

LANDSLIDES AND INFRASTRUCTURES: THE CASE OF THE MONTAGUTO EARTH FLOW IN SOUTHERN ITALY

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ABSTRACT

The Montaguto earth flow is one of the most recent landslides involving infrastructure in Southern Italy. It has been periodically active during the last 70 years. This paper provides a description of the main phases in the earth flow activity and its effects on an important Italian national road and railroad tract. The most important earth flow reactivations occurred in 2006 and 2010, when the “SS-90” National Road and the “Benevento-Foggia” tract of the National Railroad, which both connect the east coast to the west coast, were destroyed by the landslide. A preliminary analysis of rainfall data showed that the most important earth flow reactivations occurred after at least two wet hydrological years.

KEY WORDS: *Earth flow, Infrastructure, Italy, Montaguto, landslide, kinematic*

INTRODUCTION

The interaction of landslides with human linear infrastructures is often the cause of disasters (e.g. GEERTSEMA *et alii*, 2009). In industrialized countries landslides cause billions of Euro in damage every year. In Italy landslide impact on roads, railways and buildings cause millions of Euro per year in damage and restoration as well.

Data from the Italian Landslide Inventory (IFFI project - www.sinanet.apat.it/progettoiffi/), regarding landslide spatial-distribution within the Italian territory from 1116 to 2007, show that: 1) more than 70% of Italian municipalities have been affected by land-

slides; 2) more than 480,000 landslide-events have been recognized in the Italian territory affecting a total area of 20,721 km²; 3) approximately 1 million people are exposed to landslide hazard.

By the IFFI project's estimates, the railway and highway networks have been involved or could be potentially involved in more than 1800 sites and 700 sites respectively by active landslides. Most of the landslides involving highways and railways were triggered by extreme or time-prolonged rainfall events (e.g. DIODATO, 2006). Moreover, most of the Italian transport network is located in high seismic hazard areas. Thus, we have to expect potential reactivation of quiescent landslides connected to seismic activity (e.g. GRELE *et alii*, 2011).

This paper aims at describing the effects on infrastructures related to the temporal and spatial evolution of one of the most important recent landslides in Southern Italy: the Montaguto earth flow (Fig. 1). In addition, analysis of data from the Orsara di Puglia meteorological station has been carried out in order to detect the relationship between landslide activity and rainfall. The landslide was not listed into the AVI project catalogue (GUZZETTI *et alii*, 1994) preventing a correct risk analysis of potentially involved areas and infrastructures.

GEOLOGICAL AND HYDROGEOLOGICAL SETTING OF THE LANDSLIDE AREA

The Montaguto earth flow (Fig. 1) is located in the southern Daunia Mountains on the south-facing

side of La Montagna Mt. The geology in this part of the Apennine Chain is tectonically complex and large-scale structures and deformed bedding often control the geometry and behavior of landslides (e.g. FIORILLO, 2004; REVELLINO *et alii*, 2010; GRELE *et alii*, 2011).

In the earth-flow area, the Flysch of Faeto formation (Pescatore *et al.*, 1996) and the Villamaina Unit (PESCATORE *et alii*, 1996) outcrop (Fig. 2). The Flysch of Faeto formation can be widely recognized in the upper part of the valley side, from 650 m a.s.l. to the top; whereas the Villamaina Unit, it crops out in the middle and lower part. The contact between the two formations is unconformity (Pescatore *et al.*, 1996).

The structural deformation of the terrains in the landslide area resulting from Miocene and Pliocene tectonics is very complex (PESCATORE, 1978, PATACCA & SCANDONE, 1989). Fold and fault systems have been recognized with two predominant trends (NW-SE and NE-SW), leading the landslide source area to be located within a synclinal fold structure with an axis characterized by a NE-SW orientation.

The resulting hydrogeological setting also is very complex due to the geology of the area. Several springs are emerging in and nearby the landslide area from about 600 to 800 m a.s.l. The Flysch of Faeto formation, outcropping at the higher elevations, is highly fractured and therefore highly permeable. Locations of springs are typically controlled by a local permeability contrast between clayey and fractured strata. Many springs are placed in the upper part of the source area, near the main scarp, and upslope on the eastern flank of the landslide at approximately 600 m a.s.l. In May 2010, the flow of water from all the springs of the source area was estimated at 2.0 l/s. In



Fig. 1 - Oblique view from a helicopter of the the Montaguto earth flow on 27 April 2006 looking south toward the earth-flow toe

the same period and farther downslope along the eastern flank of the landslide, the water flow from a different group of springs that feed the so-called Rane lake was also approximately 2.0 l/s.

