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Research Article

Rainfall-related impacts on a terraced landscape: Sóller valley (Mallorca, Spain) December 2016-January 2017

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Keywords

*Dry-stone terraces,
Heavy rainfall,
Rock fall,
Erosion,
Mediterranean basin*

Abstract

High Precipitation Events (HPEs) are common in the Mediterranean basin, causing effects such as floods or landslides. Those effects cause impacts, ranging from economic damages to the loss of life. Amongst the damages, the impact on man-made landscapes is also common, affecting both rural and urbanized spaces. The terraced land, built across the Mediterranean, for farming purposes, suffers from HPEs when the terraces cannot cope with the large amount of falling rain. In that sense, it is important to study how rainfall affects the terraces in terms of rock fall and mass movements. Such impacts can damage the economic purpose of the farmlands but also affect other activities developed on rural spaces, like trekking or biking. In this research, the impact of precipitation over a heavily terraced valley in Mallorca is studied, both in terms of impacts and regarding human-related leisure activities as well. The methodology follows five steps, combining aerial photos and satellite images analysis with fieldwork and the study of the obtained data using computer tools. The results show how the terraces cannot cope with large amounts of rain, which increase the risk of collapse and affecting activities developed in these areas. The need of measures to protect those cultural landscapes is highlighted as well as the need of an improved statistical analysis, because results show a moderate correlation between rainfall and stones movement across terraces.

Highlights:

- Extreme rainfall events affect the terraced landscapes of Mallorca and other Mediterranean regions
- The research joins climatological aspects with cultural landscapes use
- The results highlight the impact of heavy rainfall events on the terraces, both active or abandoned
- Conservation of the dry-stone terraces is nowadays related non only to farming but also to tourism and residential activities
- The changes of land use from agriculture to housing and leisure activities increases the risk from rock-falling and terraces collapse



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1. INTRODUCTION

A High Precipitation Event (HPE) are daily events with above normal precipitation amounts (Centre from Climate and Energy Solutions, 2014). HPEs are common over the Mediterranean basin as a result from the interaction between the atmosphere, the sea and continental surfaces (Delrieu et al, 2016; Rohner, 2016). HPEs cause landslides (Gariano et al, 2017; Mandal and Maiti, 2013; Petrucci, 2013) and floods (Amengual, 2021; Insua-Costa et al, 2021) or both (Guzzetti et al, 2005; Ivankan-Picek et al, 2014).

Regarding the Mediterranean, such events affect a heavily populated area, with a presence of humankind since the Neolithic times. There was a large need of land for agricultural purposes and men built-up a system to obtain farming land, especially in mountainous areas where land was scarce. Such system is known as terraces (Figure 1) and facilitate cultivation while reducing erosion. Terraced landscapes are used around the world (Topole, 2020) and the Mediterranean is not strange to such presence.

UNESCO recognized the value of the terraced landscapes at the end of the 20th century, as they have become an important cultural heritage, as an example of humanity adaptation to the natural environment. Three European terraced regions were included in the UNESCO list of protected cultural heritage sites, one in Italy (Cinque Terre), one in Spain (Serra de Tramuntana) and the one in the Alto Douro region in Portugal (Drago et al, 2017).

Cultural landscapes are the result of a natural process combined with a human one. The value of such areas is related to ecological, cultural, historical and aesthetic roles but its main role was and still is produce food (Drago et al, 2017). Nevertheless, there is a new role as cultural destinations, related to leisure and tourism (Minguez, 2012; Klimanova and Kolbowsky, 2017).

