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DEPARTMENT OF LANDSCAPE AND URBAN PLANNING

LANDSCAPE PLANNING MASTER DEGREE

ECO HYDROLOGY OF RECLAIMED-QUARRY LANDSCAPES UNDER MEDITERRANEAN CLIMATE IN SPAIN

DIPLOMA THESIS

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Faculty of Environmental Sciences

DIPLOMA THESIS ASSIGNMENT

Ing. Ruby Stefany Garcia Moreno

Landscape Engineering
Landscape Planning

Thesis title

Ecohydrology of reclaimed-quarry landscapes under Mediterranean climate in Spain

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Objectives of thesis

General objective: To test the hypothesis that reclaimed topographies based on Geomorphic principles –such as GeoFluv method- will offer more soil water to plants than those based on the conventional slope-berm model.

Specific objectives:
- To quantify Soil Moisture Content (SMC) evolution in conventionally reclaimed quarries (slope-berm model)
- To quantify SMC temporal evolution in GeoFluv reclaimed quarries
- To estimate the influence of the substratum type on SMC

Methodology

The Thesis will be based on both, own data and available data from other research projects.

The experimental layout includes two quarry-reclamation scenarios: conventional topography (slope-berm) and GeoFluv landscapes. Own data will come from "Fortuna quarry" that has been reclaimed in TECMINE LIFE project. Provided data will come from Tecmine LIFE project as well as ECORESTCLAY LIFE project.

SMC measurements are made by means of TDR methodology, once a month during at least one year in every scenario. Measurements are made in three transects from the upper part of the slopes to the lower one with 15 measurements by transect, so 45 measurements by slope. Basic physical and chemical soil properties are also analysed. Climatic data coming from official weather stations will be processed.

The proposed extent of the thesis

60

Keywords

Quarries, Restoration, GeoFluv method, TDR

Recommended information sources

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Prague on 09. 03. 2021

AUTHOR'S DECLARATION

I hereby declare that I have independently completed this diploma thesis, titled *"Ecohydrology of reclaimed-quarry landscapes under Mediterranean climate in Spain"* and I have cited all the information sources that I used in the thesis within the resources section.

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With my signature, I also declare that the electronic version is identical to the printed version and the data stated in the thesis has been processed about the GDPR.

Prague, 2021 Ruby Stefany Garcia Moreno

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ABSTRACT

Soil moisture dynamics were analyzed in conventional and geomorphic treatments in two restored quarries in Spain. The Aurora quarry has a coastal Mediterranean climate and is located in Campredó, Catalonia and The Fortuna quarry has a continental Mediterranean climate and is located in Ademuz, Valencia.

The measurements were made using the Time Domain Reflectometry technique (TDR) and sampling points were distributed throughout the landforms and from the upper toward the bottom part of the micro basins, including areas restored with different types of substrate and by both approaches.

We tested soil moisture content (SMC) changes concerning factors as *treatment*, *substrate*, *aspect*, *landform* and *transect;* using a mixed linear model of repeated measures and a non-parametric test (Friedman test).

The areas with the geomorphic approach had higher SMC values than the areas with the conventional one. Restored areas covered by Colluvium had higher SMC than those covered by overburden. On the other hand, it was confirmed that the shadow aspect (north) had higher values than sunny (south) orientations in both quarries. The spatial distribution of soil moisture in both geomorphic restorations in quarries imitated the water flow of an undisturbed watershed. Likewise, the conventional restoration had a flow pattern of moisture that increased towards the bottom part, however, in the Aurora quarry due to the entry of runoff from the upper berm the spatial distribution of SMC in the slope was inverted; moreover rills formed in the slope has higher SMC than in the inter-rills.

Taking into account the SMC is the most limiting factor for plants development, certainly, these findings might contribute to future revegetation plan designs in the Mediterranean restored quarries.

KEYWORDS: Soil moisture content, geomorphic restoration, conventional restoration, landforms.

ABSTRAKT

Dynamika půdní vlhkosti byla analyzována konvenčními a geomorfními úpravami ve dvou obnovených lomech ve Španělsku. Lom Aurora má pobřežní středomořské podnebí a nachází se v Campredó v Katalánsku a lom Fortuna má kontinentální středomořské podnebí a nachází se v Ademuz ve Valencii.

Měření byla prováděna pomocí techniky Time Domain Reflectometry (TDR) a vzorkovací body byly distribuovány po celém reliéfu, a to od horních partií směrem ke spodní části mikropovodí, včetně částí obnovených různými typy substrátů a oběma přístupy.

Testovány byly změny obsahu půdní vlhkosti (Soil water content – SMC) týkající se faktorů jako způsob ošetření půdy, substrát, aspekt, terén a transekt; pomocí smíšeného lineárního modelu opakovaných měr a neparametrického testu (Friedmanův test).

Oblasti s geomorfním přístupem měly vyšší hodnoty SMC než oblasti s konvenčním. Obnovené oblasti pokryté Colluviem měly vyšší SMC než oblasti pokryté skrývkou. Na druhou stranu se potvrdilo, že stínový aspekt (severní orientace) měl v obou lomech vyšší hodnoty než osluněné svahy (jižní orientace). Prostorové rozložení půdní vlhkosti v obou geomorfních obnovách v lomech napodobovalo tok vody nerušeného povodí. Stejně tak konvenční obnova měla tokový vzorec vlhkosti, který se zvyšoval směrem ke spodní části, avšak v lomu Aurora v důsledku vstupu odtoku z horní bermy bylo prostorové rozložení SMC ve svahu obráceno; kromě toho mají ronové rýhy vytvořené ve svahu vyšší SMC než vyvýšeni mezilehlých rýh.

Vzhledem k tomu, že SMC je nejvíce omezujícím faktorem pro rozvoj rostlin, jistě by tato zjištění mohla přispět k budoucím návrhům plánu obnovy středomořských lomů.

KLÍČOVÁ SLOVA: Obsah půdní vlhkosti, geomorfní obnova, konvenční obnova, reliéf.

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1 Introduction

Mining is a necessary activity for life, since the beginning of civilization, people have used stone to make tools and weapons; in the XVI century mining become an efficient and mechanized industry and in the XXI century begins a modern globalized mining industry of multinational corporations, which mined material are needed in different industries; according to the (European Economic and Social Committee, 2009), 70 % of the European manufacturing industry depends on extracted substances.

However, Mining activities generate multiple negative impacts on the environment, which destroy landscape structure and ecosystem functions. Therefore to develop a sustainable mining process restoration must be included in the mining projects.

Restoration is a process of assuring the restoration of areas affected by mining to their original conditions, including ecosystem function patterns and native vegetation species and communities (Mert, 2019). However, too often the conventional restoration approach (slope and berms/ditches) leads to the inefficient establishment of vegetation and it is not able to recover the natural processes in the medium-long term.

In Mediterranean climates, the main factor limiting restoration success in mining is soil erosion due to irregular and very aggressive rainfall, which generates rills and gullies on the slopes (Jose Manuel Nicolau, 2003). Consequently, it is necessary to implement ecological restoration designs based on geomorphology (Geomorphic restoration) which simulate natural environments with smooth wavy slopes and meandering streams less sensitive to erosion (Martin Duque & Bugosh, 2014).

This document aims to analyze the ecohydrology of the conventional and geomorphological restoration approaches in two restored quarries in Spain, including factors such as substrate, aspect and spatial distribution within the restored quarries.

2 Aims

2.1 General

To analyze soil moisture content (SMC) dynamics in quarries restored with conventional and geomorphic approaches.

2.2 Specific

- To compare the soil moisture content (SMC) between a conventional restored quarry and those with geomorphological restoration.
- Analyze the soil moisture content (SMC) according to the type of substrate in the geomorphic restored quarry
- To evaluate the influence of slope aspect in the soil moisture content (SMC) in the geomorphologic restored quarry landscapes.
- Observe the spatial distribution of soil moisture in a conventional and geomorphological restoration quarry.

3 Literature review

3.1 Mining and environmental impacts

Mining and quarrying provide raw materials and inputs for energy production at a worldwide scale. According to the (European Commission, n.d.-b) in 2006, the mining industry generated about €45 billion and provided about 295,000 jobs. Moreover, construction, chemicals, automotive, aerospace, machinery and all type of equipment depend on raw materials produced by mining, those industries provide about €1.324 billion and employment for 30 million people. (European Commission, n.d.-b).

Mining raises two types of environmental concerns: the depletion of non-renewable resources and being harmful to the environment (Fugiel, Burchart-Korol, Czaplicka-Kolarz, & Smoliński, 2017). Regarding the first concern, mining harms vegetation cover, landscape and hydrological regimes. This essentially leads to alterations in nutrient cycles, soil formation, water flow, ecological functions and biodiversity (Mert, 2019).

Due to the effects of mining, the goal of reclamation is to stabilize the terrain and restore the topsoil (Feng, Wang, Bai, & Reading, 2019) to re-establish the land for new uses. Figure 1 shows the environmental impacts of a mine life cycle related to the reclamation process and its social benefits.

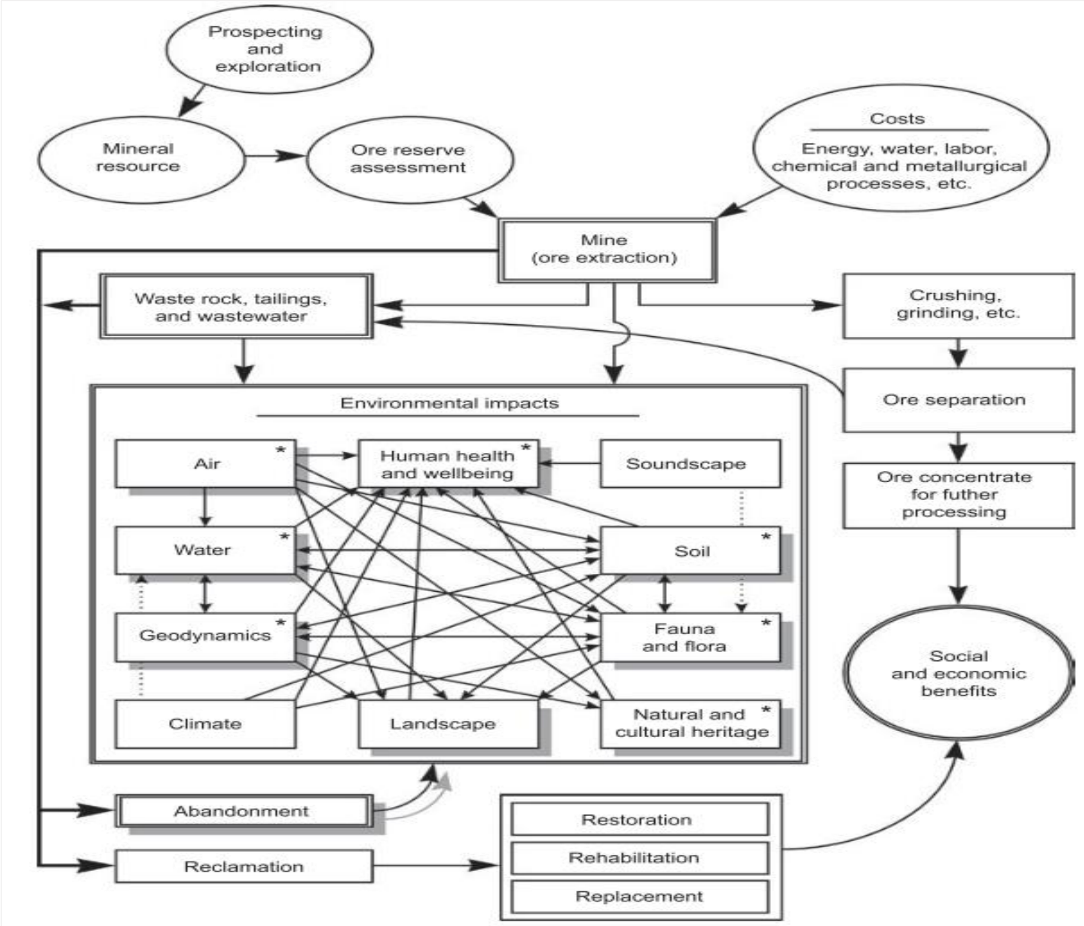

Figure 1. *Environmental impacts of a mine life cycle. Reprinted from (Vara Prasa et al., 2018)*

3.1.1 Legislative framework

The legislative framework regulates responsibility for the restoration of mine-affected areas to ensure that mining activities do not pose a risk to the environment, human health or safety. In the European Union, the Directive 2004/35/EC (European Parliament and of the Council, 2004) was promulgated regarding the prevention and repair of environmental damages. Later, The Directive 2006/21/EC (European Parliament and of the Council, 2006) was amended to include extractive waste from mining and quarries.

In Spain, quarrying is regulated by the laws Royal Legislative Decree 2994 (Ministerio de Industria y Energía, 1982) and Royal Legislative Decree 975 (Ministerio de la Presidencia, 2009), which include the responsibility for the restoration of natural areas affected by mining activities.

3.2 Restoration

After mining, the landscape should be returned to a functional unaffected state, for it, there are different solutions. *Restoration*: implies returning the site to its original conditions, including ecosystem function patterns and native vegetation species communities (Mert, 2019). However, restoration is not always possible, and then the goal becomes to partially return to the original state, which is named *Rehabilitation*. In other cases, due to economic and social reasons, the goal is *Replacement*; which replaces the initial land use with a different one to create a new landscape (Favas *et al*., 2018).

Restoration is a systematic process (Figure 2) that can be divided into 5 phases: **1.** geomorphic reshaping; **2**. Soil reconstruction; **3.** Hydrological stability; **4.** Re-vegetation and **5.** Re-building of the landscape ecology (Feng et al., 2019). Moreover, restoration can be approached in two different ways: the *"technical restoration"* which consists of using heavy machines, organic material cover and monotonous vegetation sowing (Figure 2), and the "*near-natural restoration*" approach which respects natural, spontaneous processes that can be manipulated or not (Rehounkova *et al*., 2011).

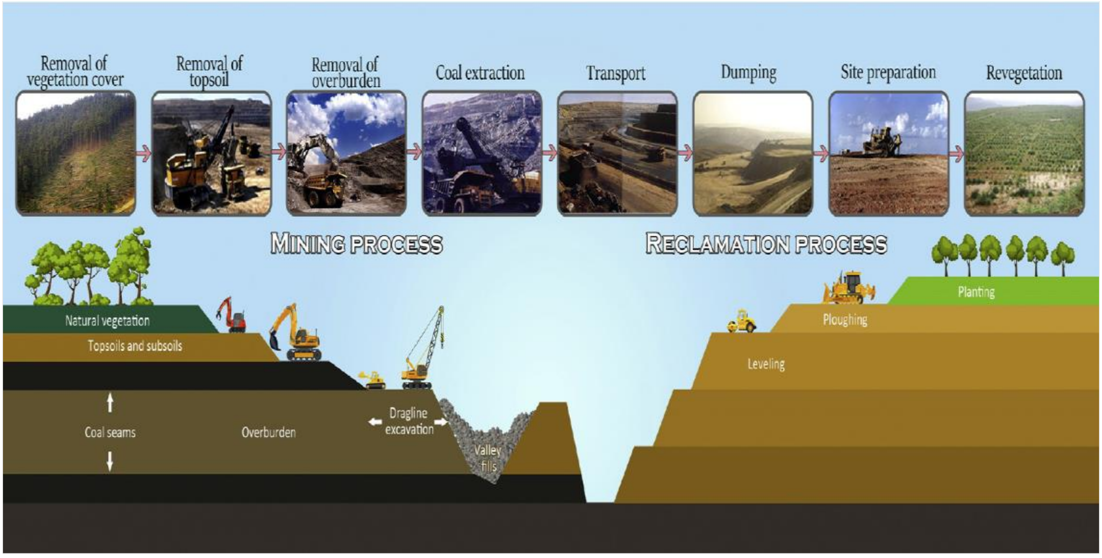

Figure 2. *Mining and reclamation process. Adapted from (Feng et al., 2019)*

3.2.1 Technical restoration

The technical reclamation process consists of levelling the topography with an overburden layer and in some cases cover it with organic topsoil to improve the substrate and establish a homogeneous vegetation cover. This approach might suppress habitat diversity and the natural value of spontaneous succession. However, quarries that contain toxic compounds, intensive erosion, or are close to human settlements need the technical reclamation process to achieve stable landforms, return the nutrient cycles and the functionality of a sustainable ecosystem (Rehounkova *et al*, 2011).

The first step of technical reclamation (level the topography) aims to achieve geotechnical stability to avoid mass movements and potential accidents. Therefore, conventional reclamation relief is modelled in the shape of a truncated pyramid with steep, rectilinear slopes and drainage ditches (Figure 3).

Figure 3*. Municipal District of Higueruelas. Valencia. Reprinted with permission of the authors from (Beseler et al., 2018)*

In the long term, this type of topography is unable to sustain functional ecosystems because it has poor ability to retain water (on-site effect) hence produces high runoff rates and sediment which affect natural watercourses (off-site effects) and increases the negative environmental impacts of mining. (Valladares *et al*., 2011).

That is the case for restored quarries located in Mediterranean climates. The slopes restored employing the conventional approach have high runoff rates that generate a loss of water in two different ways (see Figure 4) **a:** Crust formation and loss of roughness that decrease the water infiltration rate. **b:** Forming of rill networks allows runoff pathways to drive water out of the system (Moreno-de las Heras *et al*., 2011). Consequently, rainfall erosion accelerates the loss of the organic layer of soil and reduces water availability, which is key for vegetation development (Nicolau, 2002).

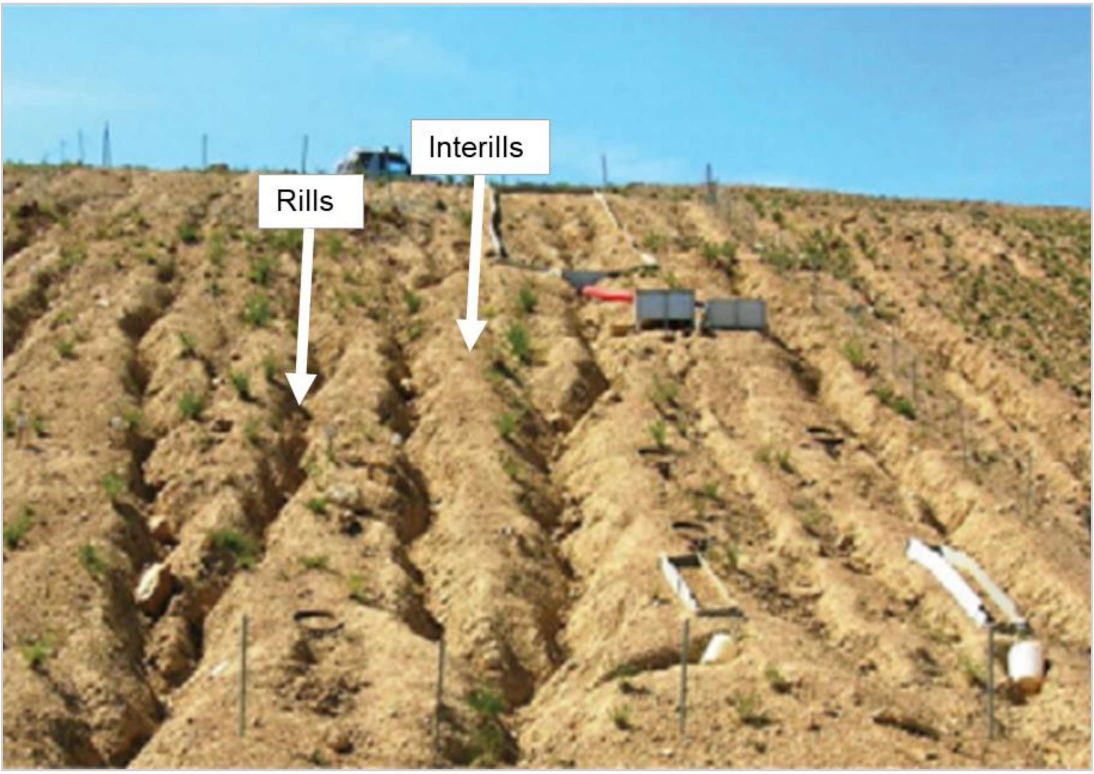

***Figure 4**. Runoff erosion in Slopes of quarry restored. Modified from: (Moreno-de las Heras et al., 2011)*

The ecohydrology of the slopes in conventional reclaimed quarries in Spain have been studied before, a study made in El Moral quarry in Teruel municipality Spain under the Mediterranean climate (Nicolau *et al*., 2012) identified three different slope types:

a) Slopes with a dense network of continuous streams, Rills and Inter-rills (Figure 4), in which the ecological succession is very limited and the vegetation is scarce (Figure 5, slopes 1)
b) Slopes with discontinuous rills and inter-rills, which have developed herbaceous communities in small isolated patches and this slope have an exporting and importing runoff dynamics between the "clear and bushes" (Figure 5, slopes type 2 and 3)
c) Slopes without erosion processes (rills and inter-rills) and that have established communities of shrub species that control the flow of water and sediments (Figure 5, Slopes 4).

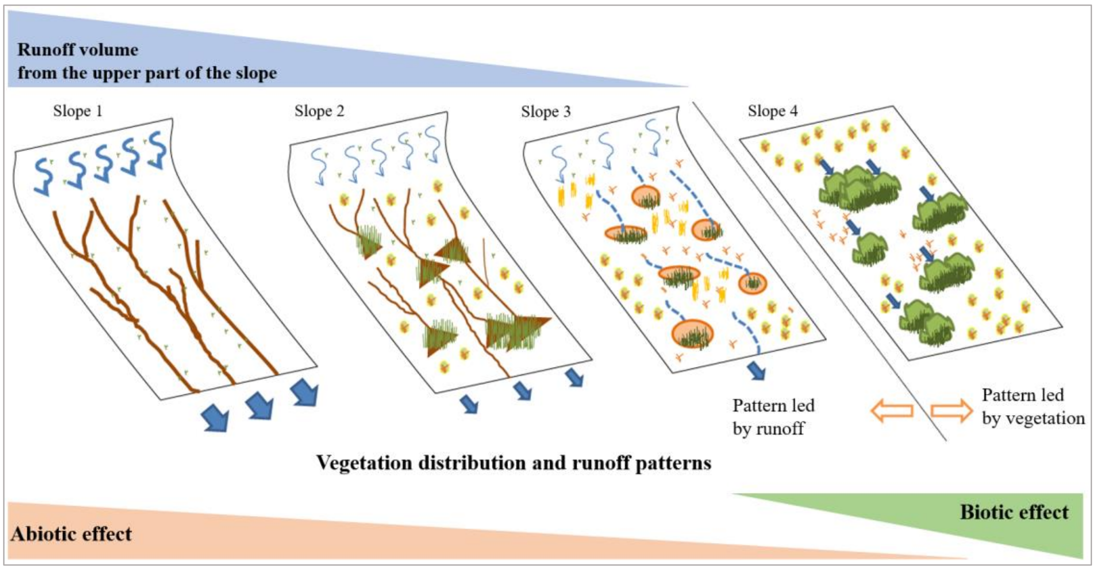

Figure 5. *Ecohydrology of restored slopes in Mediterranean quarries. Modified from (Jose Manuel Nicolau et al., 2012)*

3.2.2 Geomorphic restoration

Despite the improvement of reclamation techniques during the last decades, they have focused on revegetation rather than landform re-creation. To develop a sustainable reclaimed landscape, it must be reconstructed based on geohydrological patterns. (Devito *et al*., 2012)

Also, the reclamation technique must take into account not only landform stability design but also the heterogeneity of substrates and topography to create landforms with different scale and properties (physical and chemical) which will in turn influence water storage and movement (Macdonald *et al*., 2015) and thus ensure a stable relationship between soil, water and vegetation (Feng *et al*., 2019).

Such an approach is called "Geomorphic restoration" which designs natural landforms and streams that replicate the appearance and functionality of the natural environment. It recreates the structure of watersheds, where the high slopes, terraces and ditches (conventional restoration) are replaced by smooth wavy slopes and meandering streams (Figure 6) which decrease erosion and runoff (Zapico *et al*., 2018).

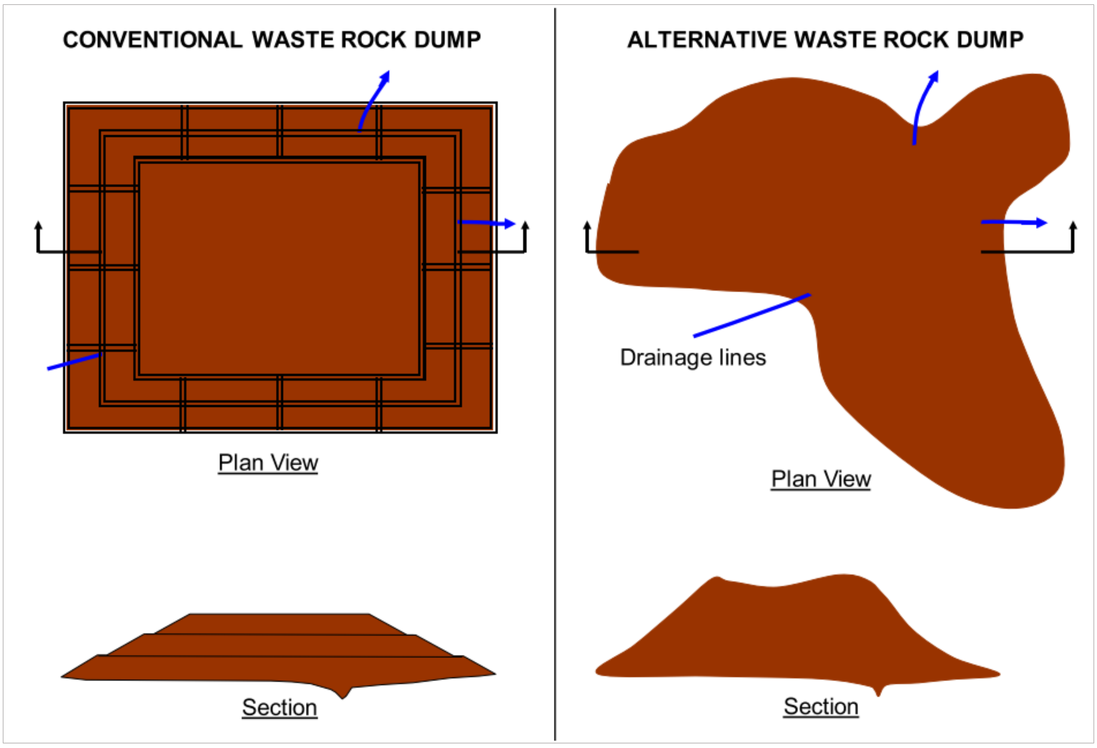

Figure 6. *Conventional and alternative layout for restoration. Adapted from (Garbarino et al., 2018)*

On one hand, the geomorphic approach addresses problems on-site as physical stability, runoff and sediment loss. Moreover, the diverse landforms promote diversity of vegetation and wildlife communities (Garbarino *et al*., 2018). On the other hand, regarding off-site effects, the geomorphic approach promotes hydrological connectivity and restored landscapes blend seamlessly with the surrounding environment. (Martin Duque & Bugosh, 2014).