THE MONTAGUTO EARTH FLOW: MAIN PHASES AND ACTIVITY

EARTH FLOW DESCRIPTION

The Montaguto earth flow is located within the Cervaro River valley at about 4566000 N and 518000 E UTM (Fig. 3). Throughout this paper, the term earth flow is used when describing the Montaguto landslide because it is composed of predominantly fine-grained material and it has a flow-like surface morphology (VARNES, 1978; KEEFER & JOHNSON, 1983; HUNGR *et alii*, 2001). However, most of the movement takes place by sliding along discrete shear surface.

The landslide is 3 km long covering an area of about 67 ha and involving about 6 millions of m³. The earth-flow width ranges from 75 m at the earth-flow neck (see below) to 450 m in the upper part of the earth-flow source area. The total elevation difference, from the toe next to the Cervaro River to the top of the 90 m high headscarp, is approximately 440 m. The average slope angle, excluding the headscarp, is approximately 7.2°.

The earth flow source area is about 900 m long and is formed by two coalescent source zones. The eastern zone has developed in a NE-SW direction, has a hopper shape and covers an area of 20 ha. The western zone has developed in a N-S direction and covers an area of 4 ha. In this area, the earth-flow movement is controlled by the bedding of the Flysch of Faeto formation. The bedding strike is about N40°E, dipping as does the hillslope and the eastern part of the source area fails with an oblique motion along the bedding planes. The terrains are very fractured, and many springs flow from these fractures, at elevations between 750-800 m a.s.l., to the landslide body.

The lower end of the source area is the narrowest part of the landslide, herein called the neck. The landslide neck is located in a structural depression created by the intersection of a syncline fold with NW-SE trending normal faults (Fig. 2).

Downhill from the neck, the landslide is located along the eastern flank of a NW-SE trending syncline and moves along a bedrock surface roughly parallel to the axis of the syncline. From 500 m a.s.l. to the base

of the hillslope, the landslide occupies a v-shaped valley, therefore only the upper part of the flanks of the valley are recognizable.

EARTH FLOW EVOLUTION

Multi-temporal analysis of the Montaguto earth flow was carried out in order to investigate earth flow modification and activity from 1954 to 2010.

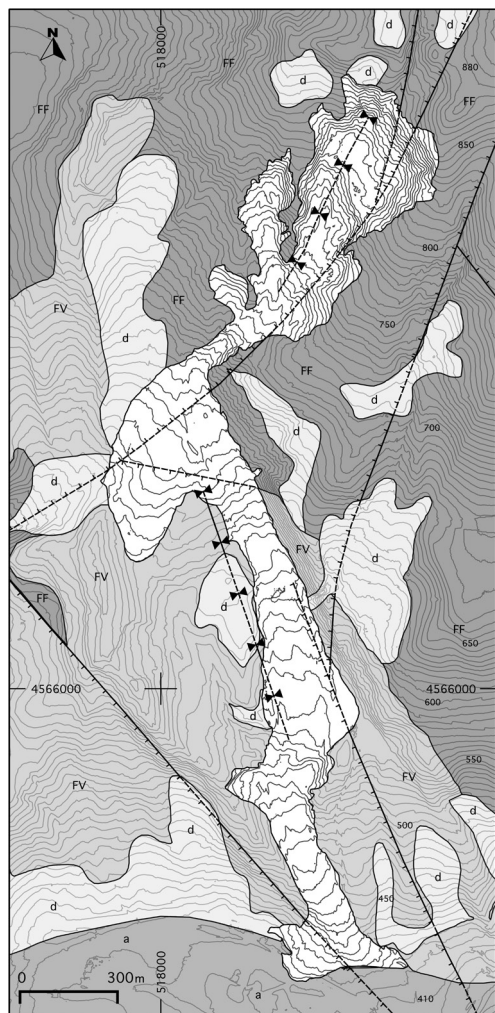


Fig. 2 - Geological map of the Montaguto earth flow. Legend: d, colluvial deposits; a, alluvial deposits; FV, Villamaina Unit; FF, Flysch of Faeto formation; line with hachures, normal fault; line with triangles, axis of fold structure. The hachured line indicates buried structures. The white area with the contour line indicates the earth-flow area. Coordinates in UTM 33 N are shown

From 2006 to 2010, earth flow features were mapped using kinematic GPS techniques, with a horizontal accuracy of about ±1 m, onto a shaded relief base map. Shaded-relief maps were created from available LiDAR data using DEM Relief Shader 2.3 QGIS-Plugin (Andreas Plesch, plugin for OSGeo public domain software, <http://www.qgis.org/>).