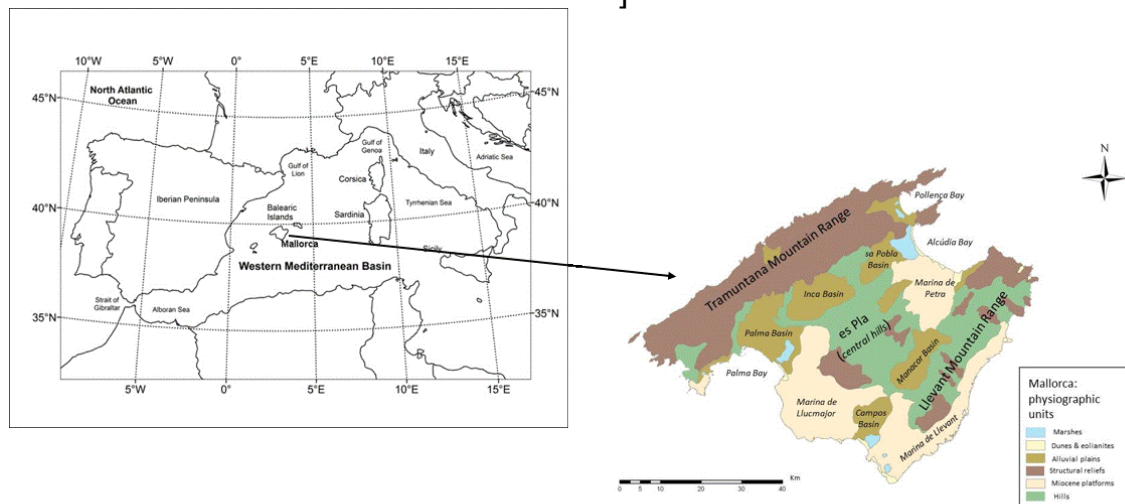
Figure 1. Terraced landscape in Banyalbufar, Mallorca. Source; Grimalt and Rosselló, 2018



As previously stated, there is a protected UNESCO landscape in Mallorca. The *serra de Tramuntana* mountain range is included in the World Heritage List since 2011 (Figure 2). Its

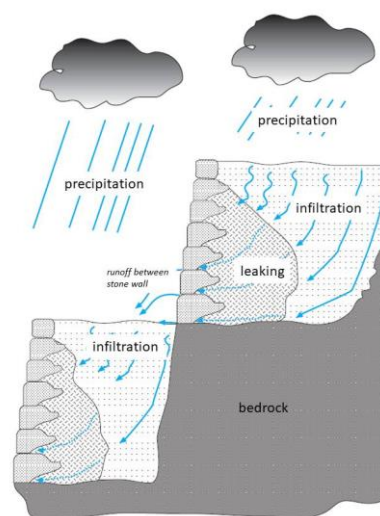
value is related to a transformed terrain for agricultural purposes on an area with scarce resources (UNESCO, 2021). The agricultural use was articulated through terraced made with dry-stone walls, thus creating productive human settlements

Figure 2. Location of Mallorca within the Mediterranean basin and the serra de Tramuntana related to the island physiographic units. Source: modified from Grimalt and Rosselló, 2018.



The dry-stone walls, known in Mallorca as *marges*, are retaining walls, which are put up to create or retain a horizontal or slightly inclined surface in order to use it as agricultural land (Figure 3). In the *Tramuntana* range, the *marges* cover the fields even arriving to altitudes around 700 meters above sea level. Along with the walls, there is a network of paths and water-regulation structures. Population living in the area has had to find agricultural lands in a reduced territory. To do so, a heavy pressure was put on the mountains slopes, at least since the 13th century, to be used as agricultural spaces, so men needed dry-stone walling to obtain arable land.

Figure 3. Scheme of the behaviour of a dry-stone terrace. Source: Grimalt and Rosselló, 2018.



The role of the dry-stone walls in the agricultural system of the mountains is reflected by the large area covered by them. At least 181 square kilometre of *marges* can be found in the 16 municipalities of the *serra de Tramuntana* and the lineal surface of the walls has been calculated to be one meter for each 10 square meters of terraced land (Rosselló, 1997).

At the start of the 20th century, a progressive withdrawal from the least productive dry-stone fields started. The process sped up after 1960 with the massive arrival of tourism to Mallorca and the abandon of agricultural activities in favour of the tourism industry, something usual in other Spanish areas (Cerdà, 2002; Marco and Morales, 1995; Romero, 2003; Arnáez et al, 2017). As a result, the dry-stone walls maintenance ceased and an important destructive process started. The rain helps to the destruction of the walls as its impact washes away the soil retained by the walls and helps the rocks fall (Grimalt et al, 1989).