4 Characteristics of the study area

This study has been made with data from two different quarries in Spain (Figure 7) southwestern Europe. In the following section, the characteristics and context of each quarry are described.

4.1 The Aurora Quarry

The Aurora quarry is located in Campredón municipality, Catalonia, Eastern Spain. The study area is part of a mine complex that belongs to CEMEX S.A. Where clay is extracted.

This area has a Mediterranean climate with a coastal influence characterized by mild winters and warm summers. Summers are dry, rainfall concentrates in autumn and winter. The average annual precipitation and temperature are 522 mm and 16 ºC respectively. However, during the study year, there was a severe drought which decreased the annual precipitation to 340 mm. (Agencia Estatal de Meteorología, 2020).

The project LIFE+ ECOREST CLAY BIO/ES/000926 (European Commission, n.d.-a) implemented a geomorphic restoration treatment in three different areas of the Aurora quarry, using GeoFluv ™ method (Martin Duque & Bugosh, 2014). This study was based on an area restored by Geo Fluv ™, called GF and an area restored by a conventional treatment called TC.

Figure 7. *Location of study quarries in Spain.*

4.2 The Fortuna quarry

The Fortuna quarry is located in the municipality of Ademuz (Valencia, Spain) and it is the property of the Sibelco mining company where they mined siliceous sand, kaolin and clay.

The area has a transitional climate between the continental and the Mediterranean areas of the Iberian Peninsula. Winters are cold and summers are warm with maximum temperatures above 40 °C, rainfall is scarce but evenly distributed throughout the year, and in winter it can be in the form of snow. (Agencia Estatal de Meteorología, 2020).

The project LIFE TECMINE (Conselleria de Agricultura Desarrollo Rural Emergencia Climática y Transición Ecológica, 2015) restored three areas of the Fortuna quarry using the geomorphic approach by GeoFluv™ method (Martin Duque & Bugosh, 2014), restored areas have been built using mine spoils or overburden materials.

This study is based on the units restored by GeoFluv™ (GFG, GFP, GFEst) and include two areas that were restored using the conventional approach (TC, TM).

5 Methodology

5.1 Experimental design

Soil moisture measurements were made using the Time Domain Reflectometry technique (TDR, Rajkai & Rydén, 1992). A Campbell TDR 100 (Figure 9) was used in the Aurora quarry (Campbell Scienfic, 2000) and a Tektronix 1502 TDR in the Fortuna quarry. Sampling points consisted of a pair of metal rods (23 cm long) nailed into the soil up to 20 cm depth with a separation between them of 5 cm (Figure 8). In the next section, the experimental design of each quarry is explained.

Figure 8. *Pair of metal rods 20 cm deep into the soil. Reprinted with the permission of the author (Lalaguna, 2016)*

Figure 9. *TDR 100 connected with sensors to metal rods. Reprinted with the permission of the author (Lalaguna, 2016)*

5.1.1 The Aurora quarry

During the restoration activities, the landforms (Divide, slope and valley) were built with different aspects (facing north and south) and two different types of topsoil were spread over the landforms: **Colluvium:** material coming from natural slope erosion; it is composed of limestone fragments, organic matter and a matrix of fine sediments and **Clayey topsoil**: natural soil removed before mine operation from abandoned field crops, then stored and finally spread out on the constructed topography.

The sampling points were distributed throughout the geomorphic restoration treatment (Figure 10), to sample the different landforms (transverse pattern) and from the upper to the bottom (longitudinal pattern), the aspect and the type of substrate (Lalaguna, 2016).

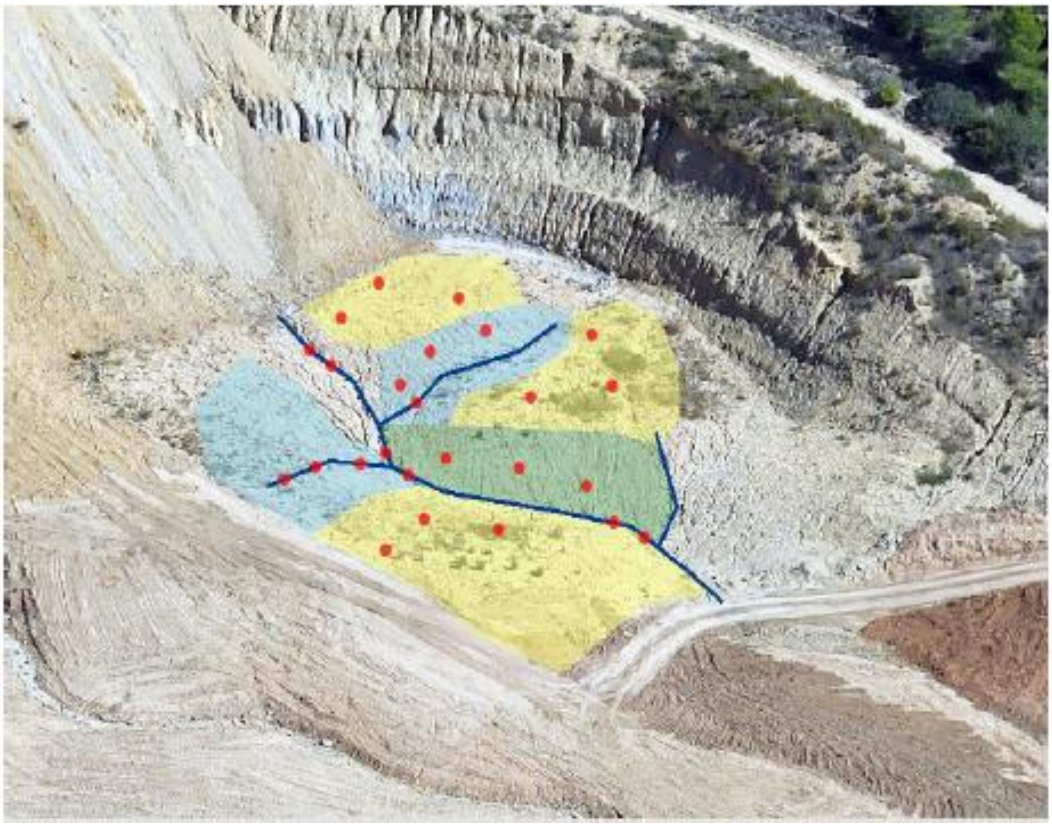

Figure 10. Distribution of sampling points on Aurora quarry. Red dots correspond to the sampling points, Blue areas are valley and yellow areas are slope. Reprinted with the permission of the author (Lalaguna, 2016).

During restoration activities, the TC slope was covered with Overburden. Additionally, over time rills and inter-rills network formed creating landforms over the slope.

The sampling points were distributed from the top to the foot of the slope (longitudinal pattern) and in the transversal landforms (Rills and Inter-rills). Forming 3 transects perpendicular to the slope with 7 sampling points each (Figure 11).

Figure 11. *Distribution of sampling points in the slope restored by the conventional approach in Aurora quarry. TA: top of the slop, TM: middle slope, TB: Bottom slope. Each transect had seven sampling points. Reprinted with the permission of the author (Lalaguna, 2016)*

Treatment	**Unit**	**Landform**	**Aspect**	**Substrate type**	**Transect**	**Sampling points** (per transects)
Geomorphic restoration	GF	Divide	North	Clayey topsoil	1	3
		Slope	North	Clayey topsoil	1	3
		Valley	North	Clayey topsoil	1	3
		Divide	South	Colluvium	1	3
		Slope	South	Clayey topsoil	1	3
		Valley	South	Colluvium	1	4
Conventional restoration	TC	Slope		Overburden	3	7

Table 1. *Sampling design in the Aurora quarry*

Soil moisture was measured between June 2015 and November 2017 in the geomorphic restoration area; with a total of 26 visits. The measures in the conventional restoration were made from November 2016 to November 2017; with a total of 12 visits. Data were collected by the research group as part of the ECOREST CLAY LIFE12 BIO/ES/000926 project (European Commission, n.d.-a) and data processed and analyzed by the author.

5.1.2 The Fortuna quarry

Sampling points were established in geomorphic and conventional treatments of the quarry: three of them within geomorphic restoration (Units GFG, GFP and GFEst); two within conventional restoration (Units TC and TM). Sampling points were also established in a vegetated area undisturbed by mining which was considered to be the reference ecosystem (ER). Table 2 summarizes the design of sampling points within the Fortuna quarry.

- **GFG**: The area was built with two micro basins, each facing north and south aspect, each of them included three landforms (divide, slope and valley). A colluvium substrate was spread in both of them and within the slopes were built micro catchments that drive surface runoff toward planting holes(Constantini et al., 2015; Velacantos et al., 2014).

  The Shady area was divided into 4 transects from the upper part to the bottom (longitudinal pattern), each transect had 5 sampling points nailed in different landforms (transverse pattern), see Figure 12.

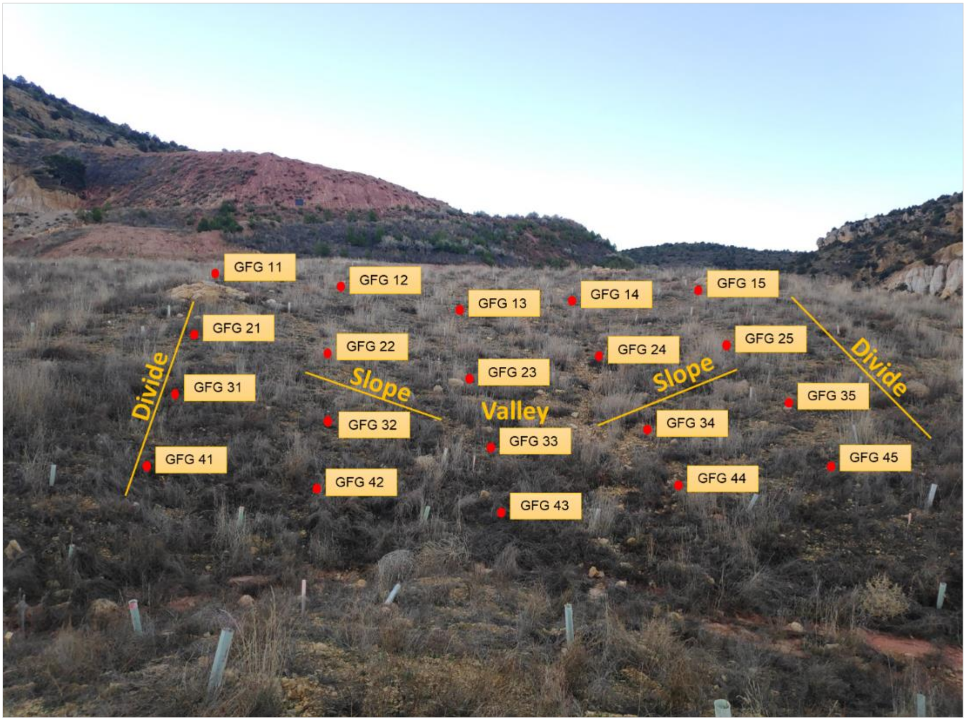

Figure 12*. Distribution of sampling points in GFG, Shady Slope unit in Fortuna quarry. Red dots correspond to the sampling points and lines show the different landforms.*

- In the area facing south, the sampling points were distributed with a longitudinal pattern and in the transversal landforms, forming 3 perpendicular transects through the micro basin with 5 sampling points each (Figure 13)

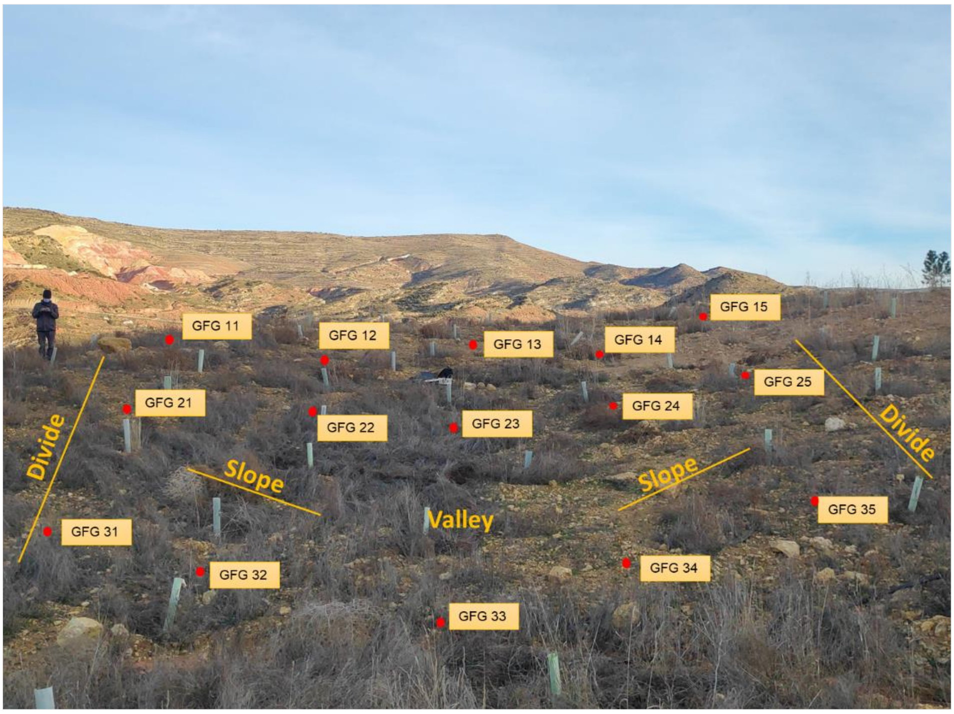

Figure 13. Distribution of sampling points in GFG, Sunny Slope unit in Fortuna quarry. Red dots correspond to the sampling points and lines show the different landforms.

- **GFEst:** This unit faces south and was covered by overburden material. Sampling points were placed in three transects perpendicular to the slope from the upper part to the bottom, each transect with 5 sampling points located in different landforms (Figure 14).

Figure 14. *Distribution of sampling points in GFEst unit (GFEst) in Fortuna quarry. The red dot corresponds to the sampling points and lines show the different landforms.*

- **GFP**: The unit was built with two areas, one facing west and the other facing east, the sampling points were distributed in each area with 3 transects, each of them with 5 sampling points through the different landforms (Figure 15).

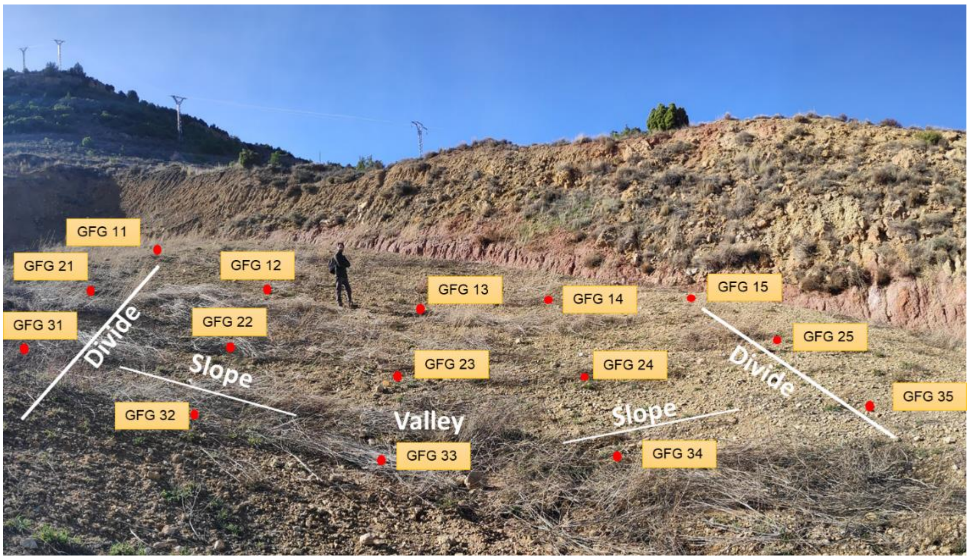

Figure 15. *Distribution of sampling points in the GFP unit in Fortuna quarry. Red dots correspond to sampling points and lines show the different landforms*

- **TC, TM**: There were 2 areas restored with the conventional approach, one of them with an organic blanket over the substrate (TM) and the other without it (TC). In both of them, sampling points were established in 3 transects from the upper part to the bottom of the slope, each transect with 5 sampling points (Figure 16).

Figure 16. Distribution of sampling points in Conventional restoration TC, TM units in Fortuna quarry. Red dots correspond to the sampling point, arrow showing the direction of the slope. Modified from: Ortophoto from Life+Tecmine project (Conselleria de Agricultura Desarrollo Rural Emergencia Climática y Transición Ecológica, 2015).

- **ER:** In an area of undisturbed vegetation 5 transects were established, each of them with 3 sampling points.

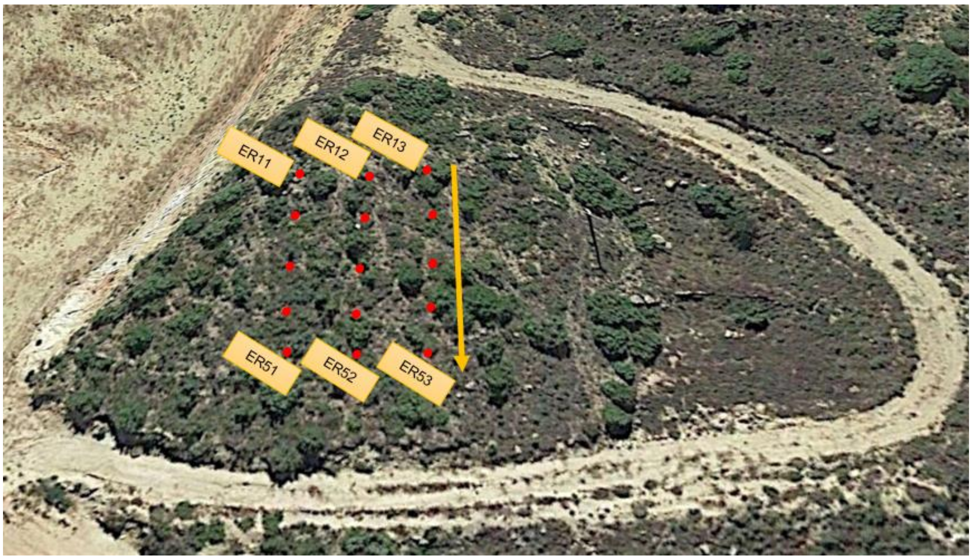

Figure 17. Distribution of sampling points in the reference ecosystem area. Red dots correspond to the sampling point, the arrow is showing the direction of the slope. Modified from: Google Earth Pro. Date capture 17/9/2017.

Treatment	Unit	Landform	Aspect	Substrate type	Transects	Sampling points (per transect)
Geomorphic restoration	GFG	Drainage divide	North	Colluvium	4	2
		Slope	North	Colluvium	4	2
		Valley	North	Colluvium	4	1
		Drainage divide	South	Colluvium	3	2
		Slope	South	Colluvium	3	2
		Valley	South	Colluvium	3	1
	GFP	Drainage divide	Este	Colluvium	3	2
		Slope	Este	Colluvium	3	2
		Valley	Este	Colluvium	3	1
		Drainage divide	West	Colluvium	1	3
		Slope	West	Colluvium	3	3
		Valley	West		1	3
	GF Est	Drainage divide	South	Overburden	3	2
		Slope	South	Overburden	3	2
		Valley	South	Overburden	3	1
Conventional restoration	TC	Slope	North	Overburden	3	5
	TM	Slope	North	Overburden + organic layer	3	5
Reference ecosystem	ER	Slope	North	Vegetation cover	5	3

Table 2. *Design sampling points in Fortuna quarry.*

Soil moisture content was monitoring during August 2019 and December 2020 with a total of 11 visits. However, the GFEst unit was measured between June 2019 and December 2020, with a total of 5 visits.

Data was collected by the research group as part of the LIFE + TECMINE project (Conselleria de Agricultura Desarrollo Rural Emergencia Climática y Transición Ecológica, 2015). The author took part in collecting data from October to December 2020 processed the data, built a database and analyzed it.

5.2 Data analysis

The hypothesis was that soil moisture values (dependent variable) change depending on Treatment, Landform, Aspect, Substrate type and Transects. When the model assumptions were met or data could be transformed (log, square root) a mixed linear model of repeated measures was used employing the “nlme” R package (Pinheiro, Bates, DebRoy, D, & R Core Team, 2014). If model assumptions were not met, a non-parametric test (Friedman) was used including the “*visit*” as a repeated-measures (Mendiburu & Yaseen, 2020). To use the Friedman test data needed to be aggregated.

To detect differences among factors, a post hoc pairwise test was carried employing the *emmeans* command of the “nlme” R package or using Wilcoxon signed-rank test if the data fitted the model requirements. All statistical tests were performed with R Studio software (R Core Team, 2020). Results were considered statistically significant if *p-values* were lower than 0.05. See Figure 18 for a diagram showing the analysis flow.

The analyses were carried out in two different time frames. 1: Using data from all visits made during the study period, 2: Using the visits corresponding to the rainy season between the end of autumn and the beginning of spring, referred to as the recharge period.

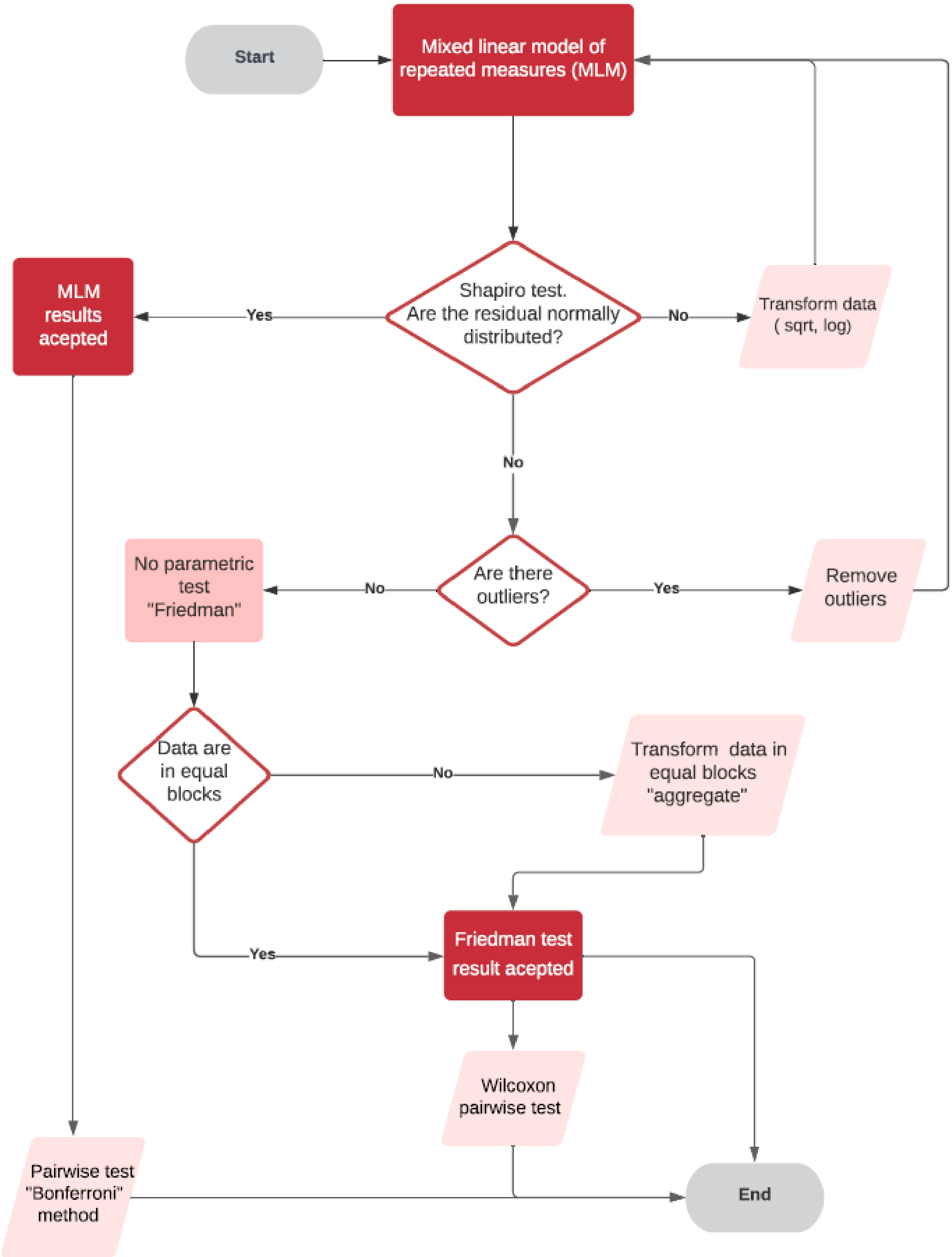

Figure 18. *Flow chart of the statistical process used to analyze soil moisture data.*

6 Results

6.1 Soil moisture content differences between conventional and geomorphic restoration treatments.

6.1.1 The Fortuna quarry

The ER unit had higher values of SMC between December 2019 and February 2019 than conventional and geomorphic restoration treatments. However, between June 2020 and October 2020 the geomorphic restored units GFG-GFP showed higher values than ER. Instead, the conventionally restored approaches (TC, TM) showed the lowest contents of soil moisture throughout the study period (Figure 19).

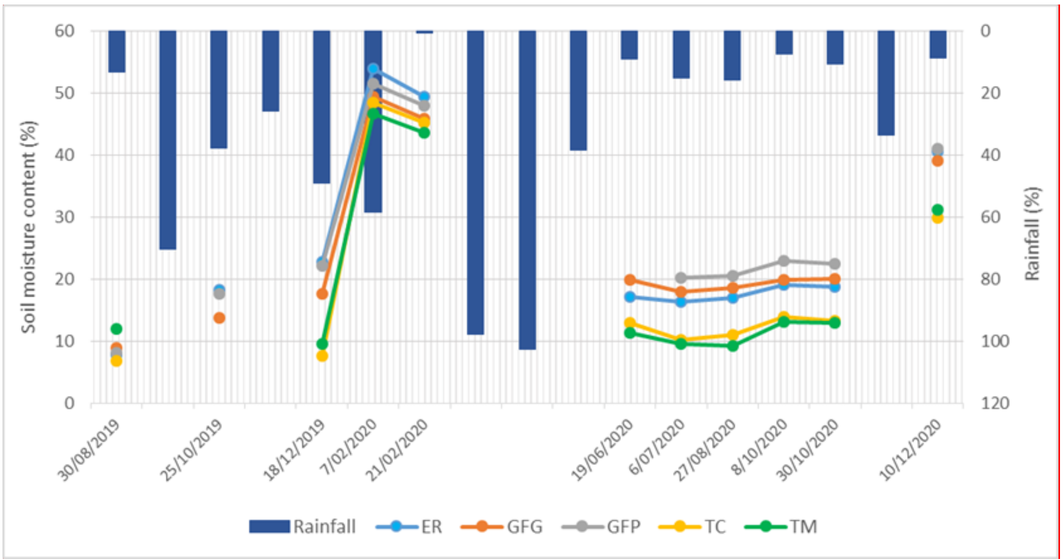

Figure 19 *Monthly rainfall and SMC per treatment in the Fortuna quarry, during the data collection period. ER: Reference ecosystem area, GFG, GFP: two units of geomorphic restoration treatment, TC, TM: two different units of conventional restoration treatment.*

The GFP unit showed 2% higher mean SMC than the ER and 7% higher than the TC and TM values, which were the lowest values among the units (Table 3).