Older mapping was obtained from both aerial photo and orthophoto interpretations (according to KEATON & DEGRAFF, 1996). We collected stereo pairs of 1954, 1976, 1985, 1991, 2003 and an orthophoto of 2005. For periods when stereo-aerial photos were available, landslide features were mapped using a stereoscope. Manually mapped features were transferred to rectified photo base maps created from aerial photos scanned at 625 dpi (4 micron pixels). Photos were rectified using between 30 and 50 Ground Control Points (GCPs). These GCPs, which were visible in both the historical photos and in the field (e.g.

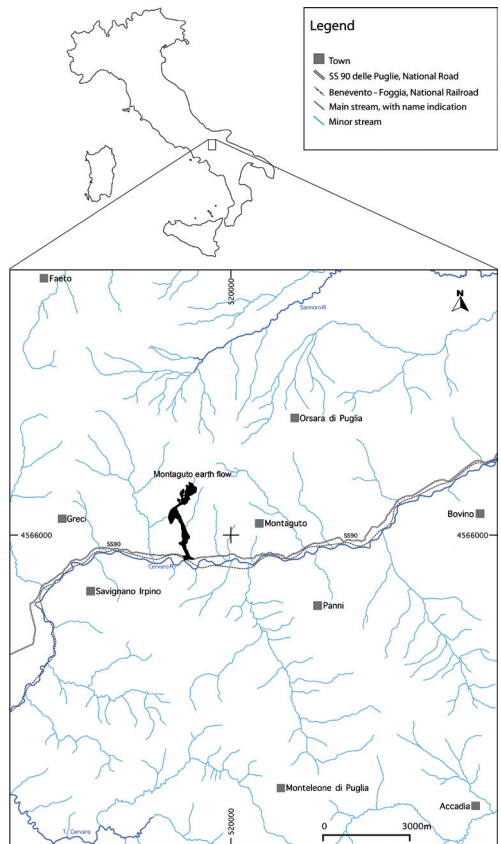


Fig. 3 Location of the Montaguto earth flow (in black) within the Cervaro-River valley. Surrounding town and drainage pattern are also shown

corners of buildings, centers of stationary trees, etc.) were surveyed using real-time kinematic Global Positioning System (GPS) techniques (e.g. GILI *et alii*, 2000) with dual-frequency GPS receivers in April 2010 (GUERRIERO *et alii*, 2013).

A description of the most important periods in earth flow evolution is provided below analyzing the earth flow features.

Since 1954, earth-flow movement alternates between long periods of relatively slow movement and relatively rapid surges, as in 2006 and 2010. The time span from 2006 to 2010 can be considered as one of the most intense active period.

In 1954 (Fig. 4a), the earth flow was about 1 km long covering an area of about 15 ha. The source area was branched in several coalescent scar zones. The landslide toe formed two different accumulation-areas. The younger deposit, which covered a surface of about 4000 m², had a fan shape and overrode the older deposit that extended for an area of approximately 3.5 ha.

In 1976 (Fig. 4b), the earth flow was larger and more complex than in 1954, measuring approximately 2 km long. The source area had expanded, bound-

ed by an irregular-shaped headscarp. Many single shallow landslides were active within the source area. The earth-flow neck was well defined, reaching about 45m in width. As the earth flow emerged from the earth-flow neck, it changed direction and moved southeast, instead of southwest. The older earth flow deposit present to the southwest of the neck in 1954 showed an enlargement of up to approximately 11 ha, but it was inactive in 1976. The active earth-flow toe reached an elevation of approximately 550 m a.s.l. and had a large pond (locally called “Lago delle Rane” see Fig. 4b) on its surface. The earth-flow creek, which flowed southeast in 1954, now flowed southwest, and it was recognized along the whole length of the earth flow.