In this paper, the evolution of five plots affected by HPEs between December 2016 and January 2017 is studied. The study plots have two main characteristics:

- (a) In three cases the terraces are abandoned and the destruction process has started
- (b) Two terraced plots are still operative and are regularly maintained.

The main purpose is to know the impact of the rain on terraced land, especially when the terraces are abandoned and to study the relation of rain with the walls destruction and soil movement.

The paper is structured as follows. Firstly, a description of the methods and data is done in part two. In part three, the heavy rain events are described. Then in part four the impact of rain on the terraces is analysed and, finally, some conclusions are outlined (part five).

2. MATERIAL AND METHODS

2.1 Research area

The island of Mallorca has a characteristic trend of the western Mediterranean basin, heavy rainfall events associated to meso-scale phenomena (Rosselló, 1999). The rain has its main impact at the end of summer and start of the autumn season.

The rain has important effects on the island, especially in terms of flooding (Grimalt and Rosselló, 2020) and landslides (Azañón and Mateos, 2005). The main mountain range, the *serra de Tramuntana* is 90 km long and 15 km wide and its highest point is the Puig Major (1445 meters above sea level). The range has a stream network formed by ephemeral courses, known locally as *torrents*. The *torrents* have as characteristic short courses but steep slopes and, as a result, a great torrentiality.

Furthermore, the area is one of the wettest of Mallorca, averaging over 1200 mm a year in the central part of the *serra de Tramuntana*. Rain can be intense, with records over 250 mm in 24 hours for a return period lower than 25 years (Grimalt et al, 1992).

The combination of both characteristics, heavy rainfall and steep slopes, produces a great risk for the population living in the valleys, as historical sources show (Grimalt, 1992; Rosselló, 1999; Rosselló and Cortés, 2020).

The study area is located in the valley of Sóller, which is in the middle of the *serra de Tramuntana* mountain range. The zone has two municipalities, Sóller and Fornalutx (Figure 4), the first sitting in the lower part of the valley while the second is located in the northeast slopes of the area.

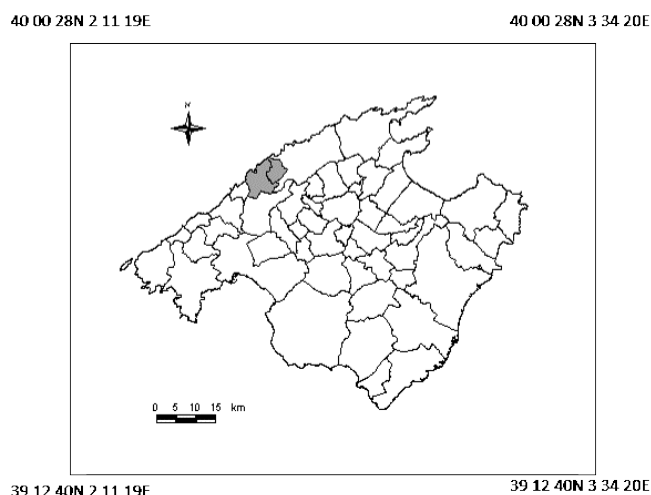
The zone limits are formed by the mountains surrounding the valley, all exceeding the 1000 meters above sea level. The altitude of the mountains and the proximity of the sea, less than 10 km, explain the steep slopes that are characteristic of the valley of Sóller (Figure 5).

The geology of the zone can be divided in two areas: (1) the lower parts of the valley are formed by Quaternary alluvial deposits while the mountain slopes are Keuper and

Muschelkalk, formed of marl and calcareous marl. (2) The highest part of the mountains has Liassic material like conglomerates and massive limestone.