Treatment	Mean ± SD
ER	25.7 ± 14.6
GFG	24.9 ± 13.4
GFP	27.7 ± 14.1
TC	20.4 ± 15.2
TM	20.2 ± 14.6

Table 3. *Mean and standard deviation of SMC per treatment in the Fortuna quarry. Data from 9 visits (n) due to technical issues in the measurement equipment.*

The results of the Friedman test showed significant differences among Fortuna treatments (chi-square = 23, df = 4, p-value < 0.01) with SMC in the unit TC significantly lower than the others (Wilcoxon test, Figure 20).

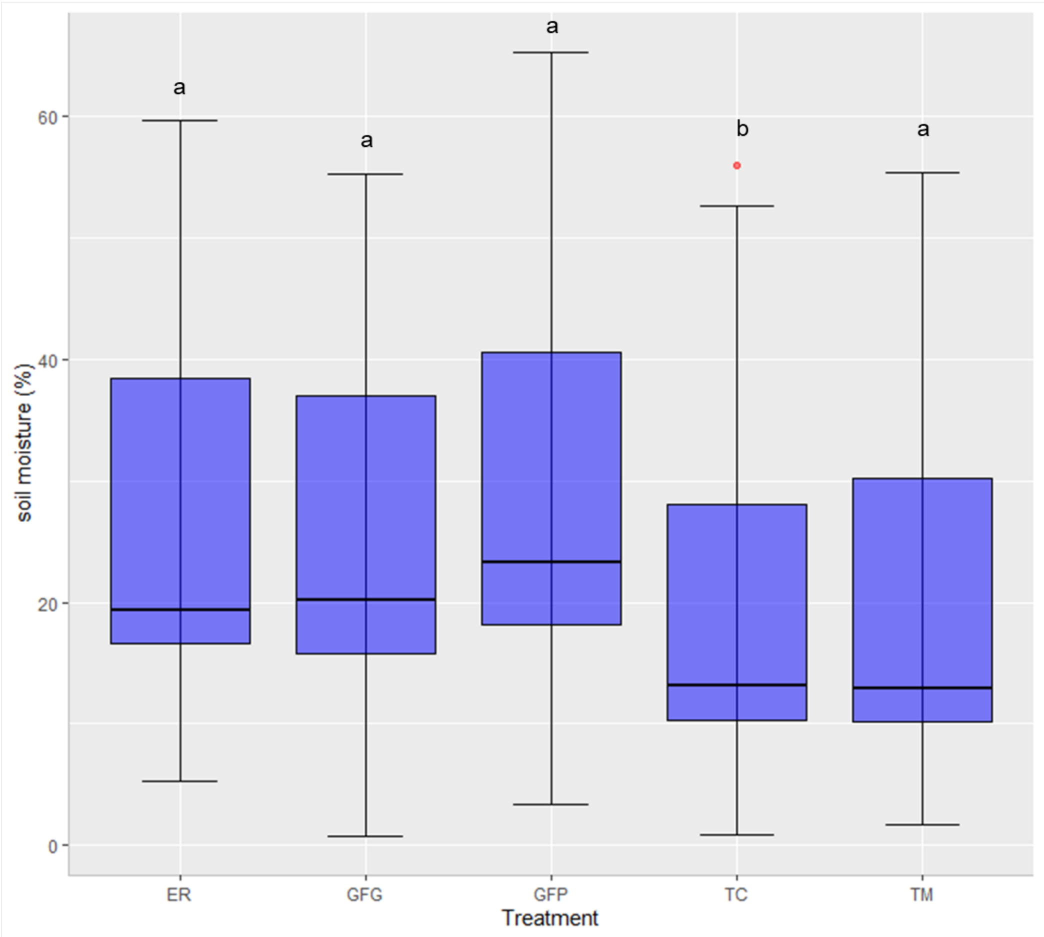

Figure 20. *SMC per treatment in the Fortuna quarry. Box shows 1st, median and 3rd quartiles, whiskers min and max values and dots represent outliers. Different letters indicate different groups based on the Wilcoxon test.*

During the recharge period, the ER presented the highest values during the months of 2019-2020. However, the GFP presented higher moisture in October and December 2020 (Figure 21).

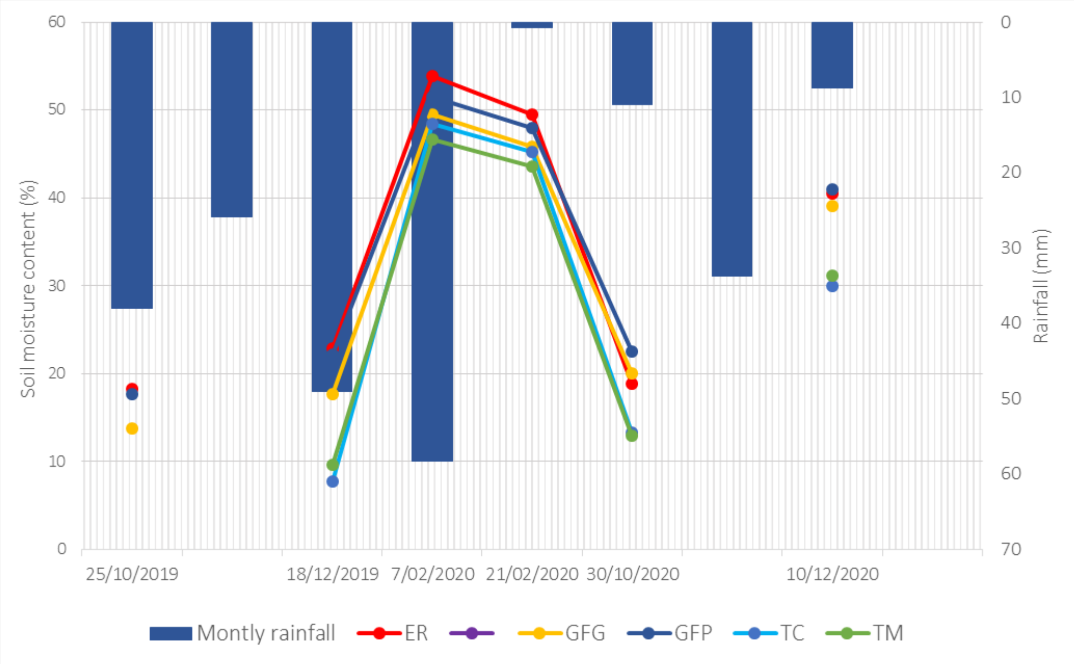

Figure 21. *Monthly rainfall amount and SMC in each treatment during the recharge period in the Fortuna Quarry. ER: Reference ecosystem area, GFG, GFP: two units of geomorphic restoration treatment, TC, TM: two different units of conventional restoration treatment*

The GFP and ER units had mean soil moisture values above 30% and a 5% higher than the TC, which had soil moisture values around 26% (Table 4). However, data collected during the recharge period were not enough to run the tests.

Treatment	Mean ± SD
ER	31.8 ± 15.6
GFG	29.4 ± 14.9
GFP	32.2 ± 14.1
TC	26.4 ± 17.5
TM	26.2 ± 16.5

Table 4*. The mean and standard deviation of SMC per treatment in Fortuna quarry, data from 7 visits within the recharge period.*

6.1.2 *The Aurora quarry*

The GF treatment had a higher SMC than TC treatment during the entire data collection period (Figure 22). In fact, the SMC mean of the GF (mean = 13.2%, SD = 5.8; n = 12) was 2.8% higher than mean SMC of TC (mean = 10.4%, SD = 7.1; n = 12), The Friedman test showed that GF and TC treatments were significantly different (chi-square = 12, df = 1, p-value < 0.01, Figure 23).

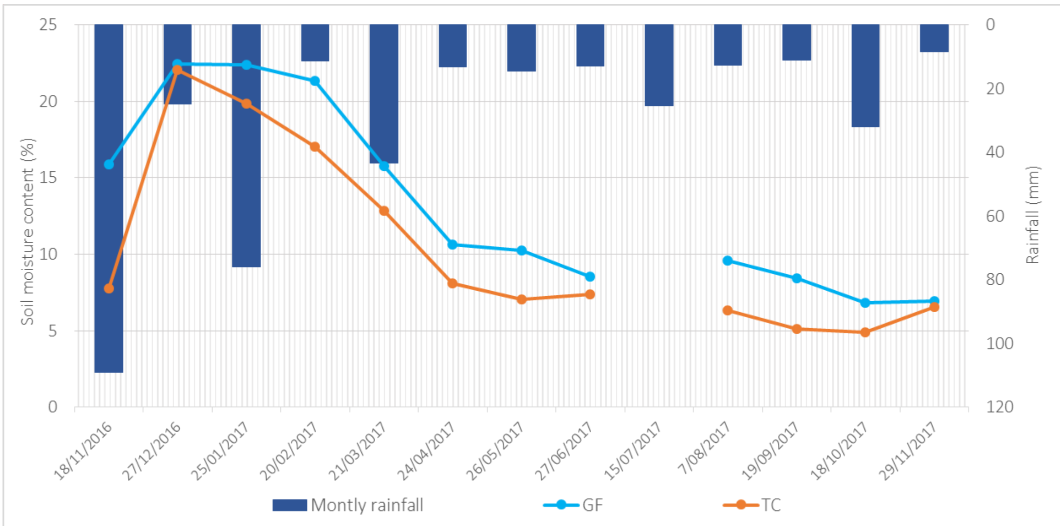

***Figure 22**. Monthly rainfall amount and SMC in each treatment in Aurora quarry. GF: geomorphic restoration treatment, TC: conventional restoration treatment.*

During the recharge period, the treatments showed the same trend (Figure 24) as the previous analysis (Figure 24), SMC at GF (mean = 15.9%, SD = 7.4; n = 6) was 2.7% higher than at TC (mean = 13.2%, SD = 7.5; n = 6). However, data collected during the recharge period were not enough to run the tests.

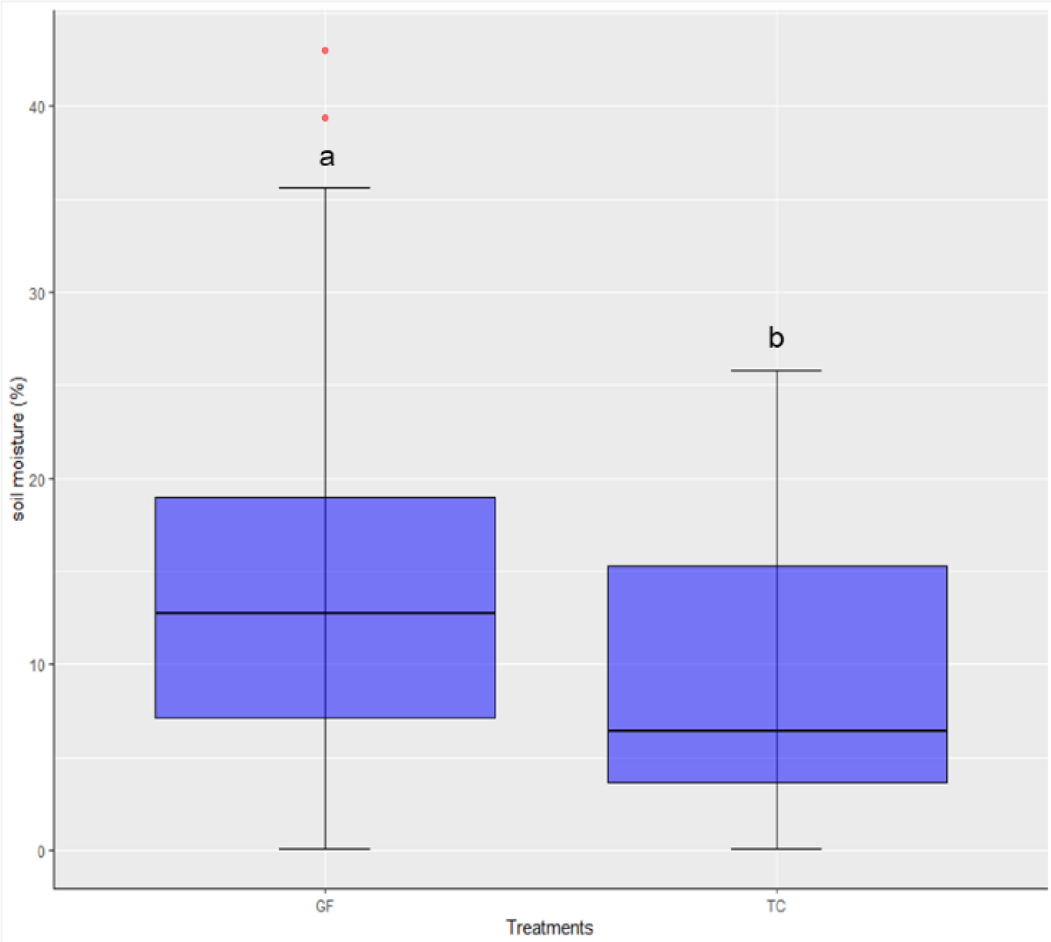

Figure 23. *SMC per treatment in the Aurora quarry. Box shows 1st, median and 3rd quartiles, whiskers min and max values and dots represent outliers. Different letters indicate different groups based on the Wilcoxon test.*

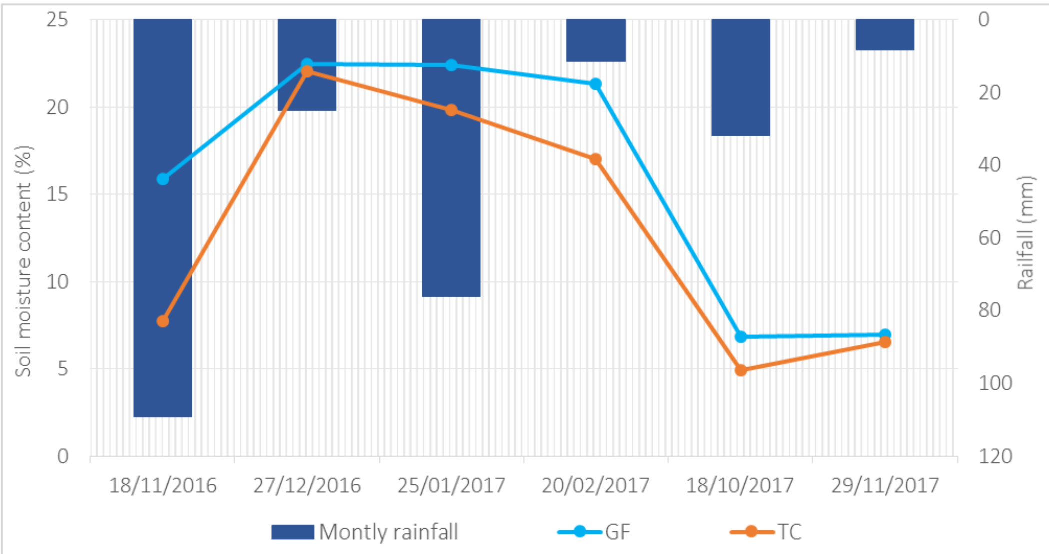

Figure 24. *Monthly rainfall amount and SMC in each treatment in Aurora quarry during the recharge period. GF: geomorphic restoration treatment, TC: conventional restoration treatment.*

Slope Inter-rills a unit of TC treatment showed lower values than the rest of the units from GF treatment throughout the study period (Figure 25), Shady slope and Shady valley units had the highest values.

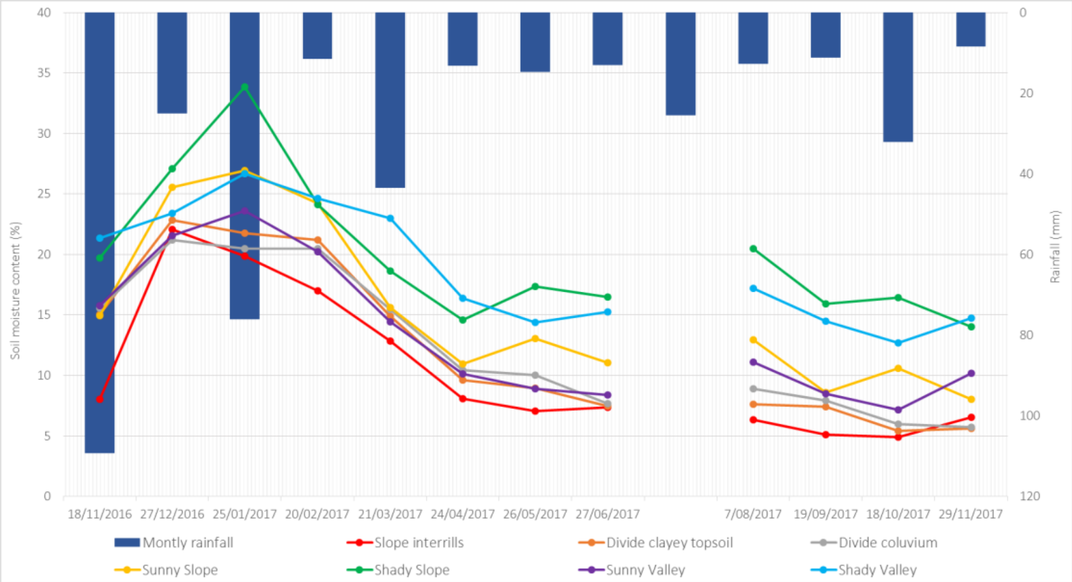

Figure 25. *Monthly rainfall amount and SMC in each unit in Aurora quarry. Sunny slope, Shady slope, Sunny Valley, Shady Valley, Divide clayey topsoil and Divide colluvium: units of GF (geomorphic restoration treatment), Slope inter-rills: a unit of TC (conventional restoration treatment).*

The shady slope had a higher SMC, which was 1% higher than in Shady Valley. Slope Inter-rills showed a 9.5% and 8% SMC lower than Shady slope and valley (Table 5).

Unit	Mean ± SD
Slope Inter-rills	10.4 ± 6.0
Divide clayey topsoil	12.3 ± 6.6
Divide colluvium	12.5 ± 5.9
Sunny Slope	15.2 ± 6.7
Shady Slope	19.9 ± 5.8
Sunny Valley	13.3 ± 5.7
Shady Valley	18.7 ± 4.8

Table 5. *The mean and standard deviation of SMC per unit of the treatments in the Aurora quarry, data from 12 visits (n).*

The Friedman test showed significant differences among units (chi-squared = 58.143, df = 6, p-value < 0.01) and the Wilcoxon test separated the units into two different groups (Figure 26).

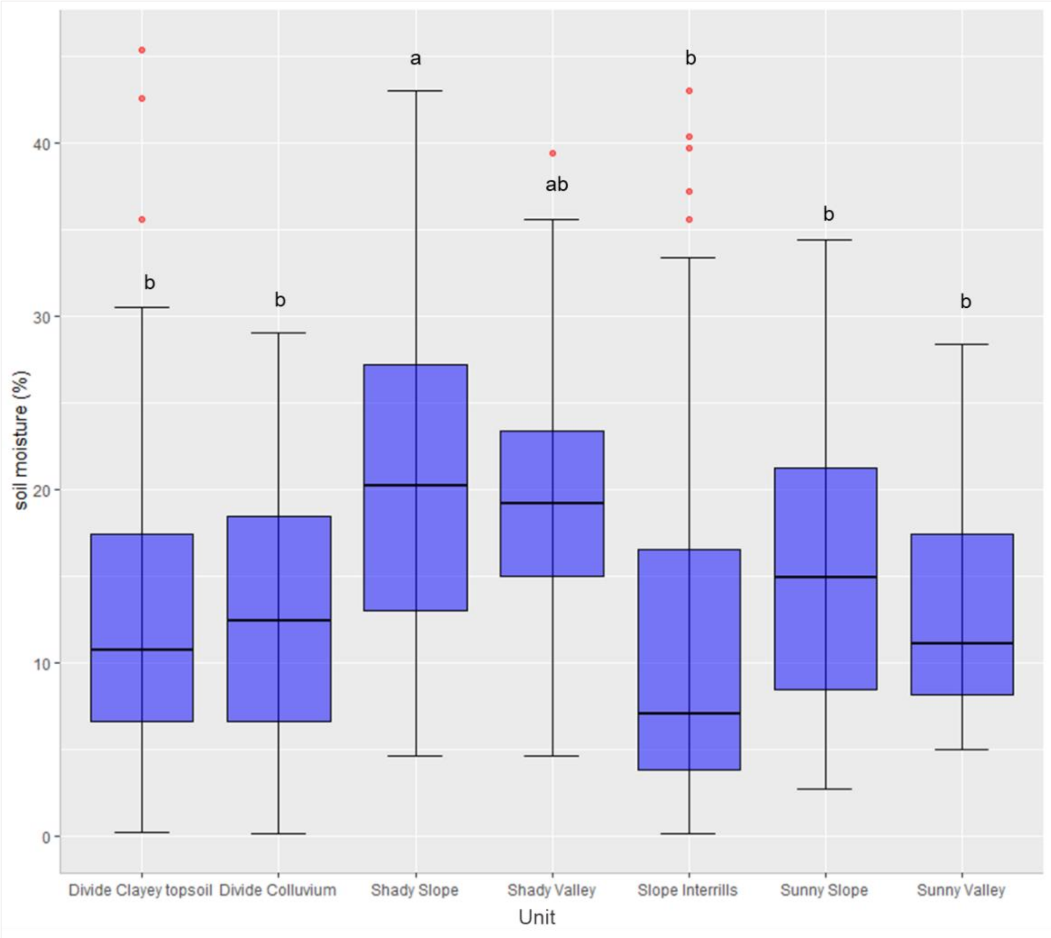

Figure 26. *SMC per units in the Aurora quarry. Box shows 1st, median and 3rd quartiles, whiskers min and max values and dots represent outliers. Different letters indicate different groups based on the Wilcoxon test.*

During the recharge period, the Shady slope unit had higher moisture values than the rest of the units (Figure 27). Divide colluvium, Divide clayey topsoil and Sunny Valley showed almost the same values along the recharge period and Slope Inter-rills had the lower value of soil moisture throughout the recharge period.

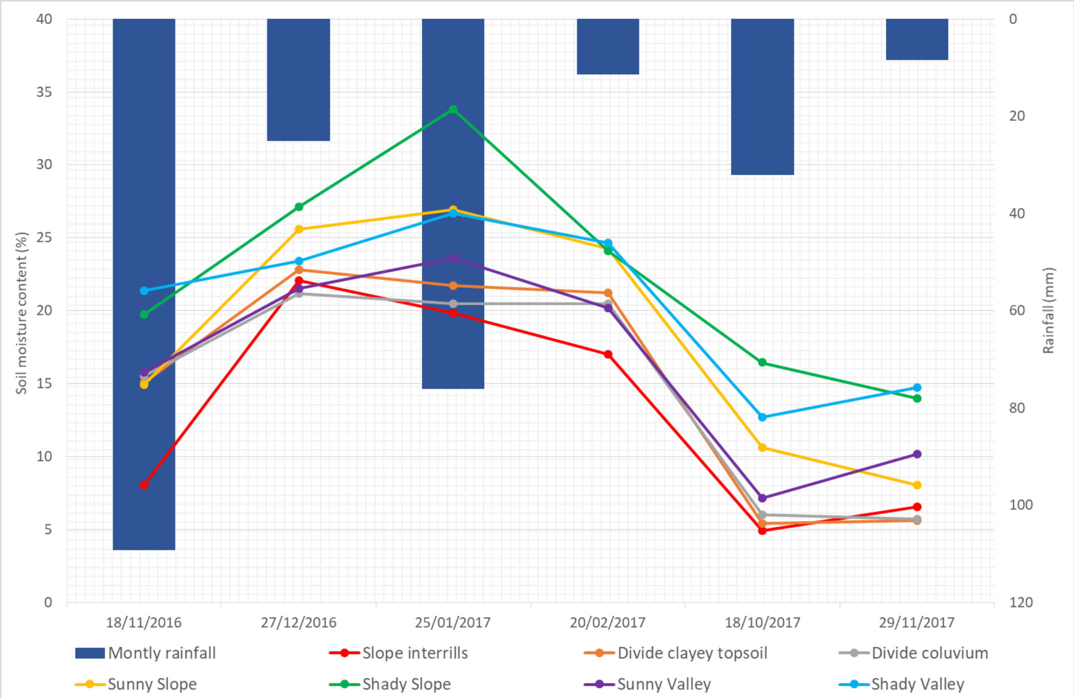

Figure 27. Monthly rainfall amount and SMC in each unit in the Aurora quarry during the recharge period. Sunny slope, Shady slope, Sunny Valley, Shady Valley, Divide clayey topsoil and Divide colluvium: units of GF (geomorphic restoration treatment), Slope inter-rills: a unit of TC (conventional restoration treatment).

The unit with the highest mean SMC during the recharge period was the Shady slope, which had 9.2% higher mean moisture than the Slope Inter rill unit of the conventional treatment which had the lowest SMC (Table 6). However, data collected during the recharge period were not enough to run the tests.

Unit	Mean ± SD
Slope Inter-rills	13.3 ± 9.0
Divide clayey topsoil	15.3 ± 8.4
Divide colluvium	15.1 ± 7.3
Sunny Slope	18.3 ± 9.4
Shady Slope	22.5 ± 9.2
Sunny Valley	16.4 ± 6.5
Shady Valley	20.8 ± 9.0

Table 6. The mean and standard deviation of SMC per units of the treatment in Aurora quarry, data from 6 visits (n).

6.2 Analysis of the soil moisture in different substrate type.

6.2.1 The Fortuna quarry

The reference ecosystem soil and the colluvium substrate registered higher soil moisture values than Overburden throughout the data collection period (Figure 28).

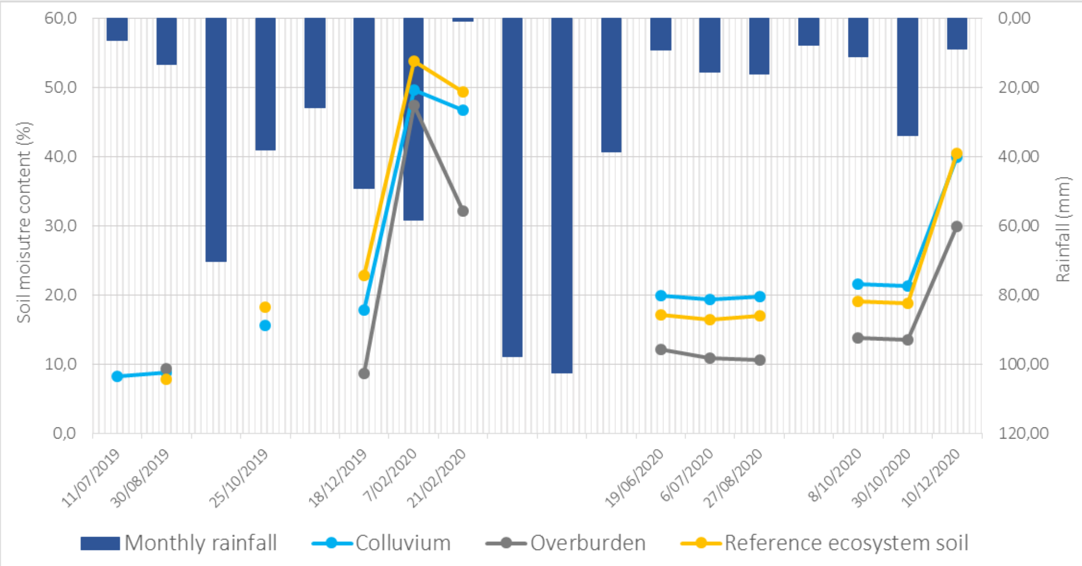

Figure 28. *Monthly rainfall amount and SMC in different substrate types across the Fortuna quarry and references ecosystem soil.*

The Colluvium substrate and the reference ecosystem soil had mean SMC values above 24%. On the other hand, the overburden substrate had a moisture content 6% lower than the other two substrates (Table 7).