From 1985 to 2005 the overall shape of the earth flow did not change significantly. The earth-flow neck had the same configuration until 2003. In 2005 it was several meters wider than in 2003 and many ponds were present within the earth flow.

In 2006 (Fig. 5a) the extent and the shape of the earth flow was notably different in comparison to that of 2005. The source area appeared to have complex boundary geometries with multiple smaller source

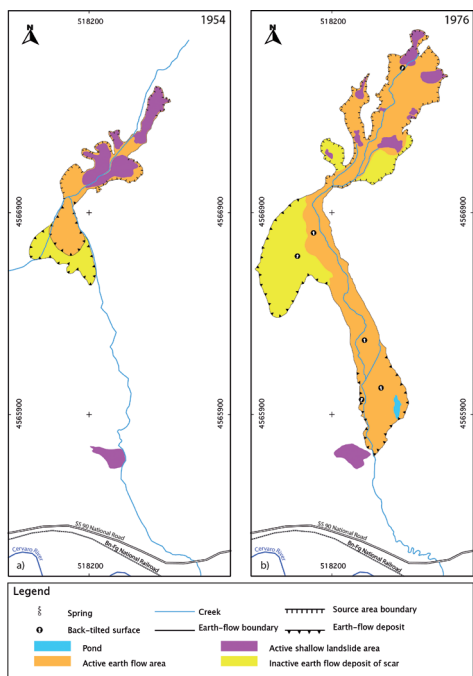


Fig. 4 - Maps of the Montaguto earth flow in 1954 (a) and 1976 (b)

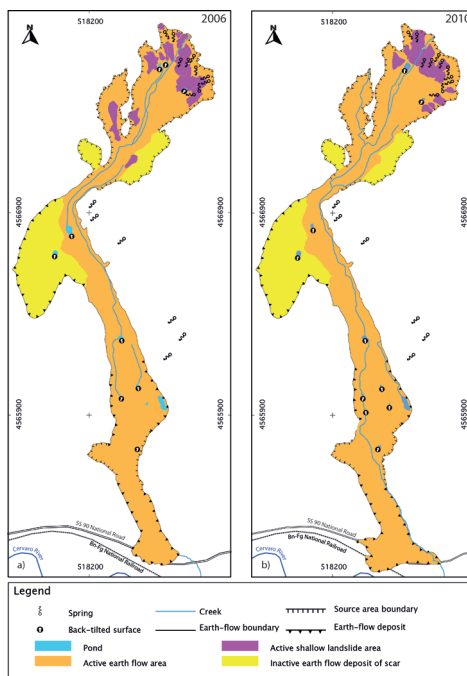


Fig. 5 - Maps of the Montaguto earth flow in 2006 (a) and 2010 (b)

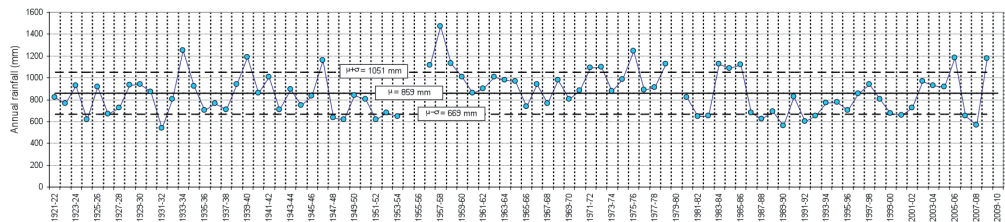


Fig. 6 - Annual rainfall historical series (Orsara di Puglia rain gauge, 650 m a.s.l.); μ and σ are the mean and deviation standards, respectively

zones, which may have been controlled by bedding (REVELLINO *et alii*, 2010; GRELLI *et alii*, 2011). Within the earth-flow body, the ponds visible in 2005 (excluding Lago delle Rane) remained in the same positions as those of 2005, but decreased in size. Lago delle Rane moved approximately 60 m to the east from its position in 2005. It became larger and separated from the main earth flow by strike-slip shear structures. From this point downslope, the v-shaped drainage valley was filled by earth-flow material from the April 2006 remobilization. The new earth-flow toe was placed on the National Road, SS90, and had a fan shape indicative of lateral expansion.