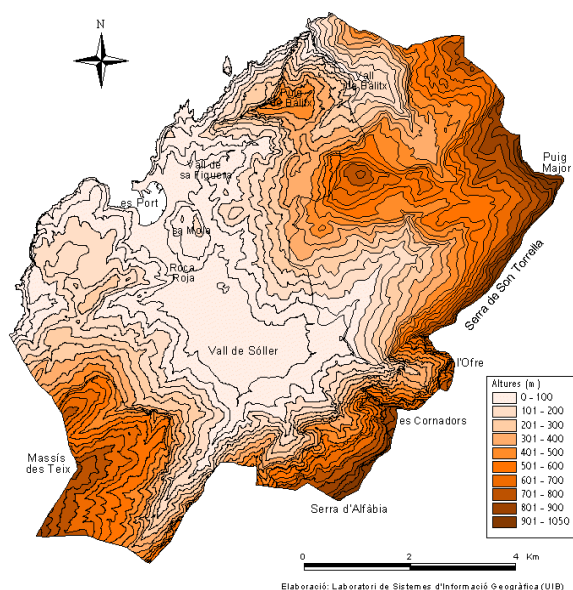
The climate is classified as Mediterranean. As is usual in the area, the minimum amounts of rain fall in summer while the maximum falls in autumn. A detailed study of rainfall shows important differences (Rosselló, 2012) due to factors like altitude or proximity to the sea. The mean annual precipitation ranges from 600 mm in the coast to 1000 mm at the highest located rain gauges and the irregularity is also notorious, with long drought periods broken by short-lived high intensity rainfall events. Annual temperatures change also during the year, depending on location and altitude. As average, the winter's minimum can be 4°C while the summer's maximum reach 30°C.

Figure 4. Location of Sóller and Fornalutx in Mallorca. Source: Rosselló, 1999.



The runoff system is organized around the *torrent Major*, an ephemeral stream with a 50-km² catchment, which is the result of the union of three streams in the middle of the town of Sóller. The fabricated channel runs through the bottom of the valley to the sea.

Figure 5. Topography of the valley of Sóller. Source: Rosselló, 1999.



Historical sources tell the presence of population in the valley of Sóller since, at least, the 9th century. The impact of inhabitants over the natural resources of the area is large as all available land was used for agricultural purposes. Even the mountain slopes were cultivated to heights of 700 meters above sea level. To do so, a dry-stone terrace system was developed and, according to Grimalt and Blázquez (1989), it was one of the most important systems of Mallorca, as 57% of the valley surface was covered by *marges*.

2.2 Methods

The methodology to assess the impact of rain on the dry-stone terraces is made of the following steps:

- (1) Obtain permission from landowners to access their properties
- (2) Survey of the zone using aerial photos and satellite images
- (3) Inventory of impacts through field work investigation
- (4) Gathering of rainfall data from official sources
- (5) Analysis of the obtained data

After the Spanish Meteorological Association issued warnings about the arrival of HPEs over the Balearic Islands, it was decided to study the impacts of rain over the terraced lands, to complete previous research undertaken years before. To be able to develop the research, the first step was to contact the owners of the plots and obtain permission to access their land during the HPEs events and afterwards. All the elected plots are located in easy access areas, either by car or by foot but with a small walking distance from a parking space.

Once the permission was granted, the research followed two directions. On the one hand, the plots historical evolution was studied using aerial photography and satellite images if available. Such research allowed characterizing the plots in terms of wall height, land slope, geological characteristics and current situation. On the other hand, once the rain started to fall, fieldwork was developed to observe the impacts of precipitation over the selected plots. In that period, measurements were taken, regarding rock fall distances, rock dimensions and soil movement using markers. For the duration of the HPEs, daily visits to the plots were scheduled to complete the obtained information. Interviews with landowners, related to the land current use, its historical evolution and future perspectives completed the research.

After the rain events were finished, the final step was the analysis of the data, using descriptive statistics, to gain knowledge of the relationship between rainfall and the dry-stone terraces observed damages.

