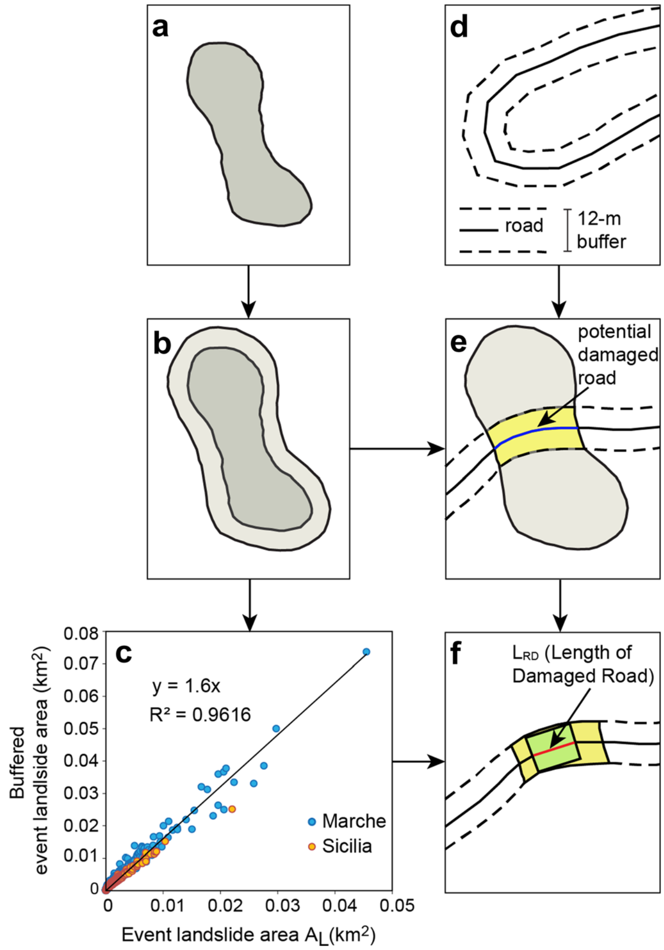

Fig. 8 Schematic representation of the GIS approach used to ascertain quantify the impact of event landslides on the road network. **a** Polygon represents an event landslide. **b** Five metre buffer drawn around the event landslide to account for mapping uncertainty. **c** Relationship between the area of the event landslides (shown in **a**) and the area of the buffered event landslides (shown in **b**). *Blue dots* are event landslides for the Marche case study, and *orange dots* are event landslides for the NE Sicily case study. **d** *Continuous line* represents a road (centreline), and *dashed lines* show boundaries of a 12-m buffer drawn around the road centreline. **e** Intersection between the 5-m buffered event landslide (shown in **b**) and the 12-m buffered road (shown in **d**). The *yellow area* shows the landslide–road intersection area. **f** The area of the *green rectangle* is obtained modifying the area of the *yellow polygon* (shown in **e**) using the scaling relationship shown in **c**. *Red line* is L_{RD}, the length of road damaged by the event landslide (shown in **a**), obtained dividing the area of the green rectangle by the 12-m constant road width. See text for explanation

Discussion

We tested our method for the quantitative assessment of the geographical impact of event landslides on a road network and for the evaluation of the related economic costs, in two different study areas in NE Sicily and in the Marche region, Italy (Fig. 1). The two case studies differ significantly: The Marche study area

Table 4 Marche case study

	Aesthetical [# (%)]	Functional [# (%)]	Structural [# (%)]	Tot [#]
Complex slide	2 (22%)	6 (67%)	1 (11%)	9
Earth flow	29 (48%)	26 (43%)	6 (10%)	61
Rock fall	2 (33%)	4 (67%)	0 (0%)	6
Earth slide	26 (30%)	37 (43%)	23 (27%)	86
Slide earth flow	18 (22%)	34 (42%)	29 (36%)	81
Soil slide	63 (55%)	47 (41%)	5 (4%)	115
Total	140 (39%)	154,843%)	64 (18%)	358

Comparison between the type of mapped landside and the type of qualitative damage estimation (aesthetical, functional and structural) made during the field surveys

Table 5 Results of the GIS intersections between the event landslide inventory map and the two road layers, for the two case studies

	Road layer	$N_{L\cap R}$ #	$N_{L\cap R}$ %	$N_{R\cap L}$ #	N_{ODR} %	L_{ODR} %	Road type
NE Sicily	TRN	95	18.3%	Na			MR
		425	81.7%	Na			SR
		520		Na			Total
	ODR	86		4	80%	96.57%	MR
Marche	TRN	167	24.5%	Na			MR
		514	75.5%	Na			SR
		681		Na			Total
	ODR	392		71	64.5%	79.9%	SR

TRN is the complete road network map, and ODR is the official damaged road. $N_{L\cap R}$ (#) is the total number of intersected landslides. $N_{L\cap R}$ (%) is the percentage of intersected landslides in the MR and in the SR. $N_{R\cap L}$ (#) is the number of road intersected by landslides, applicable only to ODR because in the TRN, the number of roads is not available. N_{ODR} (%) is the percentage of the number of ODR intersected by the event landslides. L_{ODR} (%) is the percentage of the total length of ODR intersected by the event landslides. MR is the main roads, and SR is secondary roads