From 2007 to 2009 the overall shape of the earth flow remained very similar to that of 2006, even though the landslide was actively moving in this time period, above all on the lower part of the earth-flow toe. The peak of velocity at the toe was observed by the authors during the night between the 5th and the 6th June 2009. The upper part of the earth flow toe increased its velocity reaching 4.5 m/h. Hydrologic features along the whole earth flow did not change.

On March 3rd 2010 (Fig. 5b) the earth flow toe expanded involving both the SS 90 National road and the Benevento-Foggia National railway.

RAINFALL AND LANDSLIDE ACTIVITY

The possibility of identifying a relationship between rainfall and reactivations of the landslide is investigated in this paper, through a simple statistical-empirical approach. We analyzed rainfall records of the “Orsara di Puglia” Meteorological station compiled for the hydrological year (September-August) from 1921-22 to 2008-2009.

The Orsara di Puglia Meteorological station is located about 5.5 km NE of the Montaguto earth flow at approximately 650 m a.s.l..

We used monthly data from this station for our

analysis because the series is the longest and the most continuous for this area.

Wet hydrological years occur when the cumulative rainfall in the hydrological year exceed the average values of the series of one standard deviation ($\mu + \sigma$). Dry hydrological years occur when the cumulative rainfall in the hydrological year is below the series average of the one standard deviation ($\mu - \sigma$). Based on this criterion, wet and dry years are observable in the graph in Fig. 6.

Dry years with rainfall below average, especially if consecutive, determine conditions that could inhibit landslide reactivation. For this reason the long period from 1986-87 to 2001-02 was a period of stability for the Montaguto earth flow. This long dry period was broken by 3 consecutive wet years: 2002-03, 2003-04, 2004-05. The hydrological year 2005-06 was exceptional in terms of amount of rain and in April 2006 the Montaguto earth flow remobilized, involving the SS90 National Road. Other wet years in the past that were characterized by an amount of rain higher than 2005-06 are: 1975-76, 1957-58 and 1933-34. It is important to note that only the years 1975-76 and 1957-58 followed a precedent wet year. Historical data, regarding earth flow activity, reports that the earth flow was active in 1958 (GUERRIERO *et alii*, 2013).

In order to highlight the trend of rainfall during each hydrological year and correlate it to the landslide activity, Fig. 7 shows the cumulative rainfall of all wet hydrological years when the series average is exceeded by one standard deviation in March or April. In particular in 2005-06 the rainfall amount exceeded the average of one standard deviation around March 15th. About a month later, the Montaguto earth flow remobilized.

It is important to note the absence of 1975-76. It was characterized by heavy rainfall, but only in the months of June and July.