2.3 The study plots

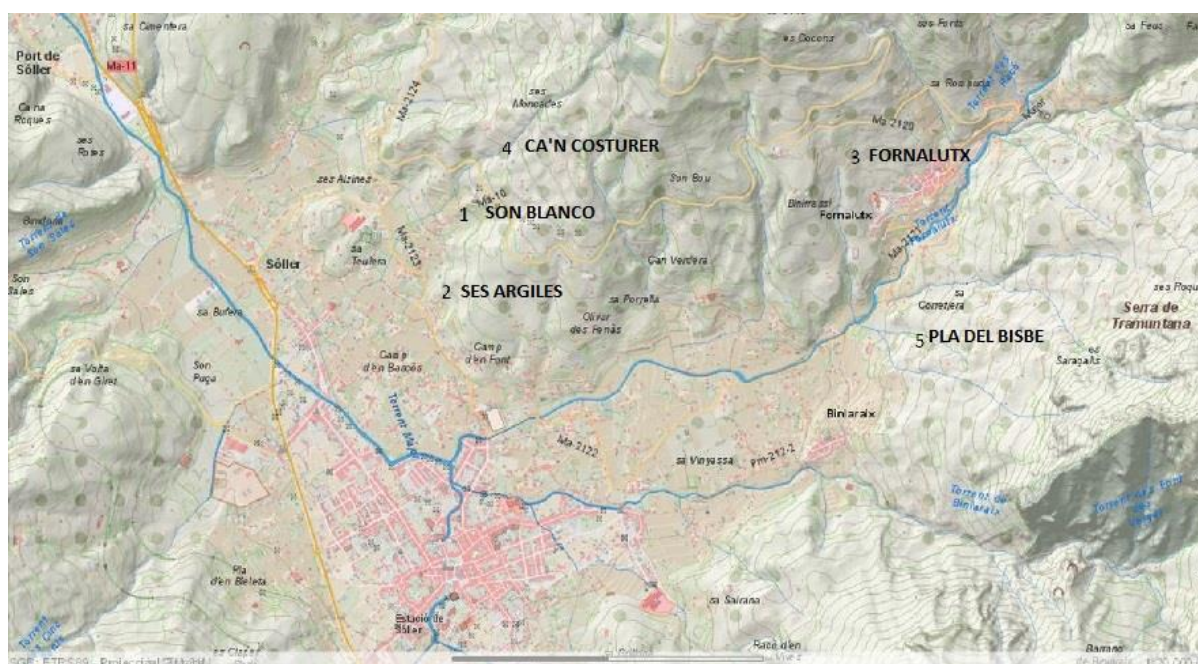
The five study plots (see Table 1) are located in the northeastern part of the valley (Figure 6). It is an area studied by Rosselló in 1997 to identify the longitude of the walled surface.

Each plot is at least 20 meters long and 10 meters width. The mean wall height is 2.1 meters while the mean wall length is 4.7 meters.

Plots number two, three and four are abandoned and the terraces have been recolonized by brush (*Hypericion balearici* and *Oleo-Ceratonion*) and pine trees (*Pinus halepensis*). Meanwhile, plots one and five are still operative and there is a maintenance when a wall collapses and the soil is routinely ploughed.

Table 1. Description of the study plots.

Plot number	Location	Mean altitude	Slope	Lithology	Uses
1	Son Blanco	90 meters	25%	Mudstone, sandstone, gypsum and volcanic rocks	Irrigated crops
2	Ses Argiles	80 meters	15%	Mudstone, sandstone, gypsum and volcanic rocks	Irrigated crops
3	Fornalutx	200 meters	20%	Mudstone, sandstone and gypsum	Dry tree crops
4	Ca'n Costurer	240 meters	28%	Mudstone, sandstone, gypsum and volcanic rocks	Dry tree crops
5	Pla del Bisbe	250 meters	20%	Gravel, sands and boulders	Dry tree crops

Figure 6. Plot's location within Sóller valley. Source: adapted from IDEIB.

3. THE DECEMBER 2016 AND JANUARY 2017 EVENTS

The Western Mediterranean area is well known for its intense rainfall events (Romero and Ramis, 2003; Amengual et al, 2009). Those events are the result of the zone characteristics, partially enclosed by sharp reliefs and a high sea surface temperature in late summer, thus favouring a high instability in autumn, which results in rainstorms that reach the maximum usually between October and December.

Mallorca is no strange to intense events (Sumner et al, 1995; Grimalt et al, 2006) and the valley of Sóller has suffered severe rainstorms as well (Rosselló, 2012). Amounts of rain exceeding 100 mm in 24 hours are usual and its impact over land and population is common. Such affectation has as effect that a large net of rain gauges has been in place throughout Mallorca and in the Sóller valley too. Those rain gauges are helpful to develop the study although the rain data available refers to daily totals and hourly intensities are unknown.