(A_S = 198 km²) is nine times larger than the study area in NE Sicily (A_S = 22 km²) but received a slightly lower number of event landslides (N_{LT} = 1438) than those occurred in NE Sicily (N_{LT} = 1480) (Table 1). Thus, despite the magnitude of the two landslide events, measured by the logarithm of the total number of event landslides, $M_L = \log_{10}(N_{LT})$ (Malamud et al. 2004) is about the same for the two landslide events (M_L = 3.17 in NE Sicily and M_L = 3.16 in the Marche area), the landslide density $d_L = N_{LT} / A_S$ was significantly larger in NE Sicily (d_L = 67.3) than in the Marche area (d_L = 7.3). The density of the landslide areas $D_L = A_{LT} / A_S$ was also significantly larger in NE Sicily (D_L = 0.068) than in the Marche area (D_L = 0.004) (Table 1). We maintain that the different metrics measure differently the impact of the landslide events on the natural landscape in the two study areas, with the impact significantly larger in NE Sicily than in the Marche area. We sustained that our method is applicable to a large range of landslide events that have caused different impacts on the landscape and the road networks.

The applicability of our method depends on the availability of the necessary data, i.e. (i) an accurate event landslide inventory map, (ii) a map of the roads in the area affected by the landslide event and (iii) as accurate as possible cost data for the landslide damage. Heam et al. (2008), Klose et al. (2015) and Vranken et al. (2013) have shown that geomorphological landslide inventories are valuable sources of information to evaluate annual landslide restoration costs. Our study extends these findings to event landslide inventories. Where an event landside inventory map is available, together with a map of the road network and reliable damage information and cost data, the geographical and the economic impact of the landslide event can be estimated effectively and with relatively little effort in a GIS.

Maps of the road (or transportation) networks are readily available from topographic base maps in digital format or from other digital cartographic sources (e.g. the global OpenStreetMap project, http://openstreetmap.org). For event inventory maps, the situation is different. Despite their usefulness, and the many

Table 6 For the two case studies, statistics of the size of the landslides that intersected the roads ($A_{L\cap R}$) and of the damaged road length (L_{RD}) estimated through the GIS analysis for the main roads (MRs), the secondary roads (SRs) and the official damaged roads (ODRs)

		NE Sicily			Marche		
Metric	Unit	MR	SR	ODR	MR	SR	ODR
$A_{L\cap R}$							
Min	m²	1.3×10^1	3.5×10^0	1.3×10^1	1.5×10^1	2.9×10^0	3.1×10^0
Max	m²	1.2×10^4	4.5×10^4	2.8×10^4	3.8×10^3	1.0×10^4	1.0×10^4
Mean	m²	1.2×10^3	1.8×10^3	2.3×10^3	3.2×10^2	3.6×10^2	3.9×10^2
Total	m²	1.1×10^5	7.7×10^5	1.9×10^5	1.4×10^4	1.7×10^5	1.6×10^5
L_{RD}							
Min	m	1.0×10^0	1.1×10^0	1.0×10^0	1.0×10^0	1.0×10^0	1.0×10^0
Max	m	2.9×10^2	5.9×10^2	1.2×10^2	2.3×10^1	7.3×10^1	4.6×10^1
Mean	m	2.1×10^1	2.1×10^1	1.6×10^1	5.8×10^0	7.8×10^0	7.7×10^0
Total	m	3.1×10^3	9.0×10^3	1.3×10^3	1.4×10^3	5.0×10^3	3.9×10^3

techniques and methods available to prepare them, event landslide maps are not prepared systematically after landslide-triggering events (Guzzetti et al. 2012). This limits greatly the possibility to perform *ex post* analyses of the impact of event landslides on transportation networks. We estimate that the cost for the production of event landslide inventories comparable to those available for our two study areas is in the range between 40,000 € and 50,000 €, for an area of 100–200 km^2. The cost for the production of the Marche event landslide inventory was about 0.4% of the cost estimated for repairing the landslide damage. We hypothesize that the proportion is similar, or remains very low, in other geographical areas and in different physiographic and societal environments. We conclude that the very low cost necessary for the production of an event landslide inventory, compared to the landslide repair costs, justifies the systematic production of event inventory maps immediately after an event (Guzzetti et al. 2012).

Our work also confirmed known problems related to the collection of reliable information on road damage and repair/restoration cost data. Klose et al. (2015), working in Germany, found that landslide restoration costs were very difficult to obtain and, where available, their accuracy and reliability was difficult to evaluate. In Italy, and in many other countries, a standard procedure for the collection of landslide damage and related cost data does not exist. Hallegatte and Przyluski (2010) sustained that after a disaster, media, insurance companies and international institutions publish numerous assessments of the cost of the disaster based on different methodologies and approaches, and consequently, they often reach different results. Similarly for geohydrological hazards, different sources often provide lumped sums without separating costs due to landslides and other damaging events and costs for restoration actions from those for mitigation activities. Lack of standards contributes negatively to the paucity of damage information and cost data.