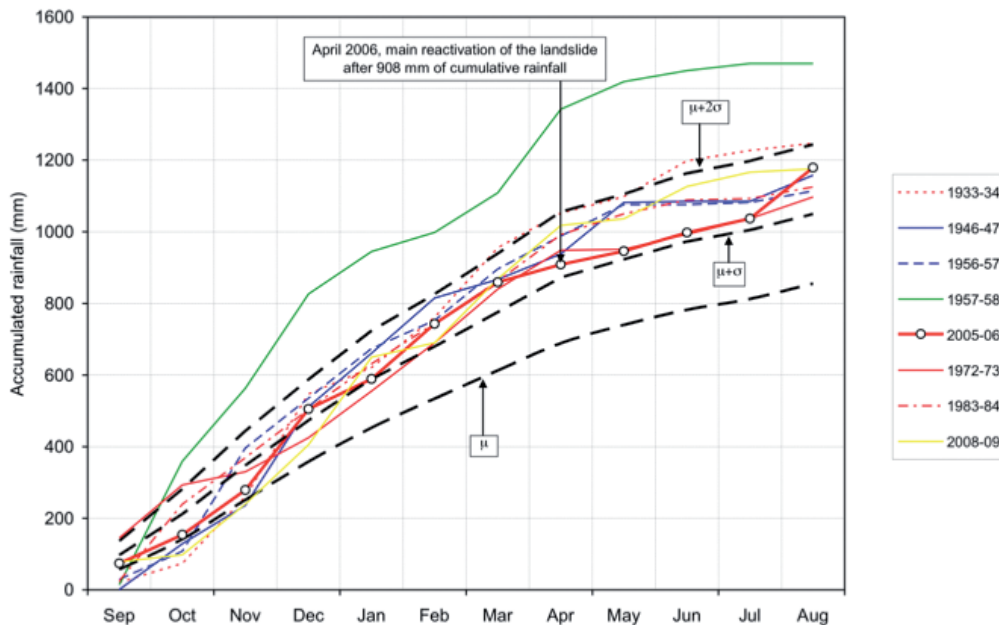


Fig. 7 - Trend of cumulative rainfall for some major wet years (coloured curves). The black dashed curves, from the bottom upwards, represent the average cumulative rainfall from September, the average plus one standard deviation, and the average plus two standard deviation, respectively. The activation of the landslide occurred in April 2006 after a rainfall event that is at least one standard deviation of the historical average

MAIN INTERACTIONS WITH INFRASTRUCTURES

As stated above, the Montaguto earth flow has been periodically active since at least 1954 (GUERRIERO *et alii*, 2013) and the most important phases in terms of effect and impact on infrastructures correspond to the reactivations of 2006 and 2010.

On April 26th 2006, for the first time, the earth flow cut the east-west trending Italian national road (Fig. 8), which connects the east- and west-coast provinces of Foggia and Avellino, damaging some buildings, and stopped at approximately 30 m from the Benevento-

Foggia national railroad. This mobilization is the largest and the most rapid documented in the last 70 years with a movement of about 6 million cubic meters of landslide material and observed velocities reaching 1 m/hour.

The National road was completely covered by the landslide for a length of approximately 250 m. This event produced the filling of the V-shape valley developed from 550 m a.s.l. Here the landslide material reached the maximum thickness of 25 m near the axis of the creek. The magnitude (volume) of this earth flow event has significant precedents in southern Italy, such as the Covatta landslide, which occurred in 1996



Fig. 8 - The Montaguto earth flow on 27th April 2006



Fig. 9 - The Montaguto earth flow on 3rd April 2010

involving the SS 647 National road and damming the Biferno River (CORBI *et alii*, 1999) or the Ruderì landslide in Basilicata region (DEL PRETE *et alii*, 1977). It was a clear hazard for infrastructure and had critical risk implications for Italian national transportation.

The 2010 event (Fig. 9) was similar to that of 2006 involving part of the earth flow toe. The volume mobilized was more than 300,000 m³ and the velocity of movement was up to 0.5 m/h. The landslide material reached and covered the railroad Benevento-Foggia. Immediately after the reactivation, the thickness of material on the railway was about 4 m. The removal of material lasted some months and at the beginning of July the railway and the national road were reopened. This event represents the peak of several weeks of activity of the earth flow at MONTAGUTO in early 2010. Before covering the railroad, the earth flow had already caused several closures of the SS 90 national road.

CONCLUDING REMARKS

Landslides are one of the most important natural hazards in Italy in terms of spatial and temporal distribution. Morphological evolution is linked to active landslide processes affecting a large part of the central-southern Apennine. Slow-velocity landslides predominate in wide areas, due to the prevalent clayey nature of the outcropping deposits. If these landslides have to be considered as a low risk for human life, they can

represent a continuing risk when they involve towns or linear infrastructures, such as roads and railroads.

This paper has provided an excursus on the main phases and activity of the Montaguto earth flow describing its interactions with important linear infrastructures. Both the SS 90 delle Puglie National Road and the Benevento-Foggia national Railroad were involved in the earth flows in 2006 and 2010, respectively. The analysis of rainfall data indicates that the most important reactivation of the Montaguto earth flow occurred after at least two wet hydrological years, although we have no data regarding the 2010 event. Before 2006, the Montaguto earth flow had been almost inactive for several decades. Historical data and climatic indications suggest that in 1958 the Montaguto earth flow had been active. After the long period of rough stability, a fast evolution and reactivation were unexpected. The lesson learnt from the Montaguto landslide, which was not inventoried in national landslide catalogs, highlights the need for new regional re-analyses along the main human linear infrastructures at least. Therefore, studies of landslide hazard and risk assessments need to consider not only the actual interaction between slope evolution and linear infrastructures but also future evolutions under possible different climatic conditions. More research should be done to assess likely future hazards and to predict slope behavior also under risk scenarios of changing climate.

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