3.1 December 2016 event

The first event took place from December 16th until the 22nd. A low affected the northeastern coast of the Spanish peninsula and the north-west area of Mallorca was heavily damaged by rain. In Sóller, seven consecutive days of rain were recorded with a maximum on the 20th when 131.6 mm/24 hours were recorded by rain gauge IES Sóller (see Table 2).

Because of the rain, some minor flooding affected the area, especially the lower parts of the valley, close to the mainstream mouth.

Table 2. Recorded rainfall in mm, December 2016.

Rain gauge	16 th mm	17 th mm	18 th mm	19 th mm	20 th mm	21 st mm	22 nd mm	Total mm
Sóller IES	20.0	3.8	17.4	81.4	131.6	113.2	19.8	387.2
Port 1	8.6	2.0	6.2	60.8	21.6	12.2	29.2	140.6
Port 2	8.4	1.8	4.8	60.3	17.7	9.6	27.9	130.5
Alfàbia	16.0	3.6	17.6	69.7	133.0	103.0	32.6	375.5

Source: AEMET and BalearsMeteo

The rain-recorded show that the highest amounts fell on the rain gauges located at the northeastern slopes of the valley and on the mountains top, while the lowest amounts fell on the coast, in both gauges located at the valley harbour.

3.2 January 2017 event

The second rainstorm lasted for eight days, from January 17th to January 24th. The long-lasting event caused important damages to the road network as well as minor flooding in basements and farmland across the valley. Furthermore, snowfall was important in the *Tramuntana* mountain range as the low humid flow from the Genoa Gulf combined with a cold air mass from Eastern Europe.

Table 3. Recorded rainfall in mm, January 2017.

Rain gauge	17 th mm	18 th mm	19 th mm	20 th mm	21 st mm	22 nd mm	23 rd mm	24 th mm	Total mm
Sóller IES	16.6	4.0	23.4	100.2	89.4	29.0	54.0	19.4	336.0
Port 1	2.8	2.0	15.8	61.2	77.8	19.0	18.6	5.2	202.4
Port 2	2.1	2.1	14.1	58.2	75.9	16.2	16.2	4.5	189.3
Alfàbia	3.8	8.5	10.1	52.7	56.3	21.3	38.9	11.5	203.1

Source: AEMET and BalearsMeteo

During the episode, rain was almost equally split with similar total amounts in all the rain gauges, even if the maximum daily amount fell again in the one located at the northeastern side of the valley, with 100.2 mm recorded on December 20th.

4. RESULTS

4.1 Field work observations

After the first's days of rain in December 2016, fieldwork consisted in locating the most affected plots and studying the damages caused by the water. In the abandoned plots of *Ca'n Costurer* and *Fornalutx* the damages were clear as walls have fell and rocks were scattered between 0.5 and 1.5 meters away from the wall. Interviews with the owners of son Blanco stated that the walls could hold the surface water during the days with small amounts of rain but during the 20th and 21st events, the surface water was running between the rocks and fell from the upper terrace to the one underneath, damaging the soil and the walls.

Once rain started on January 17th, field observations were again undertaken. The highest amount of precipitation fell between the 20th and 21st and those quantities of rain explain the results found in the research plots 3, 4 and 5, where the damages were important with walls falling down and soil being dragged away by the water flow.

In the *Ca'n Costurer* area, where the rain was supposed to be lower than in the other areas as is closer to the coast, the rainfall caused the fall of walls located underneath the one affected by the 2016 storm.

Figure 7. Collapsed wall in *Ca'n Costurer* plot.



Runoff and sediments overcame the water regulation system of the preserved walls while in abandoned zones, as *ca'n Costurer*, the raindrops exposed the bedrock dragging away the topsoil. In the plots number one and five, where is still an agricultural use of the terraces, the walls impacted by the 2016 event were reconstructed or were in the process of being rebuilt, so the January 2017 rain caused only the falling of stones from the terrace top layer and the movement of rocks still laying on the terrace's soil.