Substrate	**Mean ± SD**
Colluvium	24.1 ± 13.9
Overburden	18.9 ± 13.1
Reference ecosystem soil	25.6 ± 15.1

Table 7*. The mean and standard deviation of SMC in different substrate types in Fortuna quarry. Data from 12 visits (n).*

The Friedman test showed that substrate types were significantly different (chi-squared = 9.8, df = 2, *p*-value < 0.01). The Wilcoxon test separated two groups, overburden vs colluvium and reference ecosystem soil (Figure 29)

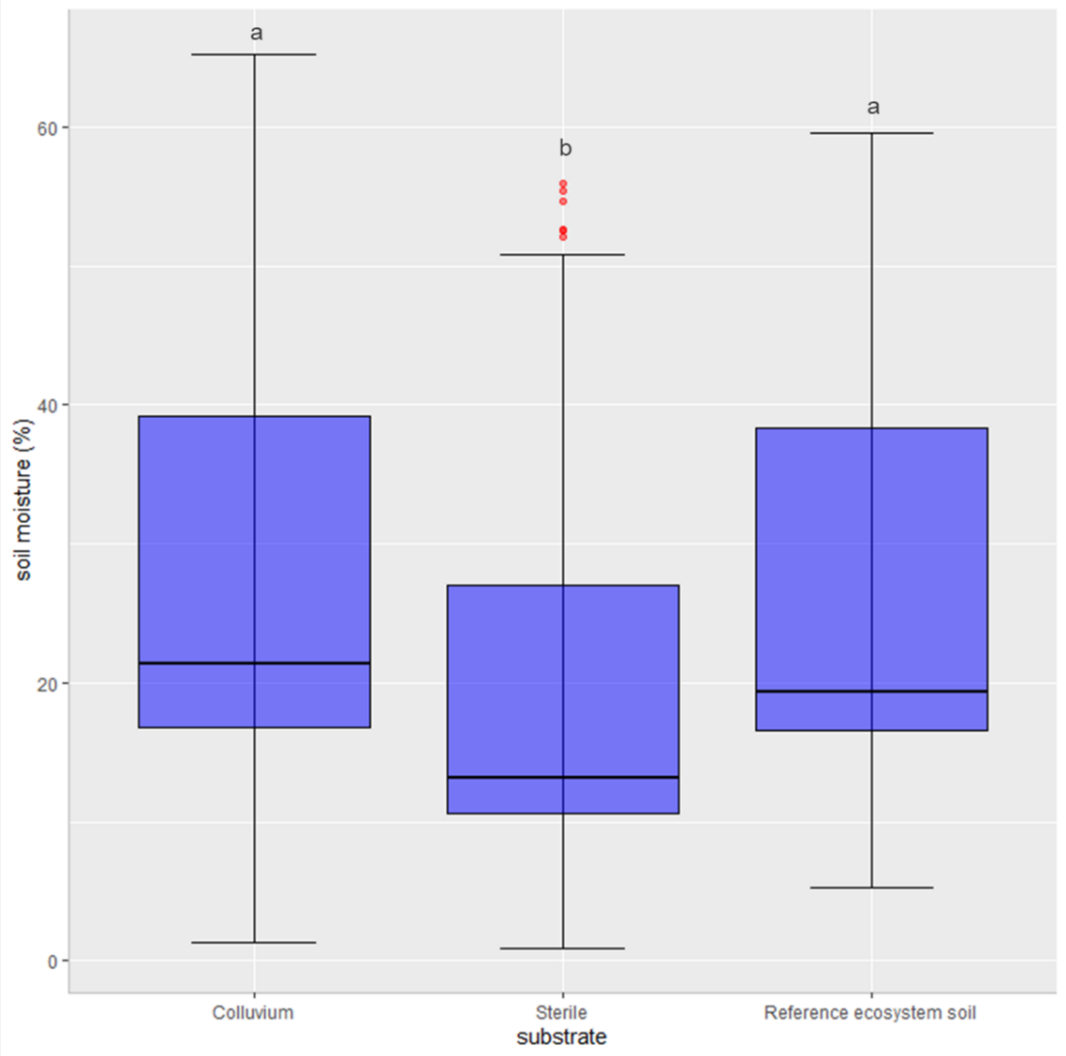

Figure 29. *SMC in substrate types in the Fortuna quarry. Box shows 1st, median and 3rd quartiles, whiskers min and max values and dots represent outliers. Different letters indicate different groups based on the Wilcoxon test. The term Sterile refers to overburden substrate.*

Inside the geomorphic treatment, taking into account the GFEst unit, the colluvium substrate (mean = 24.4%, SD = 8.7; n = 5) showed 8% higher SMC than Overburden. (mean = 16.4%, SD = 8.1; n = 5) (Figure 30) however, data collected were not sufficient for testing.

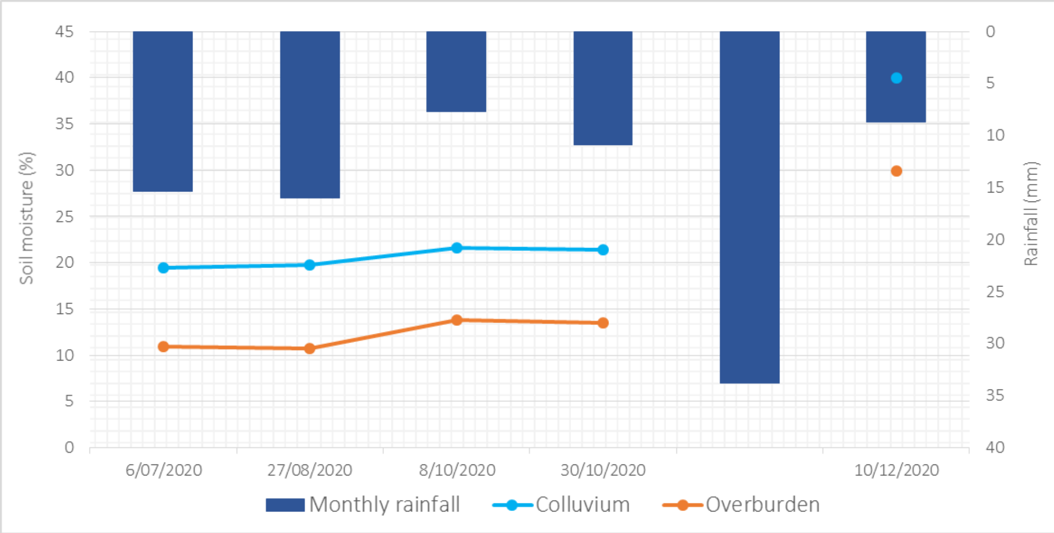

__Figure 30__. Monthly rainfall amount and SMC in different substrate types of geomorphic treatment in the Fortuna quarry during the data collection period.

6.2.2 The Aurora quarry

The Clayey topsoil and Colluvium registered higher soil moisture values than Overburden throughout the data collection period (Figure 31) and had mean soil moisture values above 13% which was a 3% higher than the overburden substrate (Table 8).

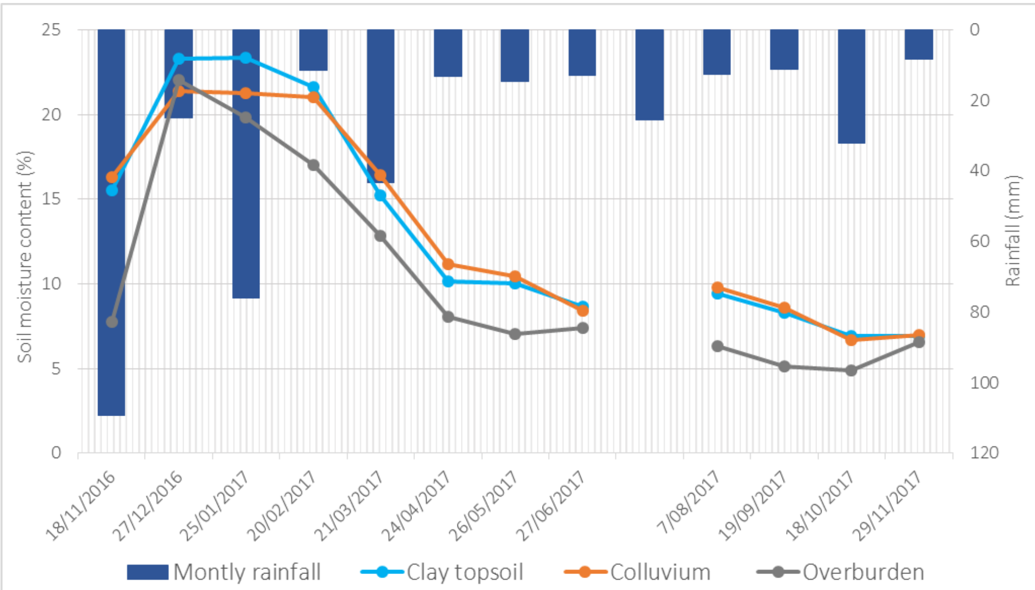

***Figure 31** Monthly rainfall amount and SMC in different substrate types in Aurora quarry.*

Substrate	Mean ± SD
Colluvium	13.2 ± 6.3
Clayey topsoil	13.3 ± 5.7
Overburden	10.4 ± 6.0

Table 8. *The mean and standard deviation of SMC in different substrate types in Aurora quarry. Data from 12 visits (n).*

The Friedman test showed that substrate types were significantly different (chi-square = 15.1 df = 2, p-value <0.05) with SMC in the overburden significantly lower than the others (Wilcoxon test, Figure 32).

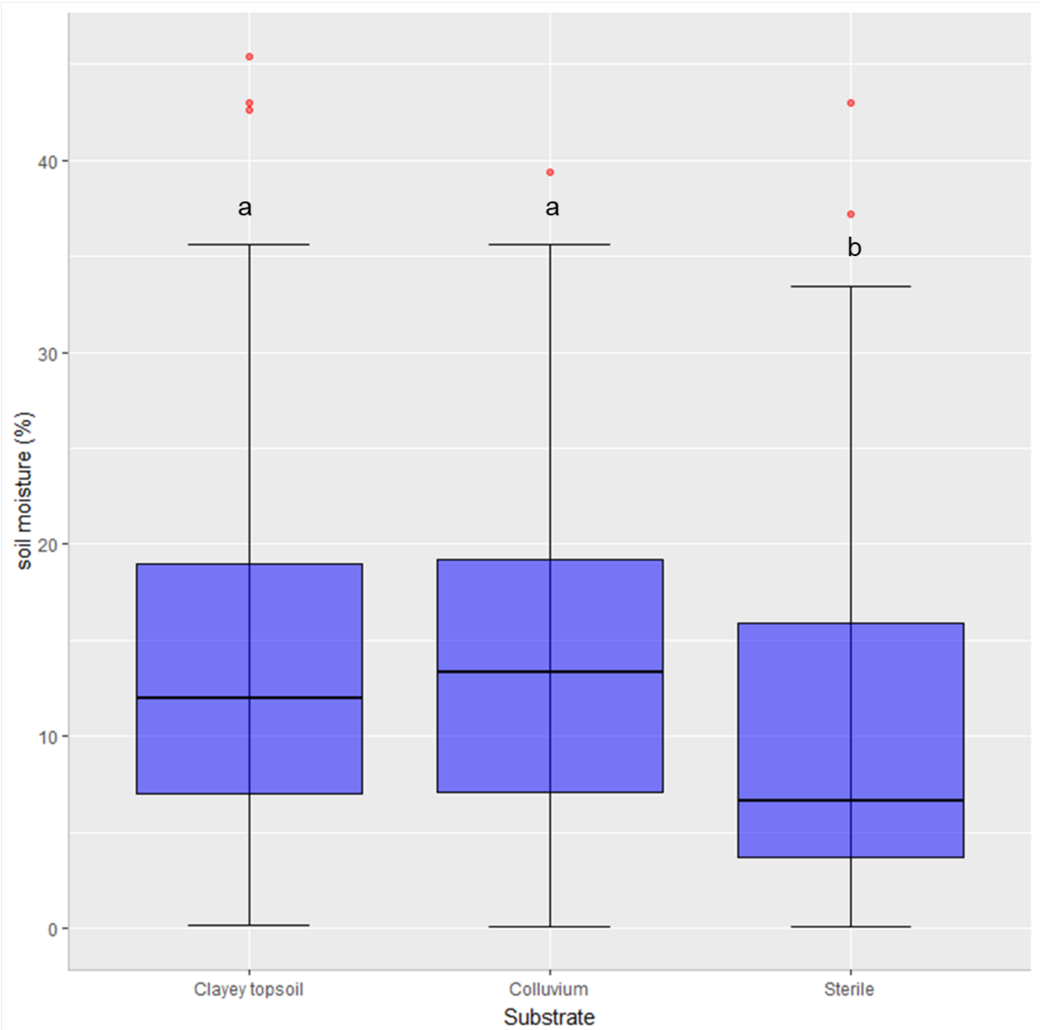

Figure 32. *SMC in substrate types in the Aurora quarry. Box shows 1st, median and 3rd quartiles, whiskers min and max values and dots represent outliers. Different letters indicate different groups based on the Wilcoxon test. The term Sterile refers to overburden substrate.*

During the recharge period, the clayey topsoil and Colluvium substrates showed higher soil moisture values than Overburden (Figure 33).

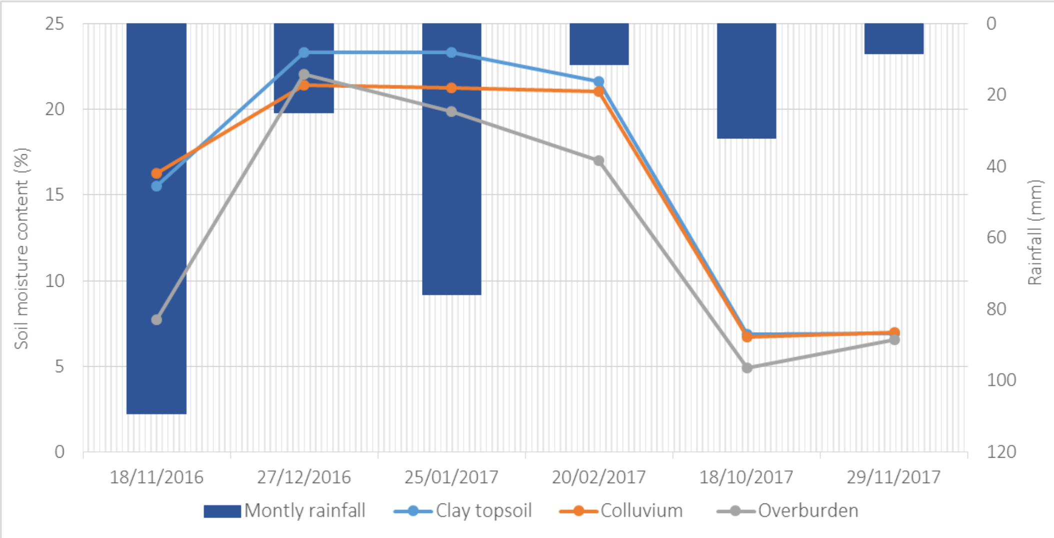

Figure 33. *Monthly rainfall amount and SMC in different substrate types in Aurora quarry during the recharge period. Clay topsoil and Colluvium substrate from GF treatment and Overburden from TC.*

The mean soil moisture value of clayey topsoil was 0.7% higher than Colluvium substrate and 2.6% than Overburden (Table 9) however, data collected were not sufficient for testing.

Substrate	**Mean ± SD**
Colluvium	15.6 ± 7.1
Clayey topsoil	16.3 ± 7.8
Overburden	13.0 ± 7.5

Table 9. *The mean and standard deviation of SMC in different substrate types in Aurora quarry during recharge. Data from 6 visits (n).*

The divide landforms of geomorphic treatment were covered with colluvium topsoil and clayey topsoil (Section 5.1.1) Soil moisture content was analyzed in those two substrate types (Figure 34) which had similar values during the data collection period, the Clayey topsoil (mean = 12.6%, SD = 5.7; n = 12) was only 0.2% higher than Colluvium (mean = 12.4%, SD = 6.3; n = 12).

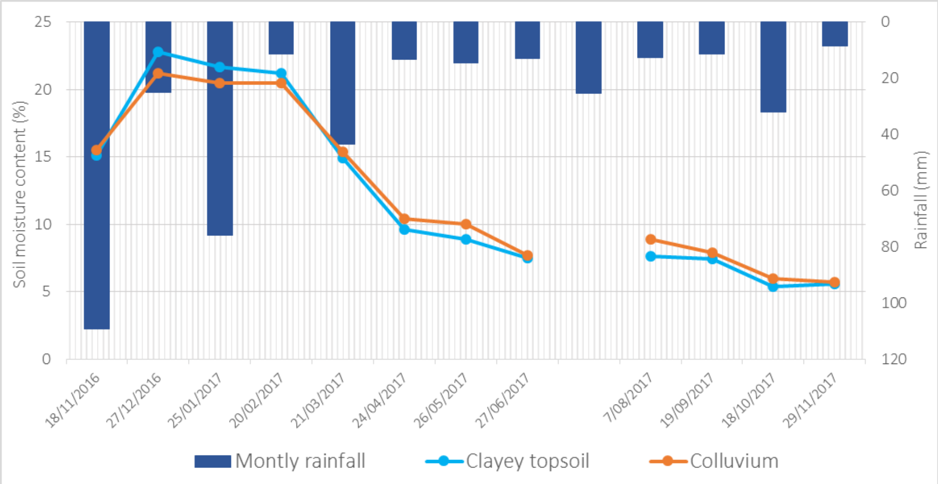

Figure 34. *Monthly rainfall amount and SMC in substrate types of the divide landform within Aurora quarry.*

The Friedman test showed that the Clayey topsoil and Colluvium were not significantly different (chi-squared = 3, df = 1, p-value > 0.05) see Figure 35.

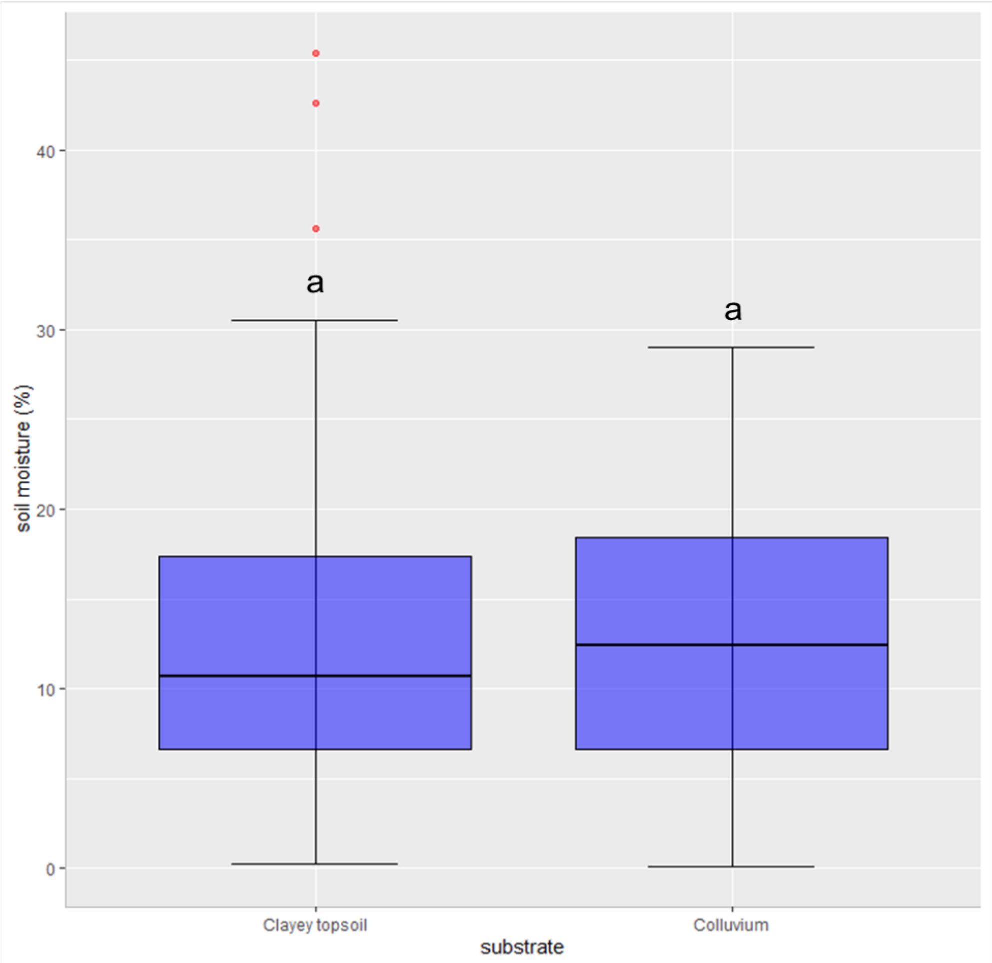

Figure 35. *SMC in substrate types in the divide landform within the Aurora quarry. Box shows 1st, median and 3rd quartiles, whiskers min and max values and dots represent outliers. Different letters indicate different groups based on the Wilcoxon test. The term Sterile refers to overburden substrate.*

The analysis made with data from the recharge period showed that the clayey topsoil had higher soil moisture values than Colluvium in the winter of 2016-2017 moreover, during the beginning of winter 2017-2018, the SMC were similar in both treatments (Figure 36). However, the clayey topsoil (mean = 15.3%, SD = 8.1; n = 6) registered a 0.3% higher mean than the Colluvium substrate (mean = 15.0%, SD = 7.3; n = 6). Data collected were not enough to run the tests.

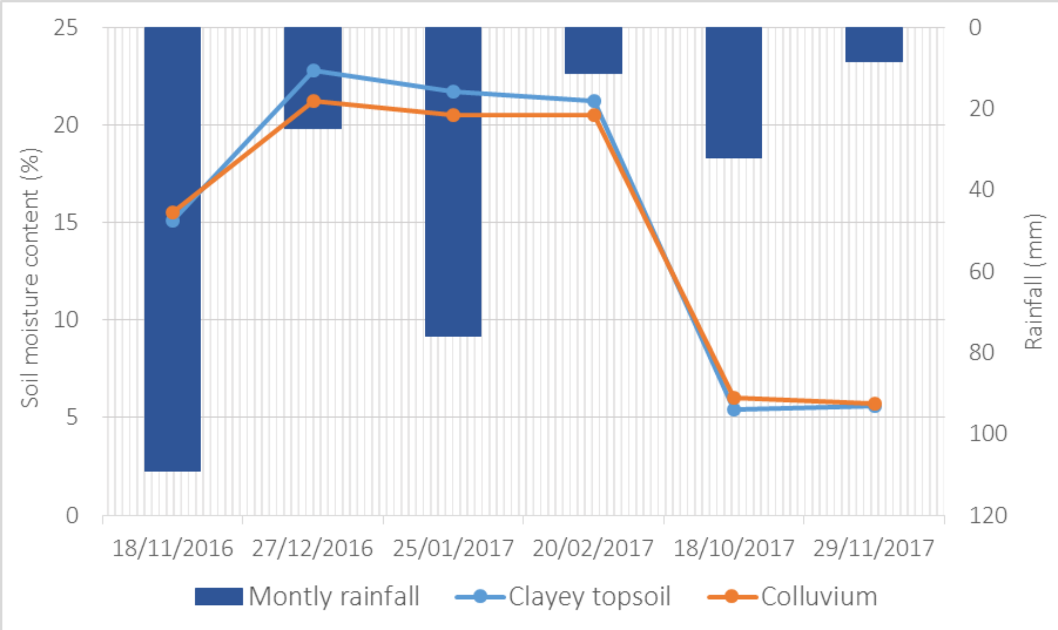

Figure 36. *Monthly rainfall amount and SMC in substrate types of the divide landform within Aurora quarry during the recharge period.*

6.3 The influence of slope aspect in the soil moisture content of the geomorphologic restoration.

6.3.1 The Fortuna quarry

Shady and sunny aspect showed similar values throughout the study period (Figure 37) however, the SMC mean of the shady aspect (mean = 25.7%, SD = 13.9; n = 11) was higher than the sunny aspect (mean = 23.7%, SD = 13.1, n = 11) moreover, significant differences were found (lme, d.f = 1.33; F = 5.61; p <0.05, figure 38).