In the Marche case study, the cost data refer to the restoration of 110 damaged SRs. Our GIS analysis has identified 71 geographical intersections between event landslides and SR (64.5%) with 31 damaged locations along SR not identified by the GIS analysis. In NE Sicily, the cost data accounted for the total amount of money allocated to repair five MRs, including a highway viaduct, while our GIS analysis revealed four geographical intersections, missing one damaged site. We explain the differences (mismatches) with (i) mistakes in the attribution of the causes of the damage in the municipality reports, including, e.g. damage caused by fallen trees attributed to a landslide, and (ii) landslide mapping errors during the reconnaissance field survey (Santangelo et al. 2010). Despite the inconsistencies, which we consider acceptable for the scope of the analysis, we maintain that the very large percentage of roads intersected by the event landslides (L_{RD}) measures the severity of the impact caused by the event landslides on the road networks, in the two study areas.

The GIS-based approach allowed estimating average unit costs per metre of damaged road ($\overline{C}_R$) and per square metre of damaging landslide ($\overline{C}_L$). Results were different in the two study areas. In the Marche area, where SR were considered, we found $\overline{C}_L$ = 1958 €/m and $\overline{C}_R$ = 49 €/m^2. In NE Sicily, where MR were considered, we found $\overline{C}_L$ = 16,287 €/m and $\overline{C}_R$ = 110 €/m^2. We explain the large range in the costs with the type of the roads: MR, including a highway in NE Sicily, and SR in the Marche area, and MR is certainly more expensive to construct, repair and restore than SR.

We can compare our event-based cost estimates with similar estimates available in the literature. Heam et al. (2008) used information on the national road network in the People's Democratic Republic (PDR) of Lao and road maintenance costs for the period 2004–2007 to estimate the annual average landslide expenditure per kilometre, which was in the range US$1000–1500. Klose et al. (2015) estimated at US$52,000 the average cost per kilometre of highway at risk of landslides in the Lower Saxon Uplands, NW Germany, in the period 1980–2010. Our unit cost estimates are quite different, and we attribute the difference to multiple factors, including the facts that (i) our estimates are for single events, whereas estimates for the PDR of Lao and for the Lower Saxon Uplands cover periods of time during which multiple landslide events may have occurred; (ii) we used restoration costs after intense (in the Marche area) vs. very intense (in NE Sicily) rainfall events, that produced a different impact on the landscape and the road networks (Tables 5 and 6); (iii) different types of roads are present in the different areas, with different engineering characteristics and maintenance levels; and (iv) in the considered areas, the social and economic environments differ, conditioning the remediation and maintenance policies and costs.

Conclusions

We proposed a method to estimate the physical and economic impact of populations of event landslides on road networks. To test the method, we used two recent rainfall-induced landslide events in NE Sicily and in Marche region. The two case studies differ for their geographical extent, the geologic and morphologic settings, the landslide types (Table 1) and the type and density of the roads (Table 2). The method produced reasonable results in both study areas. We conclude that the method is general (i.e. not site or area specific) and suited to evaluate the impact of landslides damaging roads in different geographical and physiographic settings. Our two case studies were of rainfall-induced landslides. The method can be applied to evaluate the impact of populations of event landslides caused by other triggers, including, e.g. rain-on-snow events, rapid snowmelt and earthquakes, where preliminary estimates of landslide costs have to be obtained, e.g. to request the declaration of a state of emergency and to obtain fundings to reimburse incurred and foreseen restoration costs.

The applicability of the method depends on the availability and the accuracy of the necessary information, and particularly the availability of an accurate event landslide inventory map and of reliable restoration cost data. Despite their undisputed usefulness, event landslide inventory maps are not prepared systematically after landslide-triggering events (Guzzetti et al. 2012), and landslide restoration cost data are difficult to obtain (Klose et al. 2015), and their reliability and accuracy are difficult to evaluate.

We computed different metrics to quantify the impact of the two studied landslide events on the natural landscape (including the total number of event landslides N_{LT}, the landslide event magnitude M_{L} (Malamud et al. 2004), the total area of the event landslides A_{LT}, the landslide density d_{L} and the density of landslide area D_{L}, Table 1) and on the road networks (including the size of the landslides that intersected the roads $A_{\mathrm{L\cap R}}$ and the size of the damaged road length L_{RD}, Table 6) and found that the different metrics provided complementary measures of the impacts. We conclude that different, complementary metrics should always be used to quantify the impact of a population of event landslides on a landscape, a road network or any other type or class of vulnerable elements.

Our work confirmed the difficulty in collecting accurate cost data for the direct damage caused by landslides and in using the cost data for the evaluation of the economic impact of the event landslides. Systematic availability of landslide cost data will allow for accurate and reliable *ex ante* evaluations of the economic costs of landslide events. The unit cost estimates that we statistically derived can be applied to quantify the impact of populations of event landslides when preliminary estimates of landslide costs have to be obtained, e.g. to request the declaration of a state of emergency and to obtain fundings to reimburse incurred and foreseen restoration costs.

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