4.2 Data analysis

The values obtained during the fieldwork were statistically analysed, using correlation coefficients. Three parameters (rock mean diameter, mean daily rainfall and distance from the wall) were tested to observe the existing significance of relationships. The results of the Pearson correlation test show how there is a positive relationship between the amount of rain and the distance travelled from the wall through the terrace when observed in abandoned plots. On the other hand, in maintained areas, the correlation is smaller. Even so, the values indicate a statistically moderate correlation, as r ranges between 0.44 and 0.53 depending on the boulder size (see Table 4).

Tables 5 and 6 include the values of mean daily rainfall for each event, the distance the boulder moved from the original point and the size of the boulder. The average is 0.67 meters (for boulders of 0.5 meters of diameter), while for the rocks of a 1-meter size, the average is 0.44 meters in abandoned plots. In still cultivated plots, the average is smaller, 0.47 meters and 0.36 respectively.

Table 4. Pearson's correlation values December 2016 event.

Boulder size (Ø)	Pearson's correlation
0.5 m abandoned plot	0.46
1.0 m abandoned plot	0.44
0.5 m active plot	0.51
1.0 m active plot	0.53

Table 5. Field measurements in an abandoned plot: *Ca'n Costurer* December 2016.

Mean daily rainfall (mm)	Distance (m) for a boulder Ø 0.5 m	Distance (m) for a boulder Ø 1.0 m
13.2	0.17	0.08
2.8	0.22	0.11
11.5	0.29	0.14
68	0.46	0.30
75.9	0.77	0.45
59.5	1.04	0.76
27.3	1.28	0.90

Table 6. Field measurements in an active plot: *Pla del Bisbe* December 2016.

Mean daily rainfall (mm)	Distance (m) for a boulder Ø 0.5 m	Distance (m) for a boulder Ø 1.0 m
13.2	0.15	0.12
2.8	0.16	0.12
11.5	0.20	0.14
68	0.32	0.27
75.9	0.67	0.50
59.5	0.85	0.69
27.3	0.96	0.73

The data obtained after the January event show how the rainfall affected differently the terraces. In the active ones, the walls impacted by the 2016 event were rebuilt or in the process of rebuilding, and the precipitation caused the drop of the stones from the top layer of the terrace or small movements of the stones, which were still on the terrace's floor (see Table 7). On the other hand, in abandoned plots, the rain carried away the soil of the terraces and moved further ahead of the wall the rocks that fell during the December episode (see Table 8).

Table 7. Field measurements in an active plot: *Pla del Bisbe* January 2017.

Mean daily rainfall (mm)	Distance (m) for a boulder Ø 0.5 m	Distance (m) for a boulder Ø 1.0 m
6.3	0.10	0.05
4.1	0.14	0.09
15.8	0.20	0.16
68.7	0.31	0.25
74.8	0.60	0.40
21.3	0.78	0.62
31.9	0.89	0.72
10.1	0.95	0.78

Table 8. Field measurements in an abandoned plot: *Ca'n Costurer* January 2017.

Mean daily rainfall (mm)	Distance (m) for a boulder Ø 0.5 m	Distance (m) for a boulder Ø 1.0 m
6.3	0.12	0.10
4.1	0.19	0.14
15.8	0.23	0.19
68.7	0.44	0.32
74.8	0.77	0.58
21.3	0.90	0.78
31.9	0.98	0.87
10.1	1.09	0.95

The data was again statistically analysed and the correlation results reached a positive value, even if weak and likely unimportant, with r ranging from 0.08 to 0.22 (see Table 9).

Table 9. Pearson's correlation values January 2017 event.

Boulder size (Ø)	Pearson's correlation
0.5 m abandoned plot	0.22
1.0 m abandoned plot	0.13
0.5 m active plot	0.13
1.0 m active plot	0.08

5. DISCUSSION

Centuries of man modifications over a landscape characterized by steep slopes are represented by dry-stone terraces, devoted to farming purposes. The analysis of the precipitation impact over the terraces and the soil supported by them.