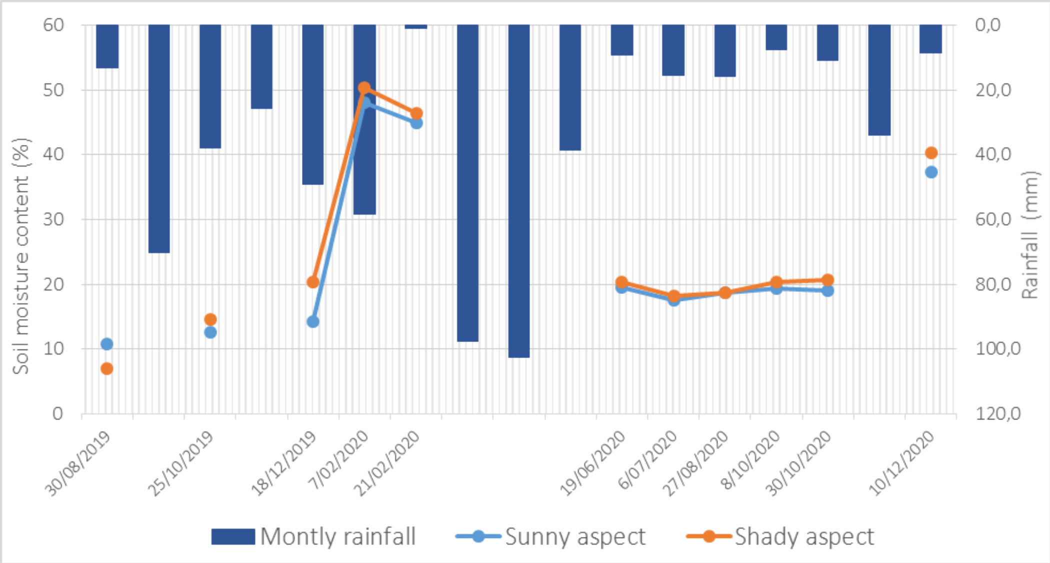

Figure 37. *Monthly rainfall amount and SMC in the aspect of the landforms of the geomorphic approach in Fortuna quarry.*

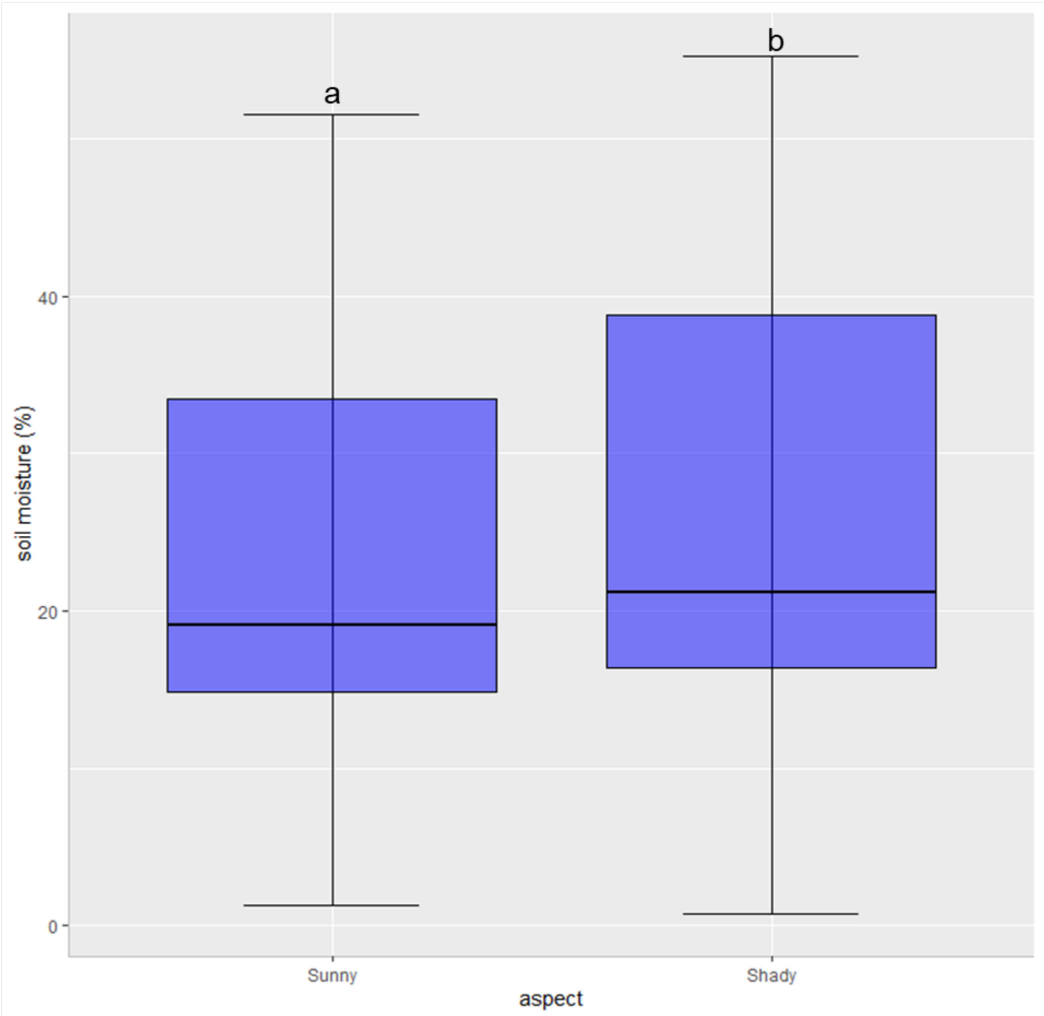

Figure 38 *SMC in aspects in the divide landform within the Fortuna quarry. Box shows 1st, median and 3rd quartiles, whiskers min and max values and dots represent outliers. Different letters indicate differences based on nlme.*

Soil moisture in the different aspect was analyzed during the recharge period (Figure 39) SMC in the shady aspect (mean = 30.5%, SD = 15.0; n = 7) was higher a 2.7% than the sunny aspect (mean = 27.8%, SD = 14.8; n = 11) however, data collected were not enough to run the tests.

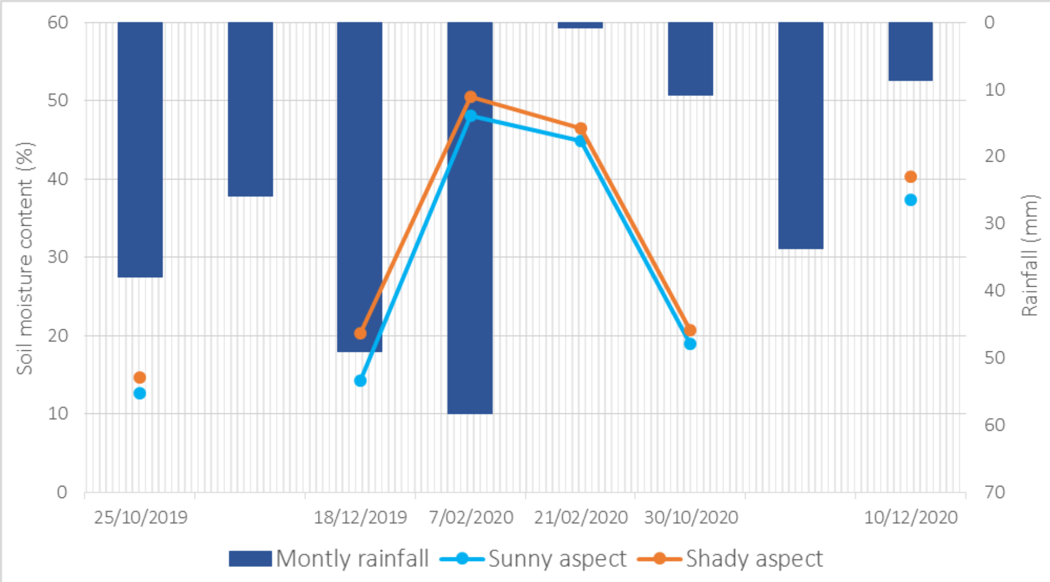

Figure 39. *Monthly rainfall amount and SMC in the aspect of the landforms in the geomorphic approach within the Fortuna quarry during the recharge period*

6.3.2 The Aurora quarry

The shady aspect showed higher SMC than sunny aspects throughout the collection data period (Figure 40): shady aspect (mean = 19.8%, SD = 8.3; n = 26) had a 4.7% higher mean SMC than the Sunny aspect (mean = 15.1%, SD = 6.3; n = 26) moreover, the Friedman test showed significantly differences among aspects (chi-squared = 22.1, df = 1, p-value < 0.01, Figure 41)

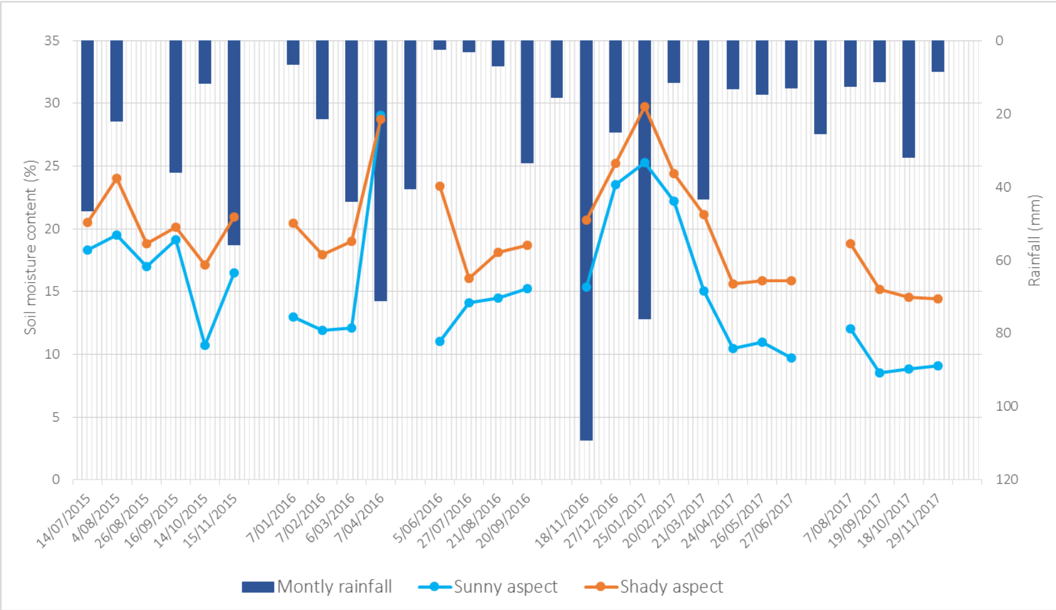

Figure 40. *Monthly rainfall amount and SMC in the aspect of landforms in the geomorphic treatment within the Aurora quarry.*

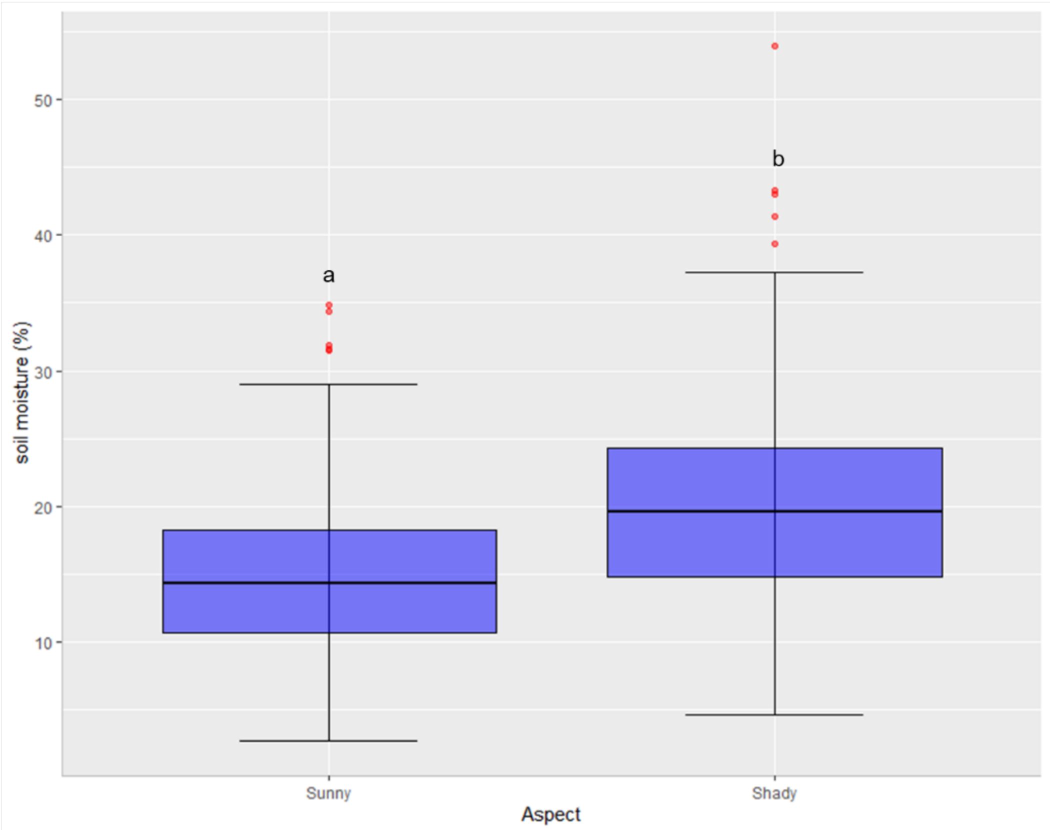

Figure 41*. SMC in aspects in the geomorphic treatment within the Fortuna quarry. Box shows 1st, median and 3rd quartiles, whiskers min and max values and dots represent outliers. Different letters indicate differences based on the Friedman test.*

Likewise, when studying data only during the recharge period, the aspects maintained the trend (Figure 42); the Shady aspect (mean = 20.6%, SD = 4.6; n = 10) was 5% higher than Sunny aspect (mean = 16.6%, SD = 5.8; n = 10), however, the data collected were not enough to run the tests.

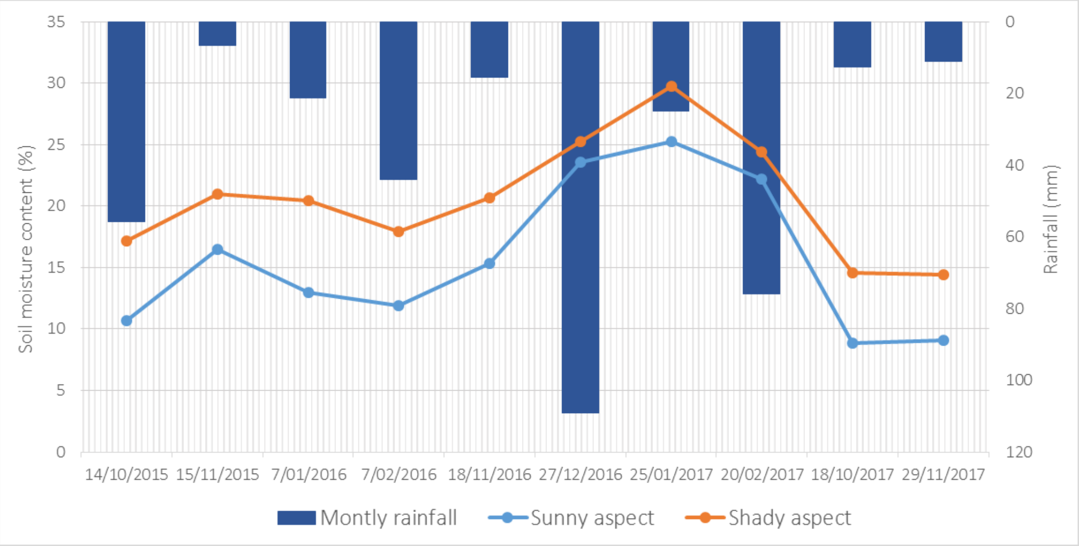

Figure 42. *Monthly rainfall amount and SMC in the aspect of landforms in the geomorphic treatment within the Aurora quarry during the recharge period.*

6.4 Spatial distribution of soil moisture in conventional and geomorphic restoration.

In study quarries, soil moisture was measured in the different landforms from the geomorphic and conventional treatments (Section 5.1). The spatial distribution (transverse and longitudinal patterns) of SMC was analyzed in each unit of both treatments.

6.4.1 *The Fortuna quarry*

- Geomorphic approach, the GFG unit:

The different landforms registered similar values during the data collection period (Figure 43). Valleys and Slopes had only 1% higher SMC than Slope (Table 10). However, differences were not significant (lme, d.f = 2.32; F = 0.37; p >0.05, Figure 44).

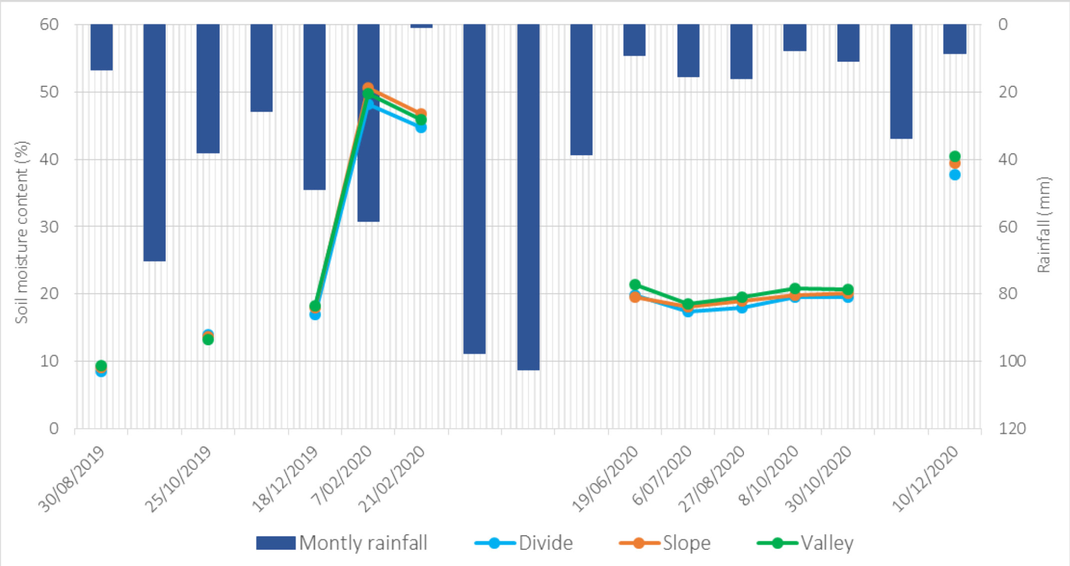

Figure 43 *Monthly rainfall amount and SMC in the landforms of the GFG unit in the Fortuna quarry.*

Landform	Mean ± SD
Divide	24.5 ± 13.2
Slope	25.2 ± 13.9
Valley	25.4 ± 13.6

Table 10*. The mean and standard deviation of SMC in the landforms of the GFG unit. Data from 11 visits (n).*

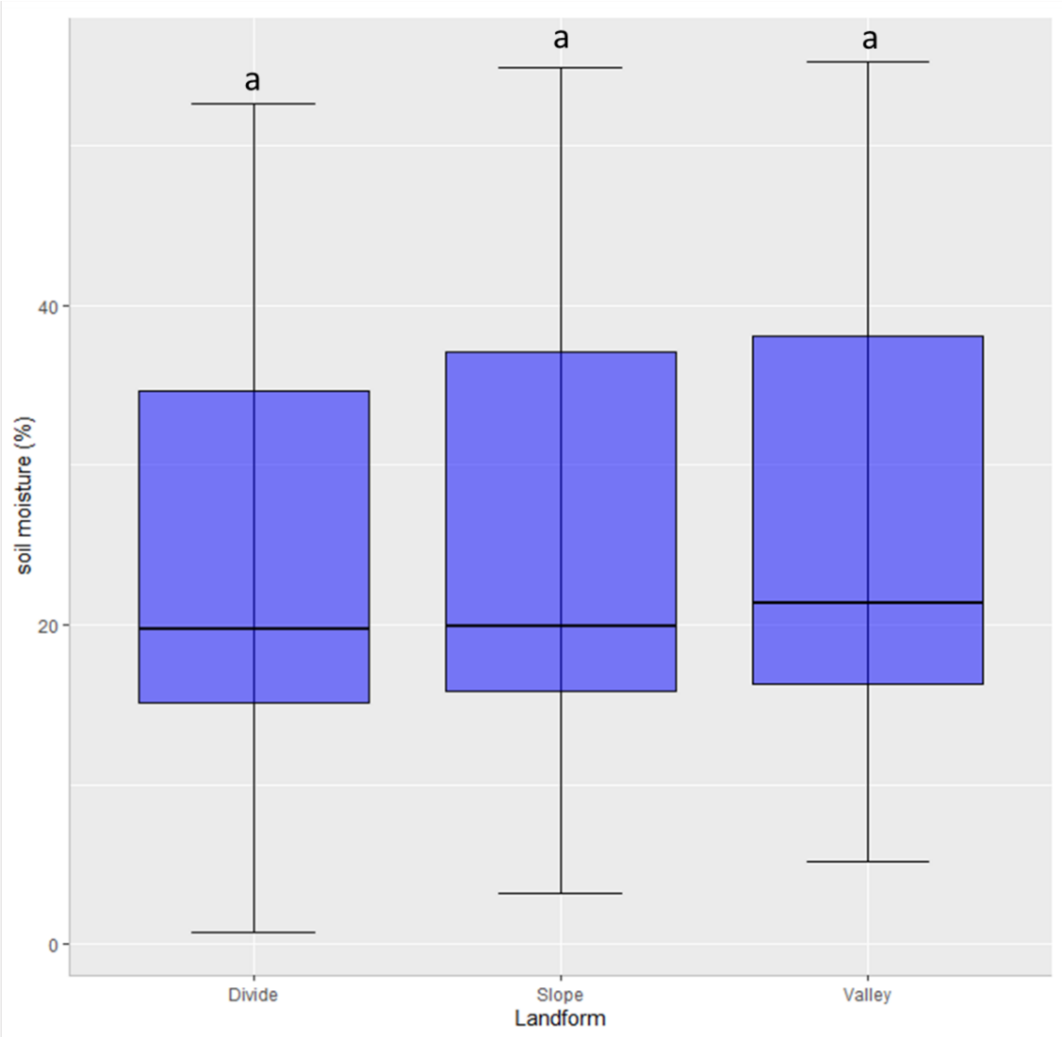

Figure 44 *SMC in the landforms of the GFG unit in the Fortuna quarry. Box shows 1st, median and 3rd quartiles, whiskers min and max values and dots represent outliers.*

During the recharge period, the landforms showed the same trend (Figure 45) as the previous analysis. The valley and slope had 1% higher mean soil moisture value than the divide (Table 11). The data collected were not sufficient for testing.

Landform	Mean ± SD
Divide	28.7 ± 14.4
Slope	29.8 ± 15.3
Valley	29.9 ± 15.0

Table 11*. The mean and standard deviation of SMC in the landforms of the GFG unit in the Fortuna quarry during the recharge period. Data from 7 visits (n).*

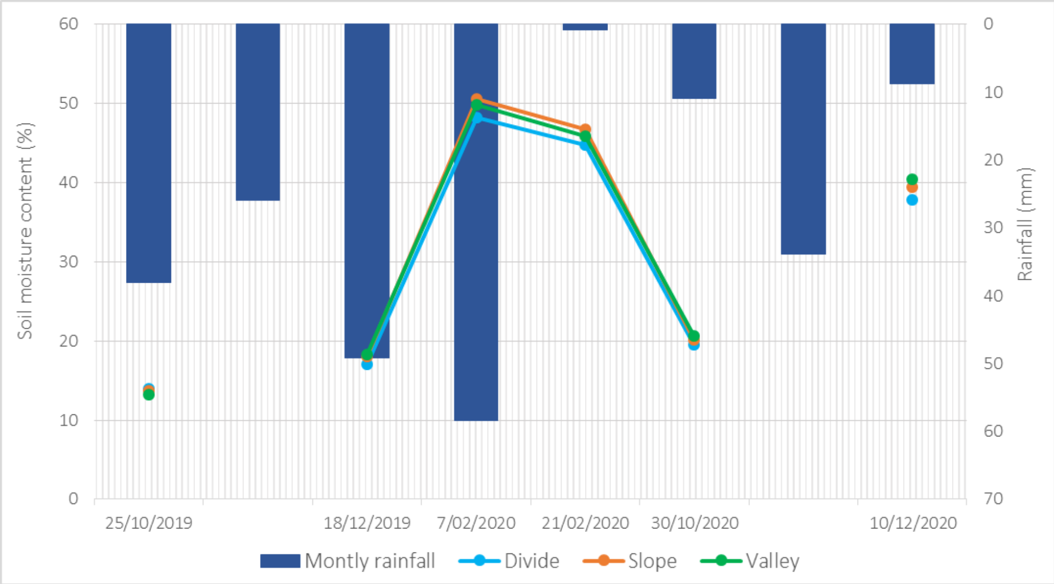

Figure 45. *Monthly rainfall amount and SMC in the landforms in the GFG unit in the Fortuna quarry during the recharge period.*

Regarding the longitudinal pattern of soil moisture in the GFG unit, transects showed similar values through the data collection period but only Low transect registered lower values from June to December of 2020 (Figure 46).

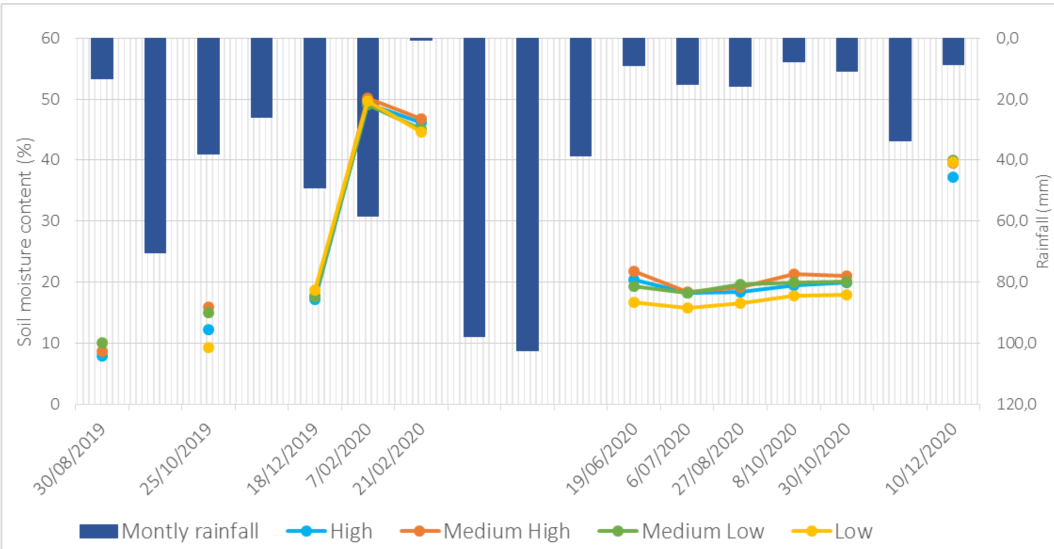

Figure 46. *Monthly rainfall amount and SMC in each transect of GFG unit in Fortuna quarry.*

Medium High transect showed a 1% higher content than the rest transects (Table 12). However, differences were not significant (lme, d.f = 3.31; F = 0.32; $p > 0.05$, Figure 47).