Amongst the impacts, it is observed that raindrops felling on the soil located in the superior part of the *marge* detach the topsoil layer, thus creating small channels, which drive runoff to the wall. The amount of soil plugs the wall drains, causing it to collapse.

When the rainfall is intense, over 50mm in 24 hours, the small channels led the superficial water to the wall where it jumps, affecting the soil of the underneath terrace, where the channel process starts again.

The fallen rocks of the terraces are affected as well by the rainwaters. In the abandoned plots, where there is not maintenance, the rocks remain where were moved by precedent storms until another rainstorm hits. In this case, the measurements done show that rocks of medium size (fifty centimetres to one meter in diameter) can be moved by surface water between one and two meters. Biggest rocks, usually located at the lower part of the walls, remain close to the remaining wall structure but show the effects of the rain as begin to break

due to their calcareous origin. The broken parts are washed away by following rainstorms and moved all along the terrace.

When a wall fell, the usual breaking pattern is called *golpe de cuchara* (spoon hit) (Figure 8). The wall breaks in the middle while the sides can remain standing. In the abandoned plots, the presence of scrub and trees helps the destruction of the walls as the roots grow between the rocks and help it fall.

Figure 8. Wall collapsed (*Son Blanco*). Example of *spoon hit* collapse.



The wall collapse starts another process, called *domino effect* (Ramón, 1997). The domino effect consists in the collapse of the walls of the terraces located downwards from the first collapsed wall as the overland flow run through the open space and concentrate in the same spot in the inferior terrace wall (Figure 9).

A final important point is the risk of collapsing walls for the population. The increase of outdoor activities, like trekking, lead to an intense use of roads and paths by people, unaware of the danger. Abandoned walls can increase the risk of landslides in an already prone landslide area. The failure of a proper maintenance and the erosion process break the protective effect of the terraces outlined by Grimalt and Blázquez (1992). The residential use of former farmlands has to be taken into account as well. Urban related activities, such as second residences or rural hotels, can easily be affected by HPEs events causing the collapsing of walls or the drop of rocks (Figure 10).

Furthermore, the colonization of the terraces by shrubs and trees in a very dry environment, especially during spring and summer, increases the risk for population as forest fires can start rapidly from lightning or by human mistake.

The statistical analysis of the data allowed highlighting the linkage between rainfall and the movement of rock of different sizes through the terrace soil. Even so, the results are moderately correlated, so it will be necessary to add parameters such as the type of soil, the terrace vegetation cover or the terrace slope, to improve the analysis.

6. CONCLUSIONS

The research herein presented is a first approach to the impact of HPEs over a terraced landscape in Mallorca. The effects of two events allows reaching some conclusions related to the study area. Nonetheless, those results should be compared with other terraced areas to be applicable to all of Mallorca.

Figure 9. Domino's effect example. *Ses Argiles* plot.



Figure 10. Damages of falling walls on outdoor activities.



The impact of rainfall over dry-stone walls is important. The amounts of rain, exceeding 50 mm/24 hours, and the short time of precipitation (usually less than 6 hours) have as effect that the *marges* cannot cope with the volume of precipitation. It does not matter if the terraced fields are abandoned or not, the HPEs provokes the fall of the walls as well as the destruction of the soil retained in the terraces. The damages caused by the rain worsened by following precipitation events, especially if there is not maintenance and a quick repair of damages.

The conservation of the dry-stone walls is not only related to agricultural activities. In some cases, the land ownership plays a key role in the maintenance of the system. The touristic use of the terraced lands (rural tourism) has the effect of preserving the walls as cultural heritage to attract visitors. In the other hand, weekend farmer activities can have the opposite effect as the fallen walls can remain down for long periods, which increase the risk of collapse of close still standing walls.

The study of the rain impact on terraces and dry-stone walls must be continued, taking into account the risks above mentioned. References about erosion rates and runoff are common (Vera and Marco, 1998; Lasanta et al, 2001) but the study of vulnerability should be improved.

The probable increase of high rainfall events due to the climatic change scenario and the continuous use of the mountains with non-farming purposes, such as residential or as a touristic resource, lead to the need to improve our knowledge.

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