Transect	Mean ± SD
High	24.2 ± 13.0
Medium-High	25.5 ± 13.3
Medium-Low	24.9 ± 13.2
Low	24.7 ± 14.2

Table 12. *The mean and standard deviation of soil moisture content in each transect of GFG unit in Fortuna quarry. Data from 11 visits (n).*

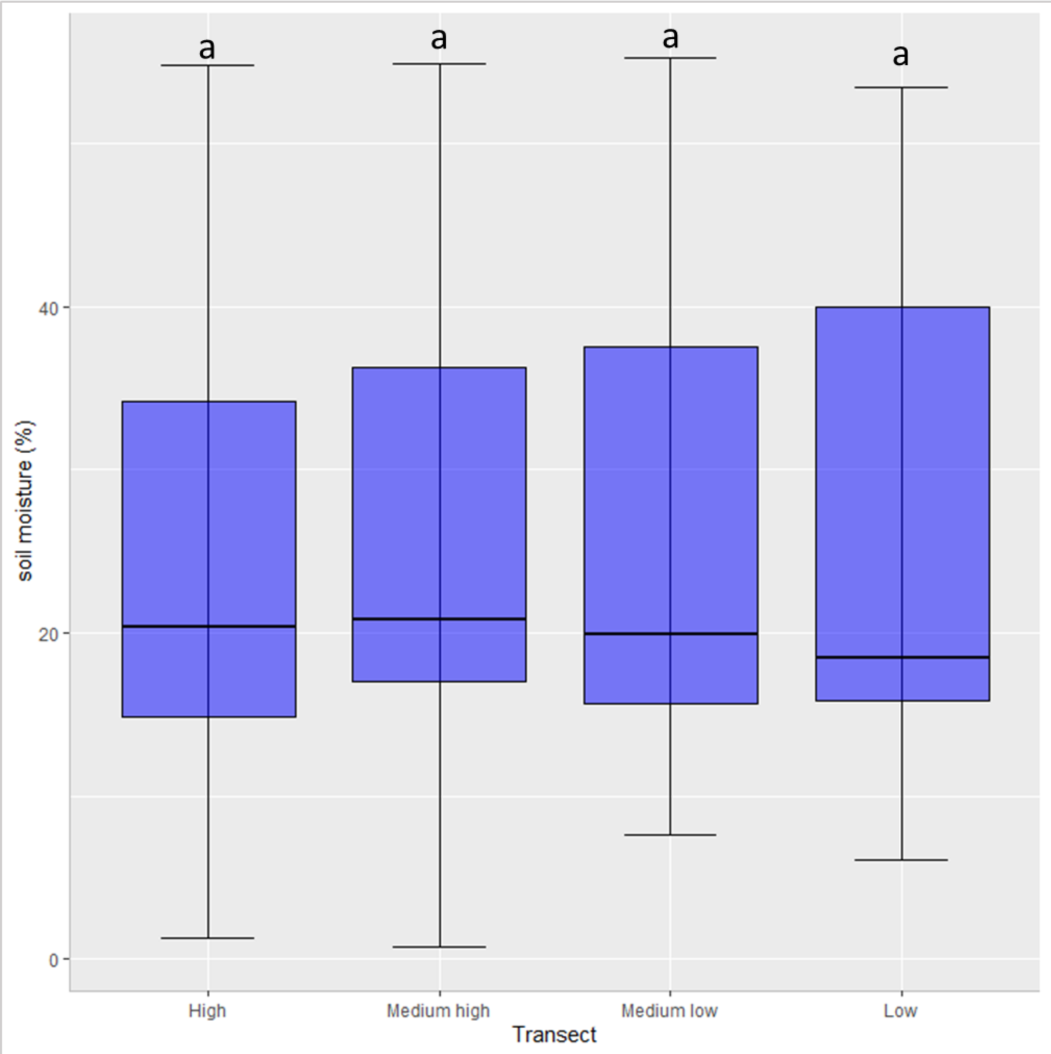

Figure 47*. SMC in the landforms of the GFG unit in the Fortuna quarry. Box shows 1st, median and 3rd quartiles, whiskers min and max values and dots represent outliers.*

During the recharge period, transects showed the same trend (Figure 45) as the previous analysis. The medium-high transect showed a 2.2% higher mean soil moisture than the Low transect (Table 13). However, data collected were not sufficient for testing.

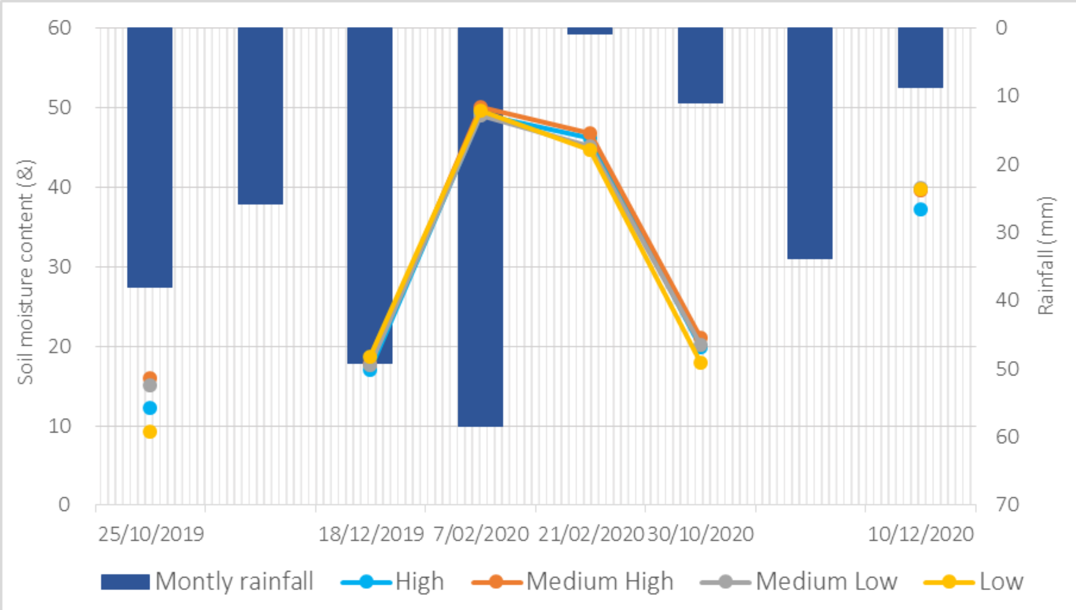

__Figure 48__. Monthly rainfall amount and SMC in transects of the GFG unit in the Fortuna quarry during the recharge period.

Transect	Mean ± SD
High	28.7 ± 15.1
Medium-High	30.4 ± 14.6
Medium-Low	29.6 ± 14.5
Low	28.2 ± 15.9

__Table 13__. The mean and standard deviation of SMC in transects of the GFG unit in the Fortuna quarry during the recharge period. Data from 7 visits (n).

- Geomorphic approach, the GFP unit:

The Slope landform registered lower SMC than other landforms (Figure 49) hence, the valley transect was 3.1% higher than the Slope (Table 14).

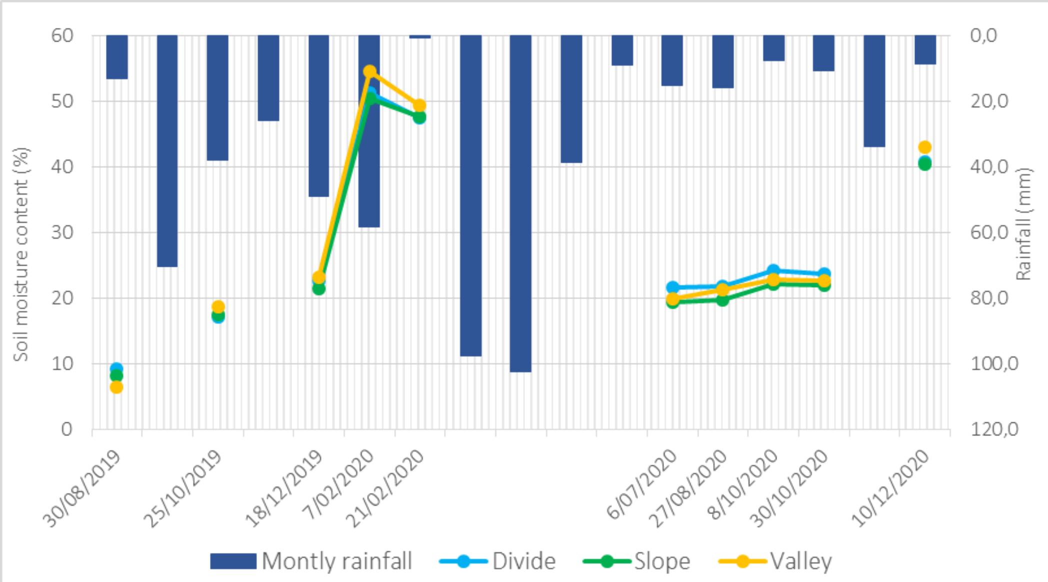

***Figure 49**. Monthly rainfall amount and SMC in each transect of GFP unit in Fortuna quarry during the data collection period.*

Landform	Mean ± SD
Divide	28.0 ± 13.7
Slope	26.8 ± 14.1
Valley	29.9 ± 15.0

***Table 14**. The mean and standard deviation of SMC in landforms of the GFP unit in the Fortuna quarry. Data from 10 visits (n).*

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The Friedman test showed significant differences among landforms (chi-squared = 7.4, df = 2, p-value < 0.05) with SMC in Slope significantly lower than the others (Wilcoxon test, Figure 50).

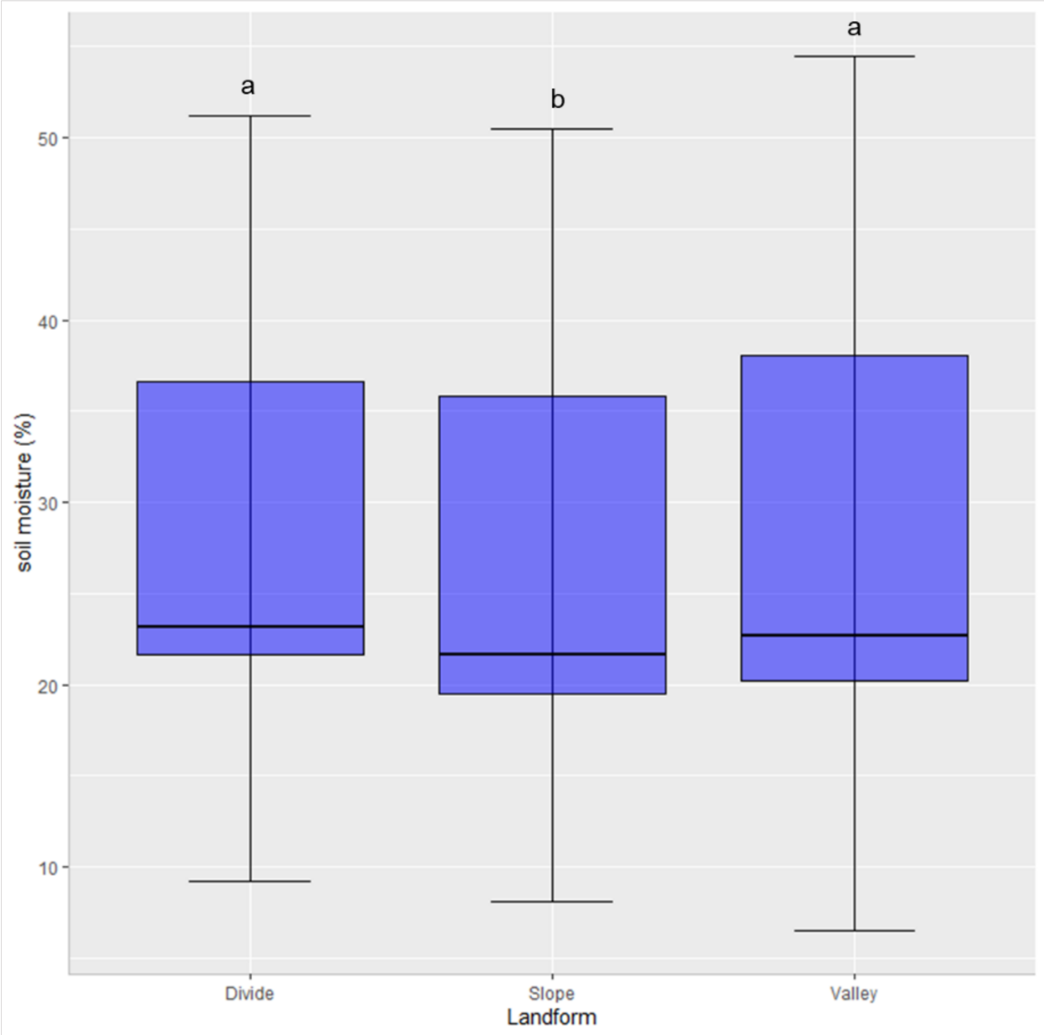

Figure 50. *SMC in landforms of the GFP unit in the Fortuna quarry. Box shows 1st, median and 3rd quartiles, whiskers min and max values and dots represent outliers. Different letters indicate different groups based on the Wilcoxon test.*

During the recharge period, the Valley landform registered higher soil moisture content than the other landforms (Figure 51), which had 2% higher soil moisture content than Slope (Table 15). However, data collected were not sufficient for testing.

Landform	**Mean ± SD**
Divide	33.8 ± 14.4
Slope	33.2 ± 14.6
Valley	35.2 ± 15.6

Table 15. *The mean and standard deviation of SMC in landforms of the GFP unit in the Fortuna quarry during the recharge period. Data from 6 visits (n).*

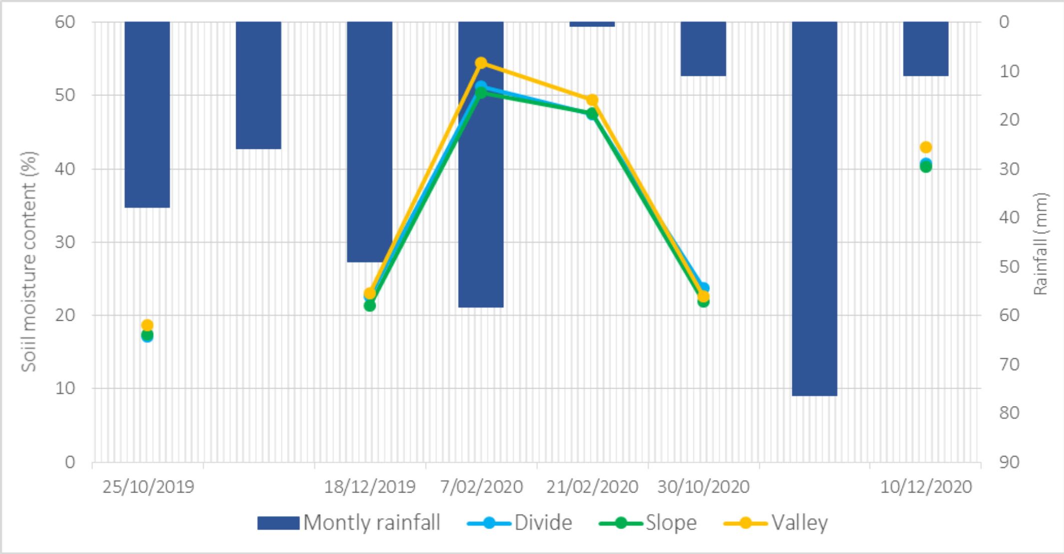

__Figure 51.__ Monthly rainfall amount and SMC in landforms of the GFP unit in the Fortuna quarry during the recharge period.

Regarding longitudinal soil moisture pattern, the Low transect registered higher values than the rest of transects (Figure 52).

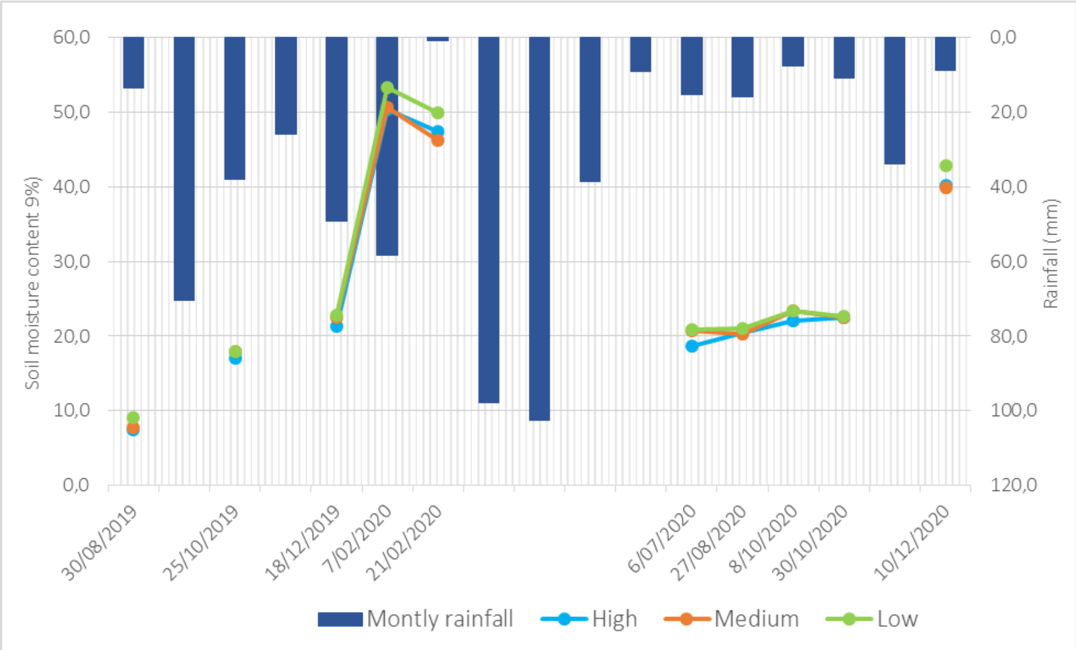

__Figure 52.__ Monthly rainfall amount and SMC in transects of the GFP unit in the Fortuna quarry.

The low transect was a 1.5% higher SMC than the High transect (Table16) also the Friedman test showed significant differences among the transect (chi-squared = 7.4, df = 2, *p*-value < 0, 05) with SMC in the Low transect significantly higher than the others (Wilcoxon test, Figure 53).

Transect	Mean ± SD
High	27.0 ± 14.0
Medium	27.6 ± 13.3
Low	28.5 ± 15.0

Table 16*. The mean and standard deviation of SMC in transects of the GFP unit in the Fortuna quarry. Data from 10 visits (n).*

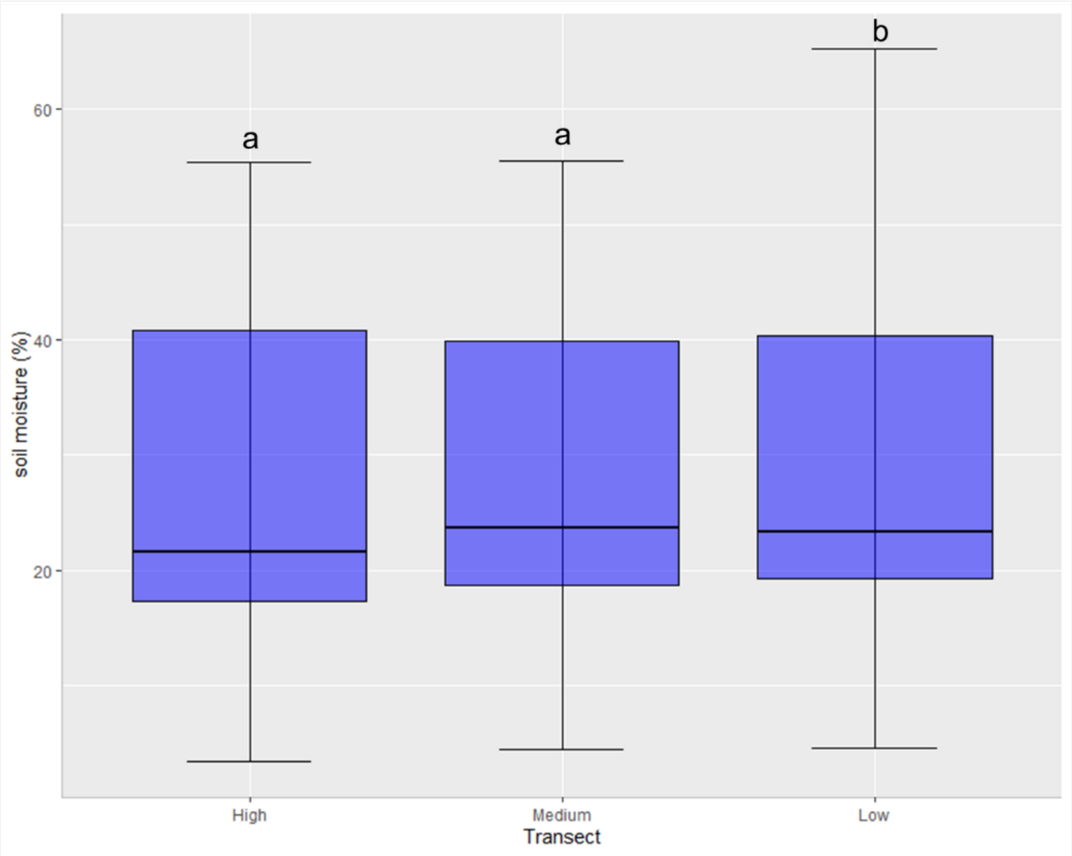

Figure 53 *SMC in transects of the GFP unit in the Fortuna quarry. Box shows 1st, median and 3rd quartiles, whiskers min and max values and dots represent outliers. Different letters indicate different groups based on the Wilcoxon test.*

During the recharge period, transects showed the same trend (Figure 54) as the previous analysis. SMC at the low transect was 1.5% higher than the high transect (Table 17). However, data collected were not sufficient for testing.

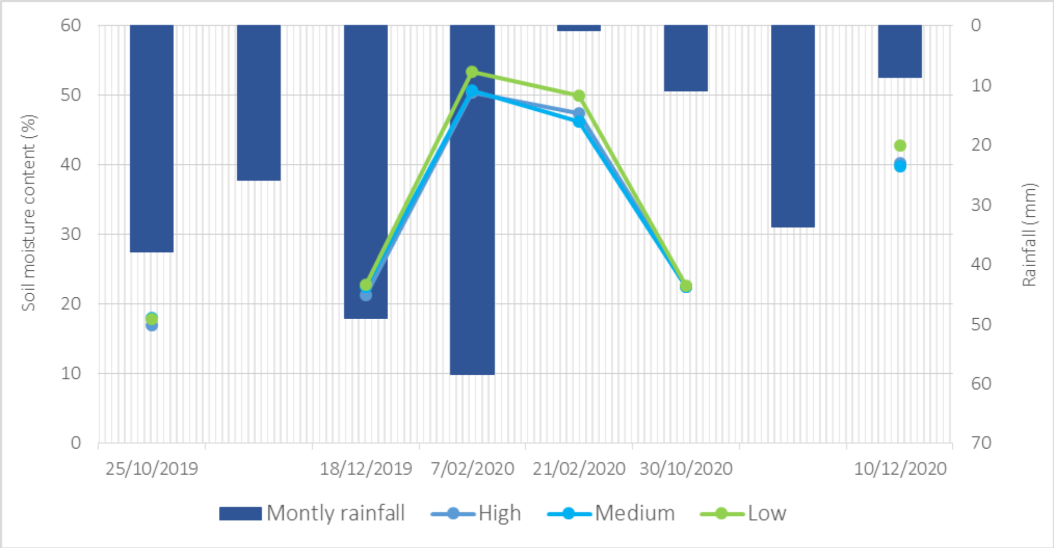

Figure 54. *Monthly rainfall amount and SMC in transects of the GFP unit in the Fortuna quarry during the recharge period.*

Transect	**Mean ± SD**
High	27.0 ± 14.0
Medium	27.6 ± 13.3
Low	28.5 ± 15.0

Table 17. *The mean and standard deviation of SMC in each transect of the GFP unit in the Fortuna quarry during the recharge period. Data from 6 visits (n).*

- Geomorphic approach, GFEst unit:

Landforms in the GFEst showed similar soil moisture values (Figure 55) however the Valley landform registered a 1% higher SMC than Divide and Slope landforms which showed soil moisture contents above 16% (Table 18). However, data collected were not sufficient for testing.

Landform	**Mean ± SD**
Divide	16.1 ± 6.0
Slope	16.5 ± 7.3
Valley	17.0 ± 8.5

Table 18. *The mean and standard deviation of SMC in landforms of the GFEst unit in the Fortuna quarry. Data from 5 visits (n).*

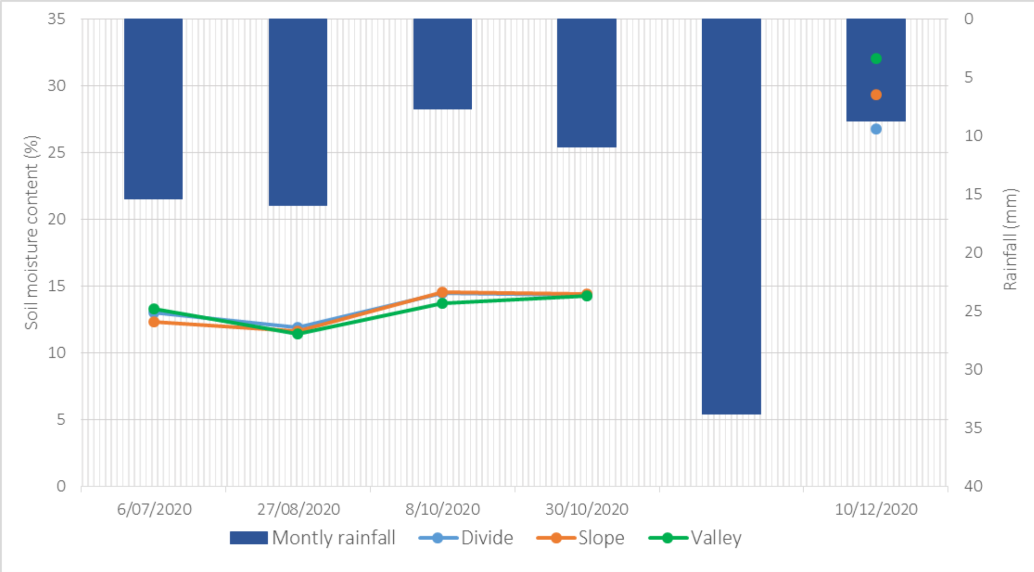

Figure 55. *Monthly rainfall amount and SMC in landforms of the GFEst unit in the Fortuna quarry during the data collection period.*

On the other hand, transect registered similar soil moisture contents, the low part showed 15.9% mean soil moisture and High and Medium transects above 16% (Table 19), however, data collected were not sufficient for testing.

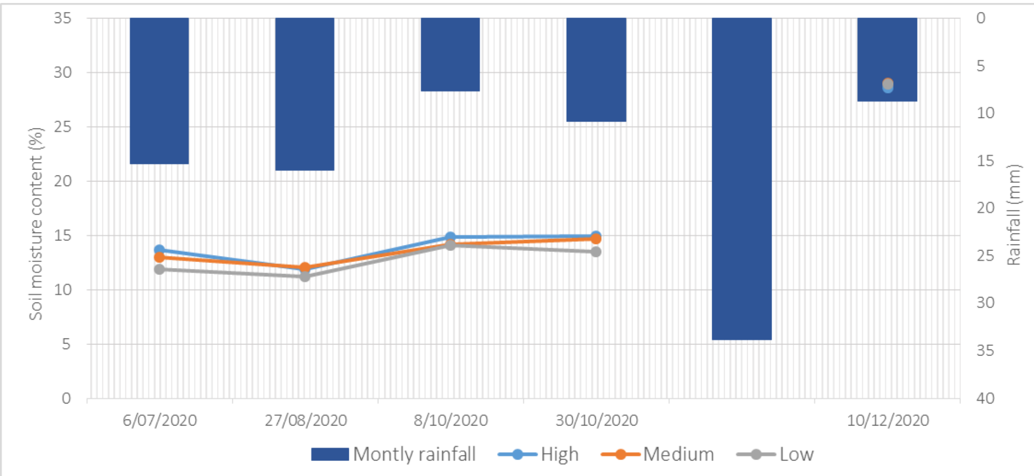

Figure 56. *Monthly rainfall amount and SMC in transects of the GFEst unit in the Fortuna quarry during the data collection period.*

Transect	Mean ± SD
High	16.8 ± 6.7
Medium	16.6 ± 7.0
Low	15.9 ± 7.4

Table 19. *The mean and standard deviation of SMC in each transect of the GFEst unit in the Fortuna quarry. Data from 5 visits (n).*

- The Conventional treatment, TC unit:

The low transect registered higher soil moisture values higher than medium and high transects throughout the data collection period (Figure 57).

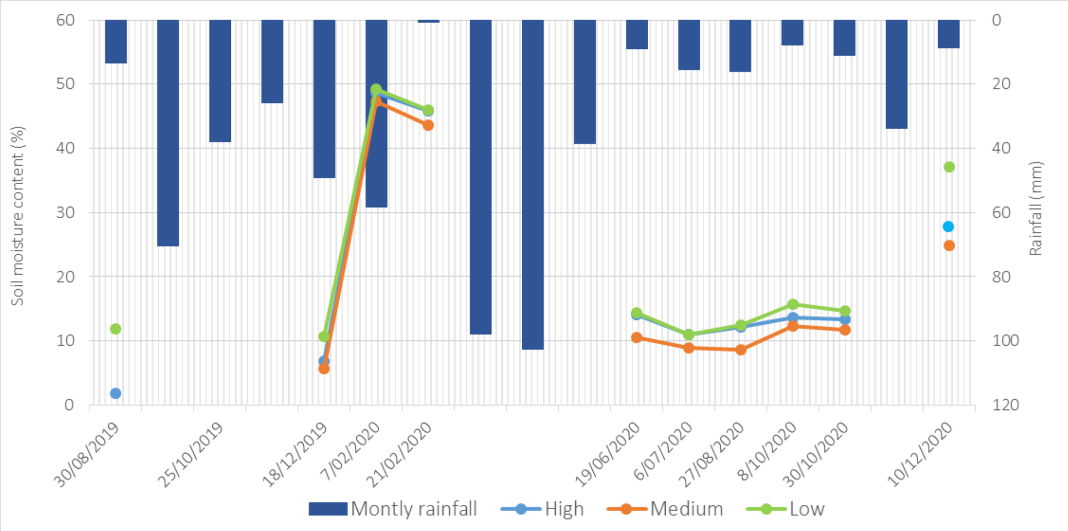

Figure 57. *Monthly rainfall amount and SMC in transects of the TC unit in Fortuna quarry.*

The low transect had a 3% higher SMC than the medium transect (Table 20) the transects were significantly different (Friedman test, chi-squared = 18, df = 2, *p*-value < 0.05) and the Wilcoxon test confirmed the differences among each other (Figure 58).

Transect	Mean ± SD
High	19.5 ± 16.0
Medium	19.3 ± 15.8
Low	22.3 ± 15.4

Table 20. *The mean and standard deviation of SMC in transects of the TC unit in the Fortuna quarry. Data from 10 visits (n).*

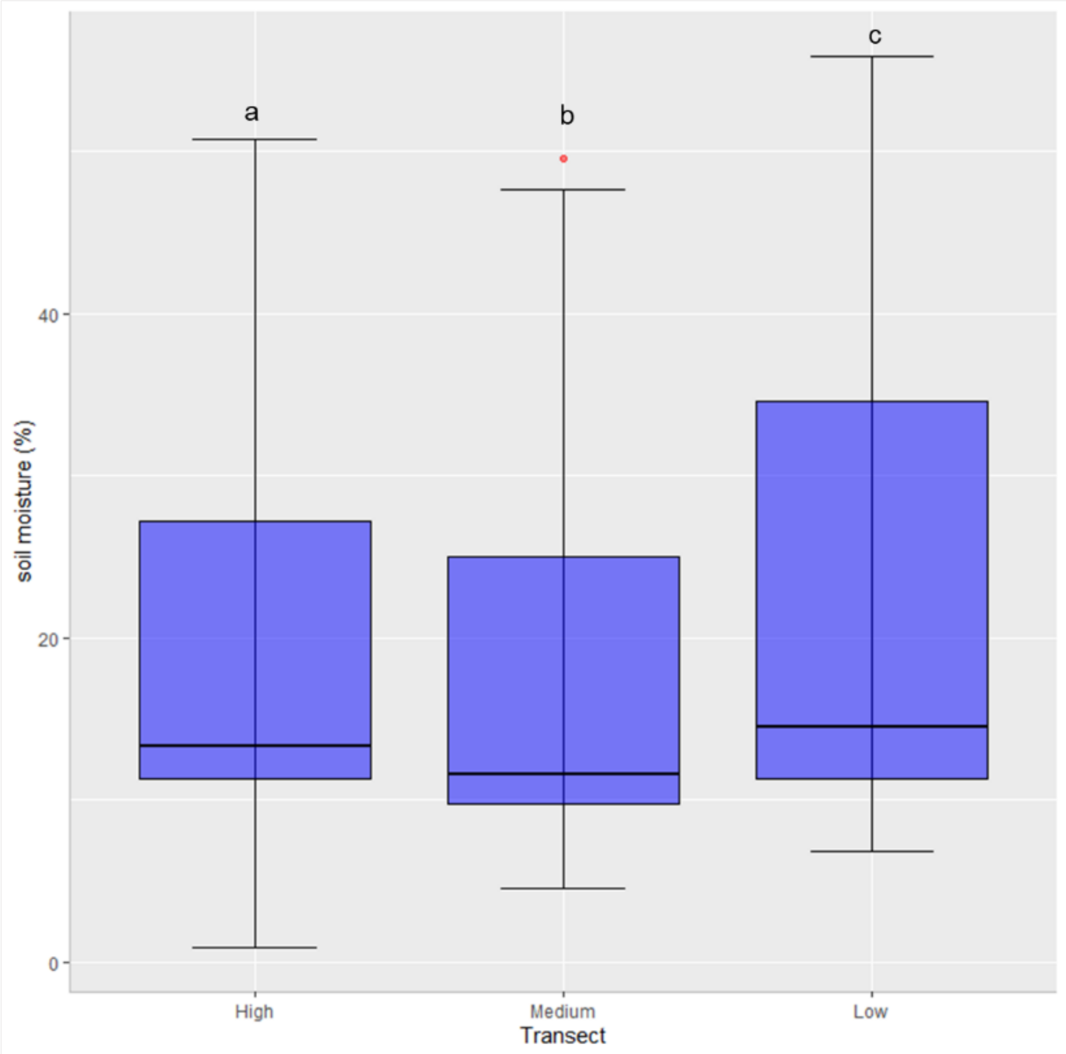

Figure 58. *SMC in transects of the TC unit in the Fortuna quarry. Box shows 1st, median and 3rd quartiles, whiskers min and max values and dots represent outliers. Different letters indicate different groups based on the Wilcoxon test.*

During the recharge period, the values of transects were similar (Figure 59) although, the low transect had a 3% higher SMC than the High transect (Table 21). However, data collected were not sufficient for testing.

Transect	Mean ± SD
High	28.5 ± 18.8
Medium	26.7 ± 18.6
Low	31.6 ± 17.8

Table 21. *The mean and standard deviation of SMC in transects of the TC unit in the Fortuna quarry during the recharge period. Data from 5 visits (n).*

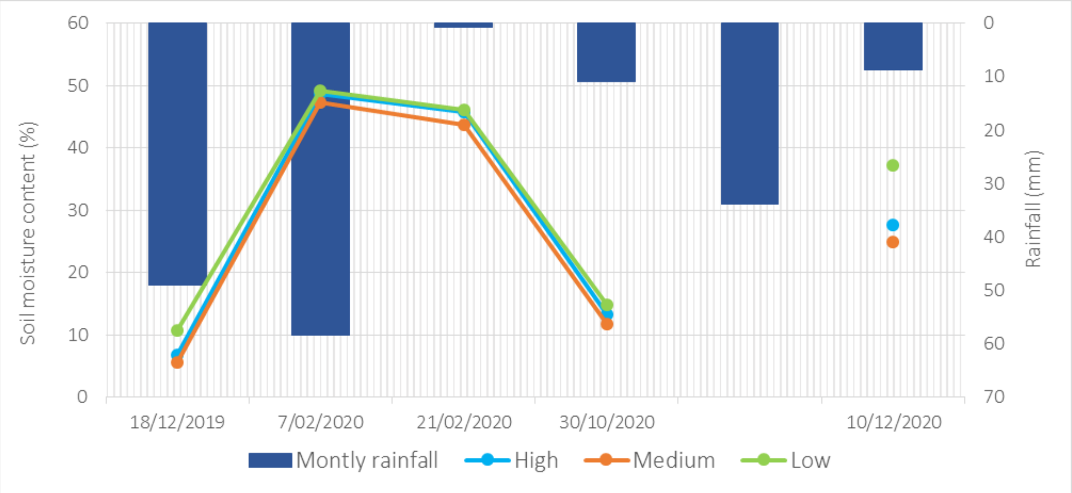

Figure 59. *Monthly rainfall amount and SMC in transects of the TC unit in the Fortuna quarry during the recharge period.*

- The conventional treatment, TM unit:

Low transect registered higher soil moisture content than medium and high transects throughout the data collection period, medium and high transects showed similar values between June and December 2020 (Figure 60).

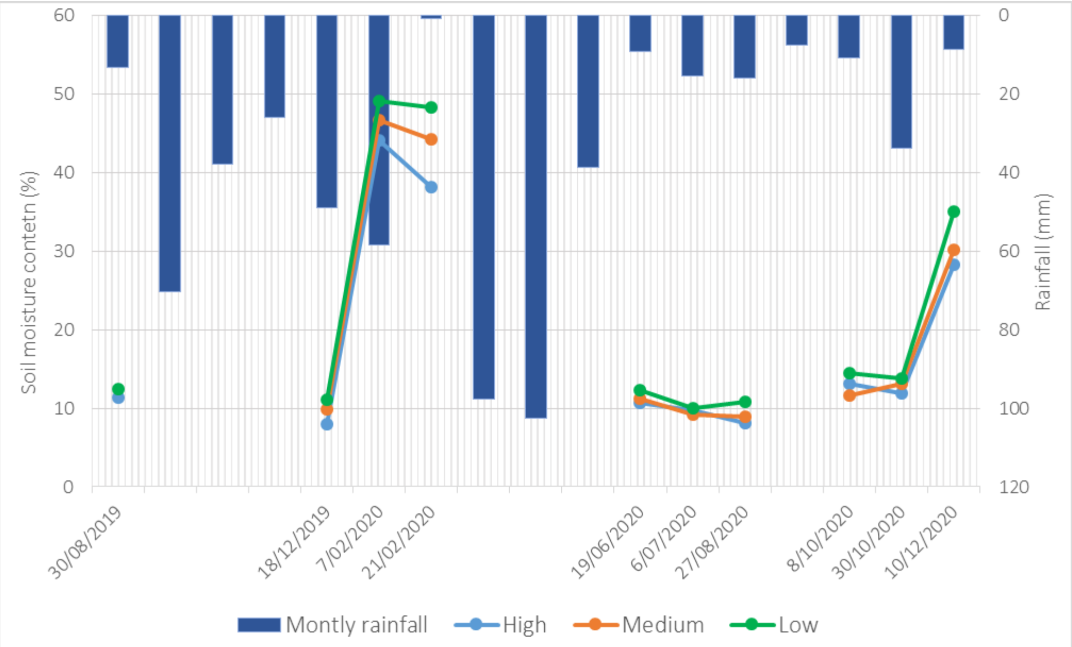

Figure 60. *Monthly rainfall amount and SMC in transects of the TM unit in the Fortuna quarry.*

The low transect had a 3.4% higher mean SMC than the high transect (Table 22), the Friedman test showed significant differences (chi-squared = 14.8, df = 2, p-value < 0. 05) with SMC in the Low transect significantly higher than the others (Wilcoxon test, Figure 61).

Transect	Mean ± SD
High	18.3 ± 13.4
Medium	20.6 ± 15.6
Low	21.7 ± 16.0

Table 22. *The mean and standard deviation of SMC in transects of the TM unit in the Fortuna quarry. Data from 10 visits (n).*

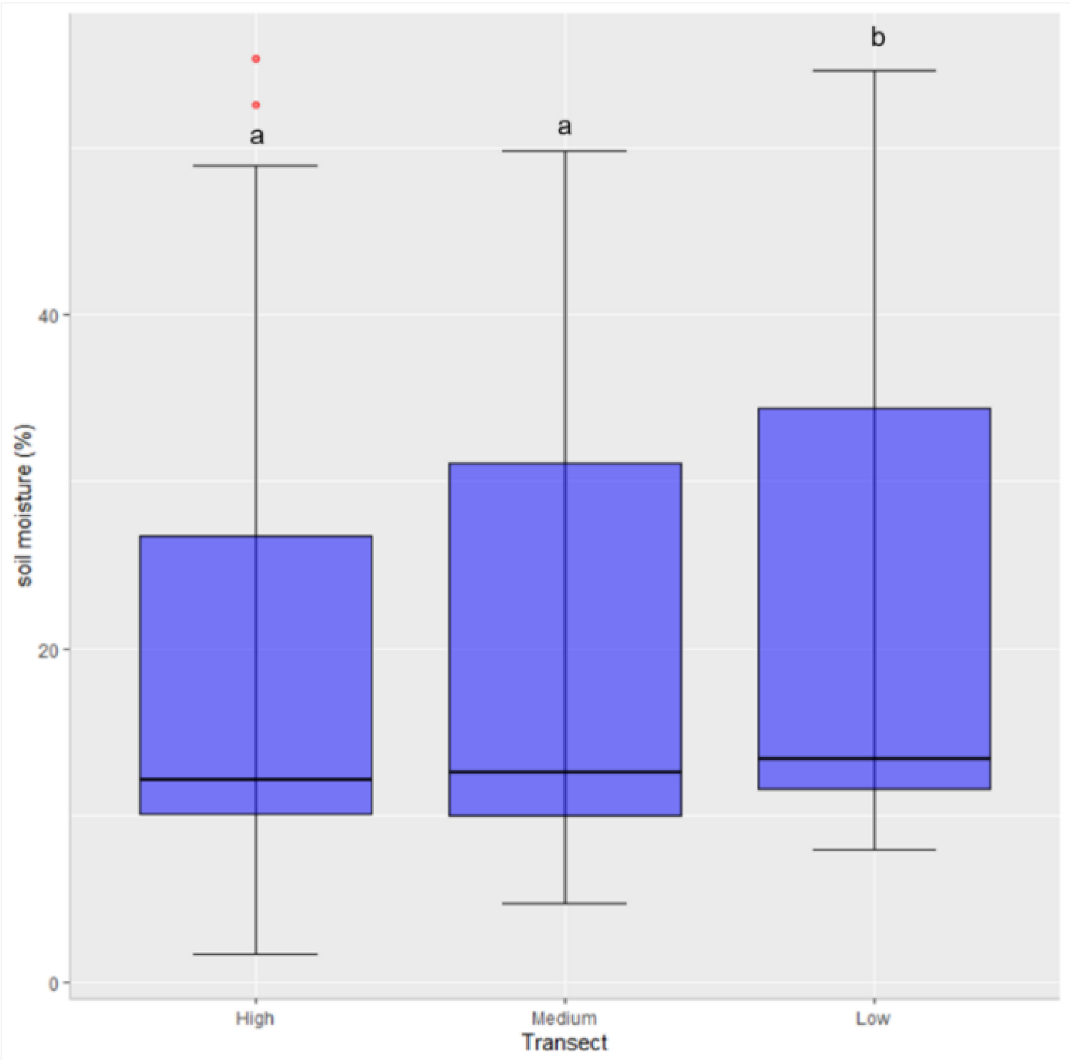

Figure 61. *SMC in transects of the TM unit in the Fortuna quarry. Box shows 1st, median and 3rd quartiles, whiskers min and max values and dots represent outliers. Different letters indicate different groups based on the Wilcoxon test.*

During the recharge period, transects showed a similar trend of SMC as the previous analysis (Figure 62), the low transect had a 4.8% higher mean soil moisture value than the High transect (Table23), however, data collected were not sufficient for testing.

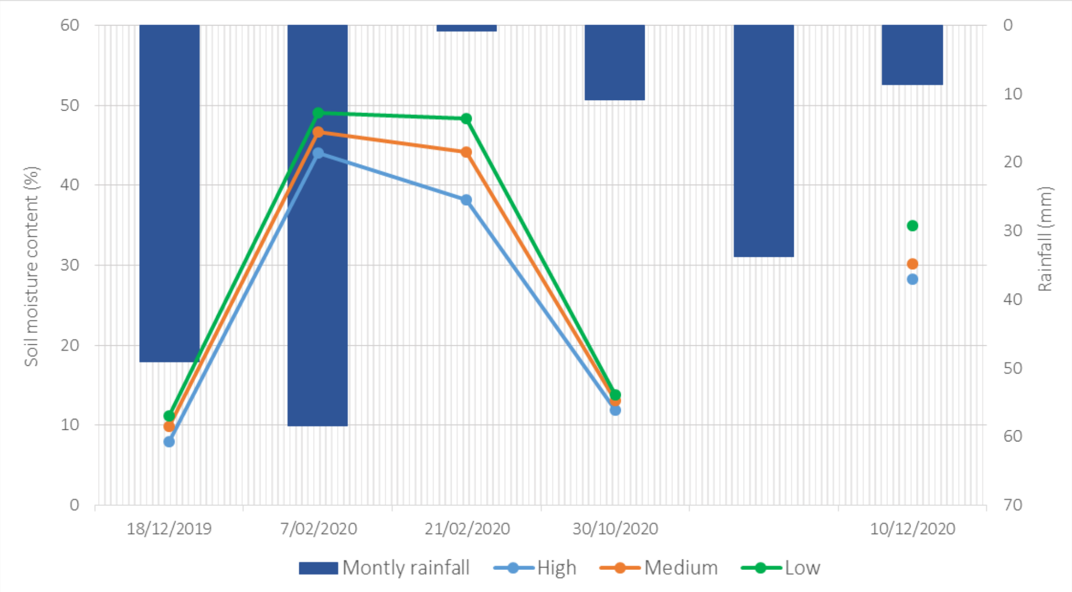

Figure 62. *Monthly rainfall amount and SMC in transects of the TM unit in the Fortuna quarry during the recharge period.*

Transect	Mean ± SD
High	26.1 ± 15.8
Medium	28.8 ± 17.1
Low	31.5 ± 18.2

Table 23. The mean and standard deviation of SMC in transects of the TM unit in the Fortuna quarry during the recharge period. Data from 5 visits (n).

6.4.2 The Aurora quarry

- The geomorphic treatment GF:

The slope landform showed higher SMC than Valley and Divide landforms in the last months of the data collection period (Figure 63).

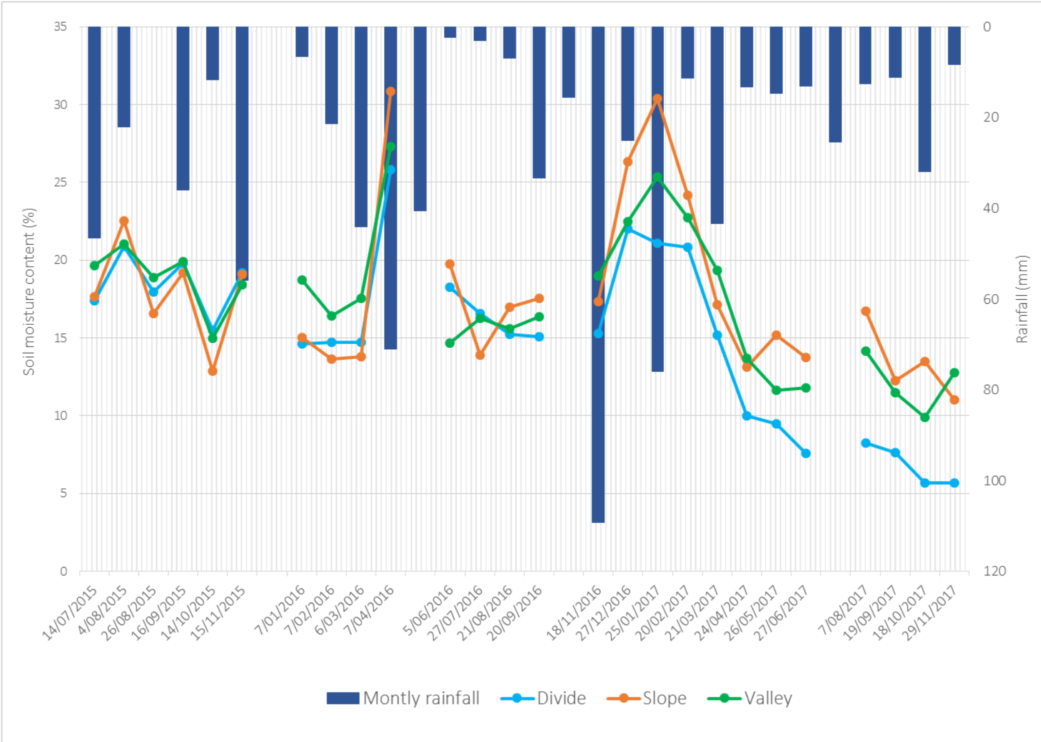

Figure 63. *Monthly rainfall amount and SMC in landforms of the GF treatment in Aurora quarry.*

Slope and Valley landforms had mean SMC above 17% and were 2% higher than the divide landform mean content (Table 24). Furthermore, the Friedman test showed the landforms were significantly different (chi-squared = 13, df = 2, p-value < 0, 01) with SMC in the Divide landform significantly lower from the rest (Wilcoxon test, Figure 64).

Landform	Mean ± SD
Divide	15.2 ± 5.4
Slope	17.7 ± 5.3
Valley	17.3 ± 4.3

Table 24. *The mean and standard deviation of SMC in landforms of the GF treatment in the Aurora quarry. Data from 26 visits (n).*

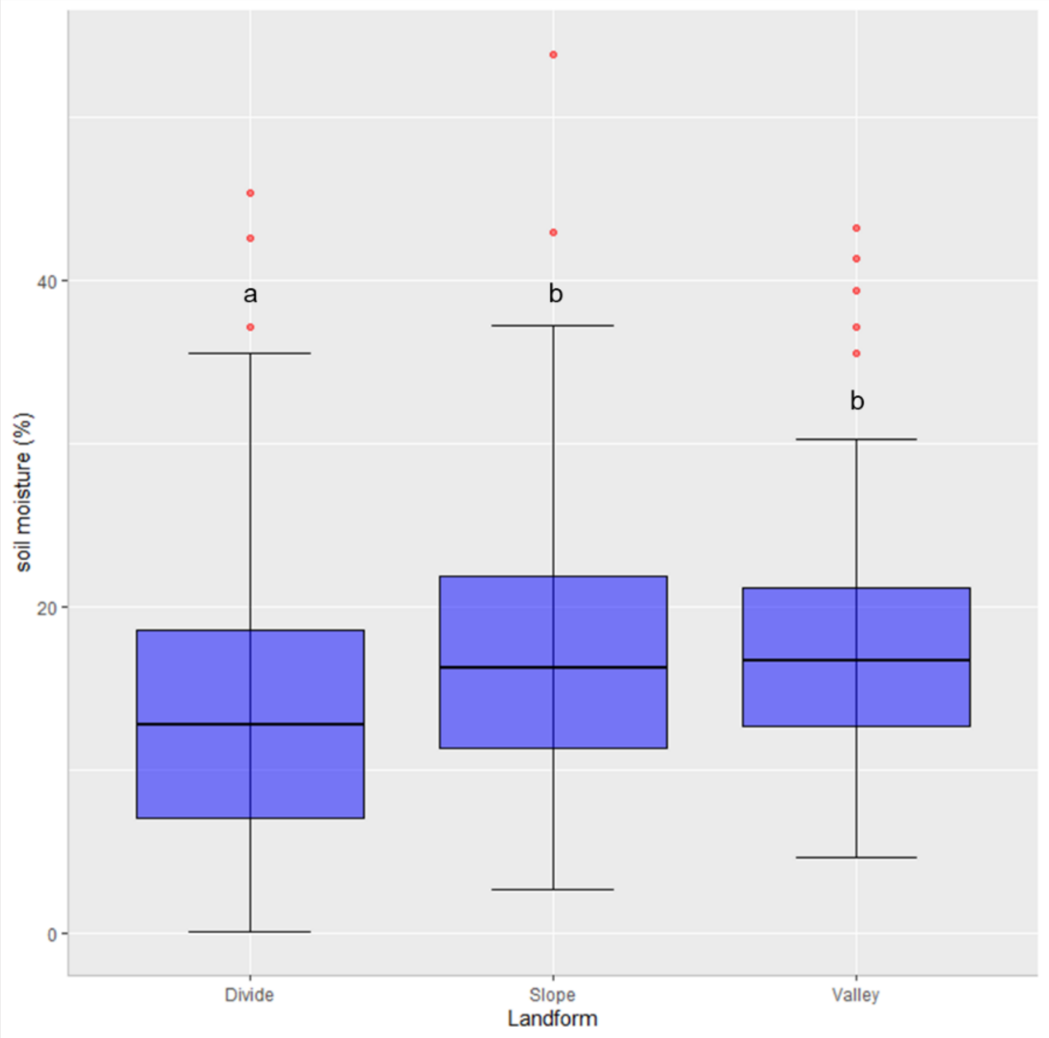

Figure 64. *SMC in landforms of the GF treatment in the Aurora quarry. Box shows 1st, median and 3rd quartiles, whiskers min and max values and dots represent outliers. Different letters indicate different groups based on the Wilcoxon test.*

During the recharge period, the divide landform showed lower values than slope and valley landforms in winter of 2016-2017 and October and November of 2017 (Figure 65).

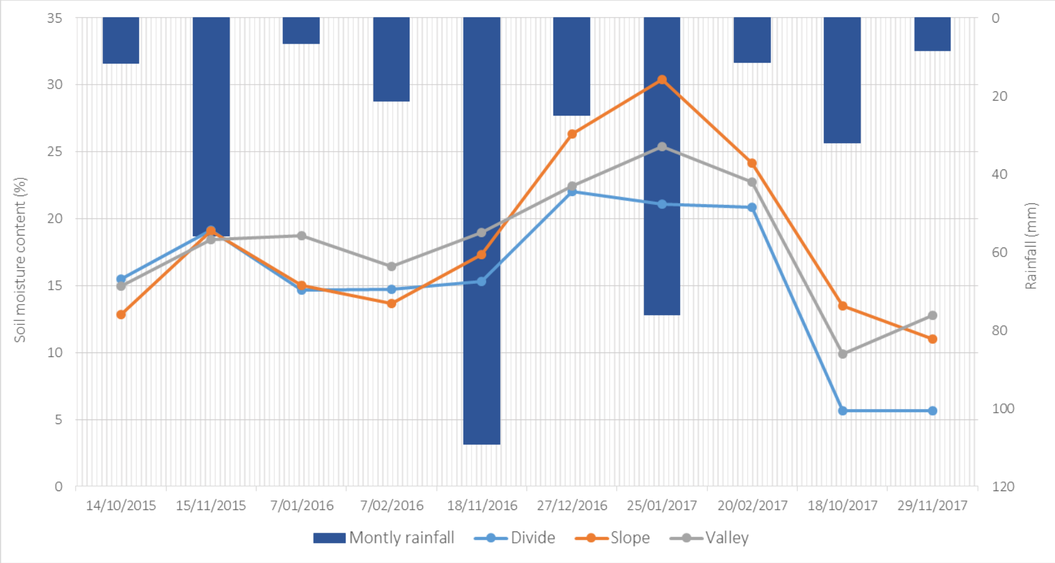

Figure 65. *Monthly rainfall amount and SMC in landforms of the GF treatment in the Aurora quarry during the recharge period.*

The divide landform had a 2.8% lower mean SMC than slope and valley landforms which had means above 18% (Table 25), however, the Friedman test did not find statistically significant differences between the landforms (chi-squared = 3.8, df = 2, p-value > 0.05, Figure 66).

Landform	**Mean ± SD**
Divide	15.5 ± 5.9
Slope	18.3 ± 6.5
Valley	18.1 ± 4.7

Table 25. *The mean and standard deviation of SMC in landforms of the GF treatment in the Aurora quarry. Data from 10 visits (n).*

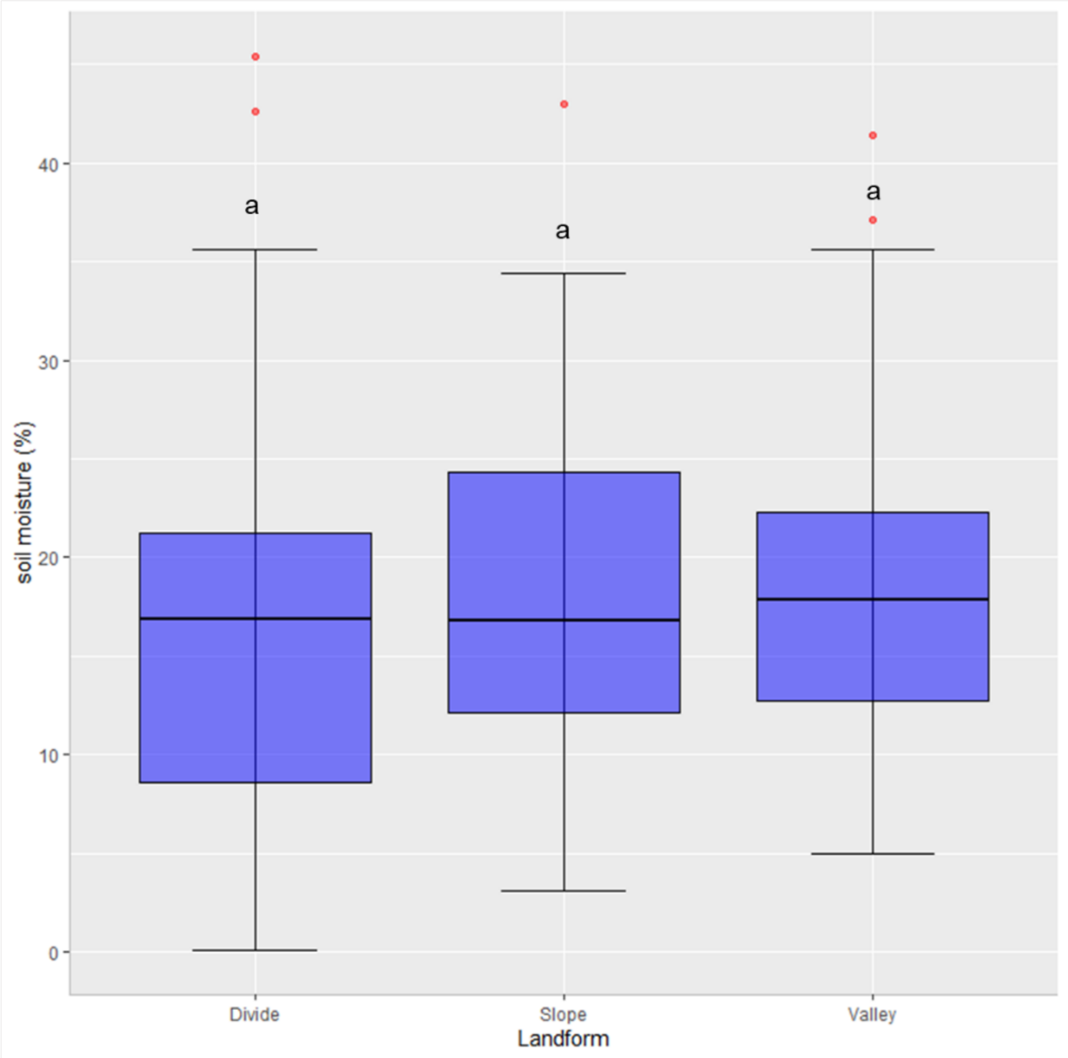

Figure 66. *SMC in landforms of the GF treatment in the Aurora quarry during the recharge period. Box shows 1st, median and 3rd quartiles, whiskers min and max values and dots represent outliers.*

Regarding the longitudinal pattern, the high transect showed lower values than Medium and Low transects, those last ones, had similar values during the last months (Figure 67).

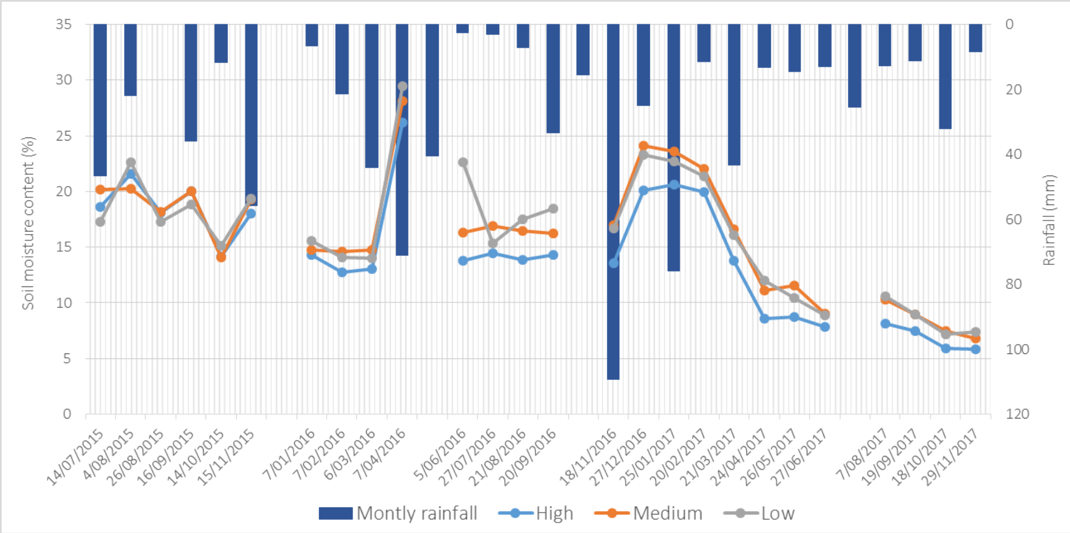

Figure 67. *Monthly rainfall amount and SMC in transects of the GF treatment in Aurora quarry.*

The high transect was 2% lower mean SMC than Medium and Low transects which had mean values around 16% (Table 26).

Transect	Mean ± SD
High	14.4 ± 5.4
Medium	16.1 ± 5.4
Low	16.3 ± 5.5

Table 26. *The mean and standard deviation of SMC in transects of the GF treatment of the Aurora quarry. Data from 26 visits (n).*

Additionally, the Friedman test showed significant differences between landforms (chi-squared = 25.9, df = 2, p-value < 0.01) with SMC in the high transect significantly lower than the others (Wilcoxon test, Figure 68).

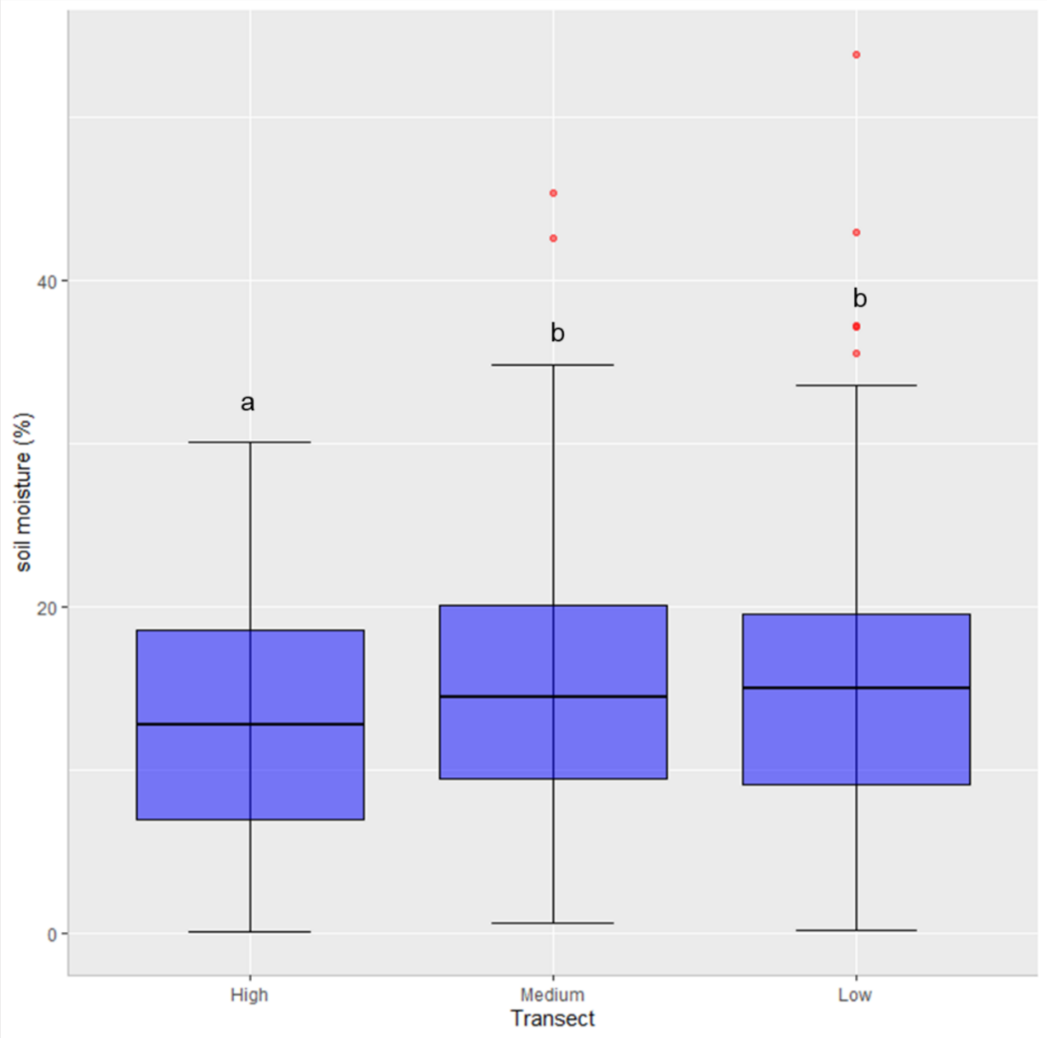

Figure 68. *SMC in transects of the GF treatment of the Aurora quarry. Box shows 1st, median and 3rd quartiles, whiskers min and max values and dots represent outliers. Different letters indicate different groups based on the Wilcoxon test.*

During the recharge period, transects had a similar trend of SMC as the previous analysis (Figure 69), the high transect had a 2% lower mean SMC than the medium and low transects (Table 27). The Friedman test found significant differences between the transects (chi-squared = 12.2, df = 2, p-value < 0.01) with SMC in the high transect significantly lower than the others (Wilcoxon test, Figure 70).

Transect	Mean ± SD
High	14.5 ± 5.4
Medium	16.4 ± 6.1
Low	16.3 ± 5.7

Table 27. *The mean and standard deviation of SMC in transects of GF treatment of the Aurora quarry. Data from 10 visits (n).*

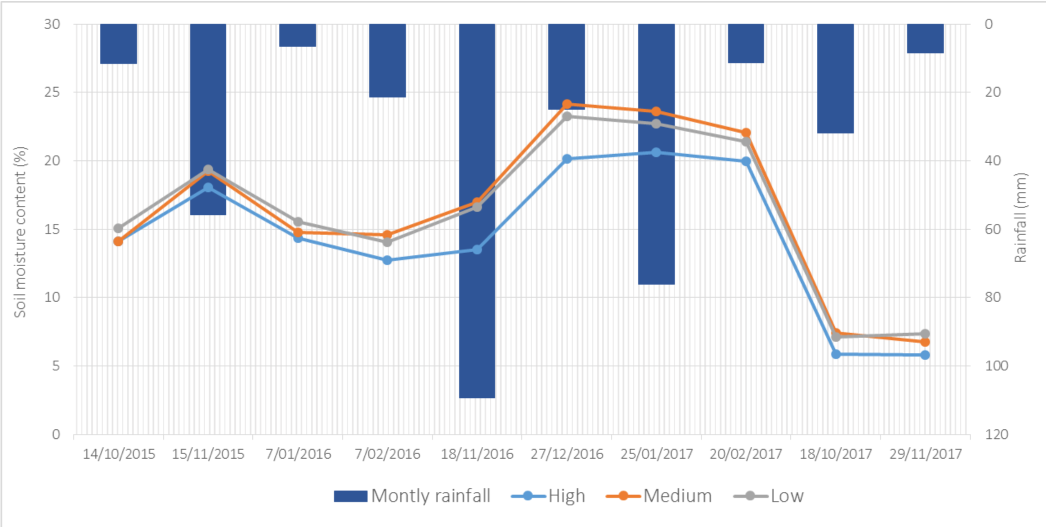

Figure 69*. Monthly rainfall amount and SMC in transects of the GF treatment in Aurora quarry during the recharge period.*

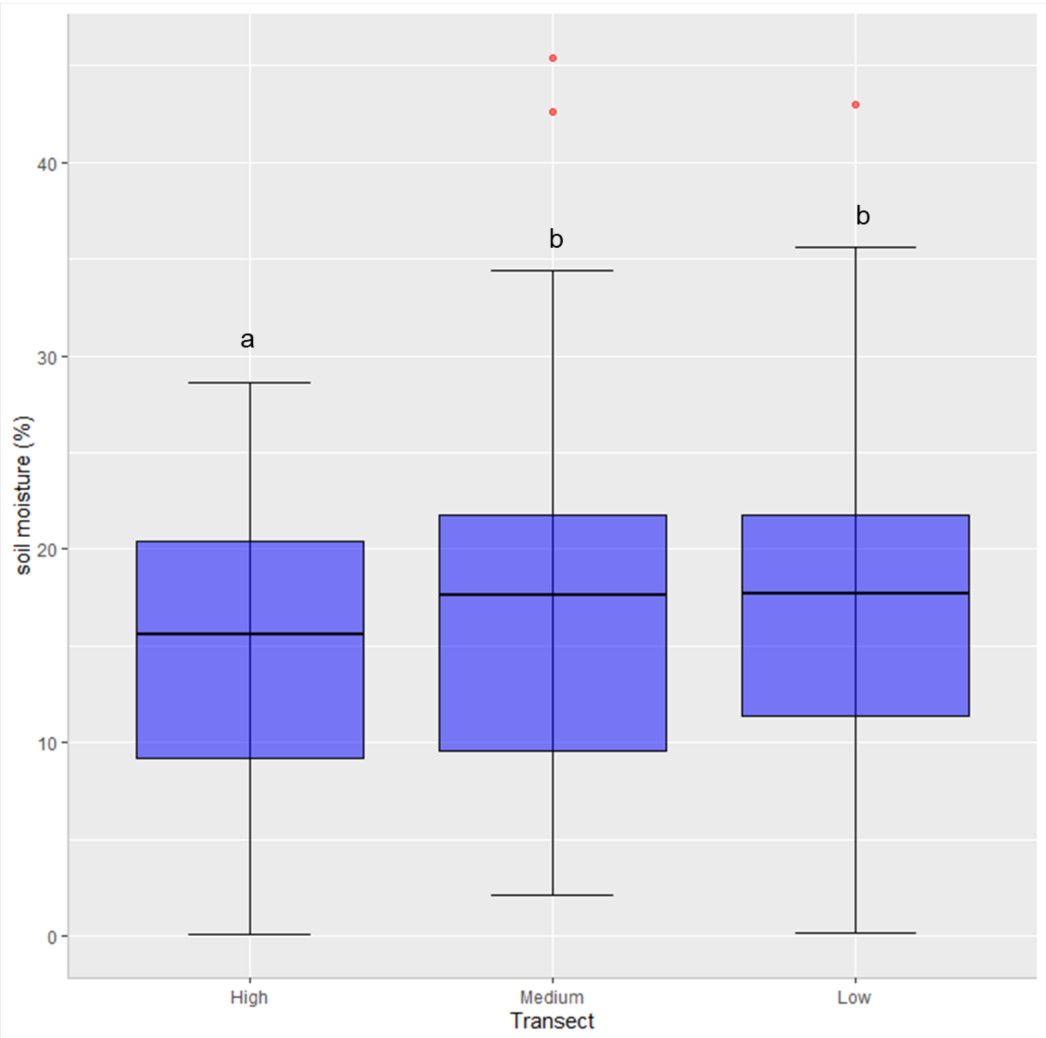

Figure 70*. SMC in transects of the GF treatment of the Aurora quarry during the recharge period. Box shows 1st, median and 3rd quartiles, whiskers min and max values and dots represent outliers. Different letters indicate different groups based on the Wilcoxon test.*

- The conventional treatment TC:

The Rills landform registered higher SMC than Inter-rills landform throughout the data collecting period (Figure 71) In fact, the SMC mean of Rills (mean = 20.0%, SD = 5.2; n = 12) was 9.6% higher than Inter-rills (mean = 10.4%, SD = 6.0; n = 12) moreover, the Friedman test revealed significant differences between the landforms (chi-squared = 12, df = 1, p-value < 0, 01, Figure 72).

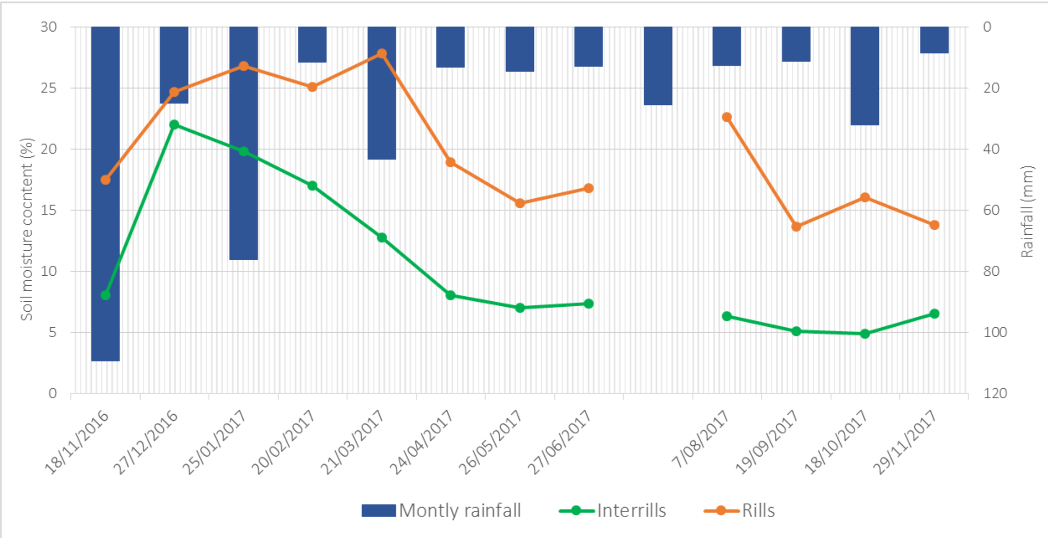

Figure 71. *Monthly rainfall amount and SMC in landforms of the TC treatment in the Aurora quarry.*

During the recharge period, the landforms had a similar trend of SMC as the previous analysis (Figure 73): the Rills (mean = 20.7%, SD = 5.7; n = 6) was 7.6% higher than the Inter-rills landform (mean = 13.1%, SD = 7.4; n = 6) however, data collected were not sufficient for testing.

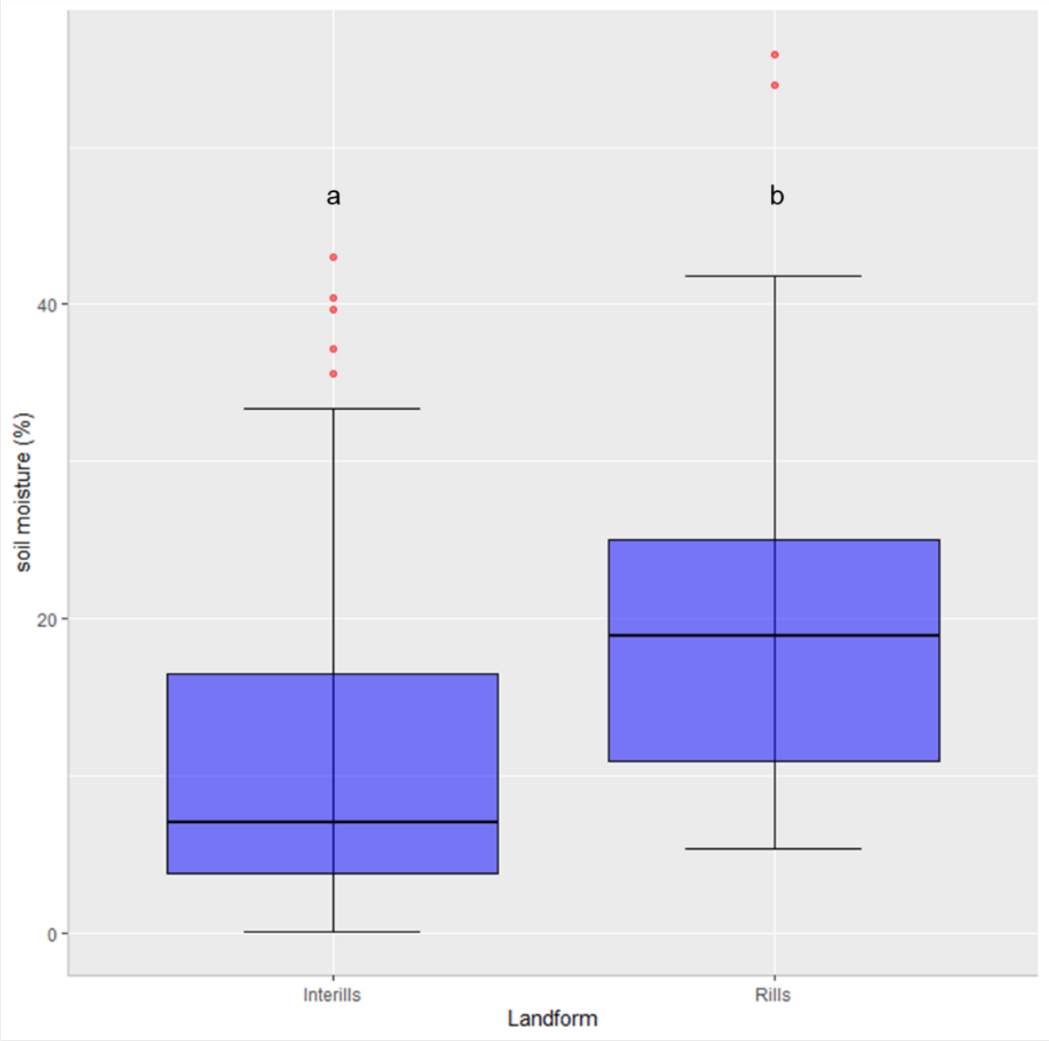

Figure 72. Soil moisture content in landforms of the TC treatment in the Aurora quarry. The box plot shows medians, 2nd and 3rd quartiles, and outliers. Different letters indicate different groups based on the Friedman test.

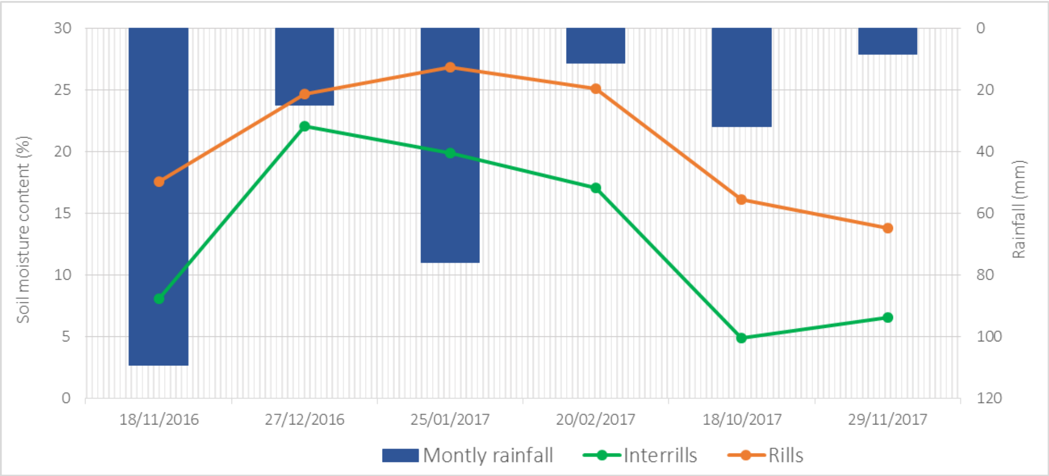

Figure 73. Monthly rainfall amount and SMC in landforms of the TC treatment in the Aurora quarry during the recharge period.

Regarding the longitudinal pattern of soil moisture, the high transect of the TC treatment registered higher SMC than medium and low transects throughout the data collection period (Figure 74).

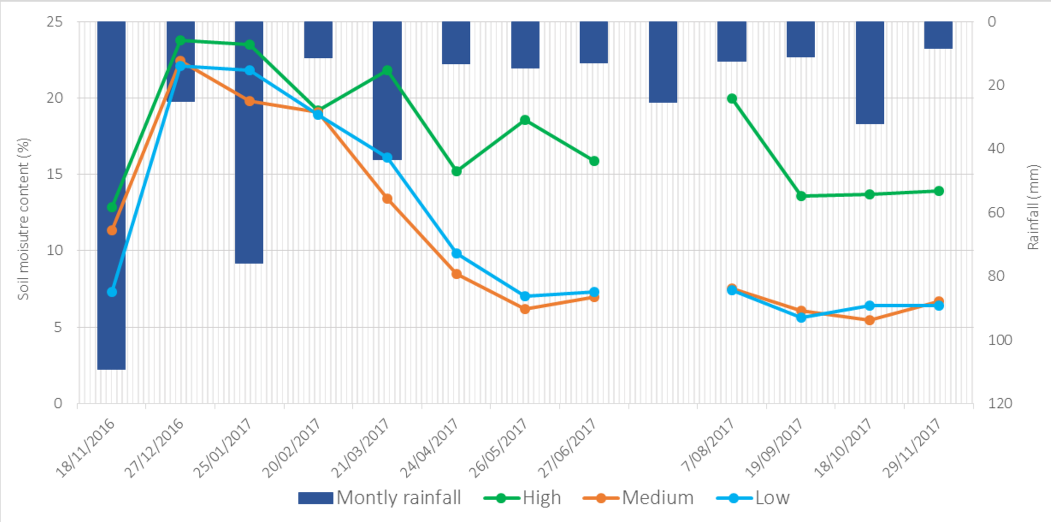

Figure 74 *Monthly rainfall amount and SMC in transects of the TC treatment in the Aurora quarry.*

The high transect had a 6% higher mean SMC than Medium and Low transects, which both values were around 11% (Table 28) moreover, the Friedman test found significant differences between the transects (chi-squared = 18, df = 2, p-value < 0, 01) with SMC in the high transect significantly higher than the others (Wilcoxon test, Figure 75)

Transect	Mean ± SD
High	17.7 ± 4.0
Medium	11.1 ± 6.1
Low	11.4 ± 6.4

Table 28. *The mean and standard deviation of SMC in transects of the TC treatment in the Aurora quarry. Data from 12 visits (n).*

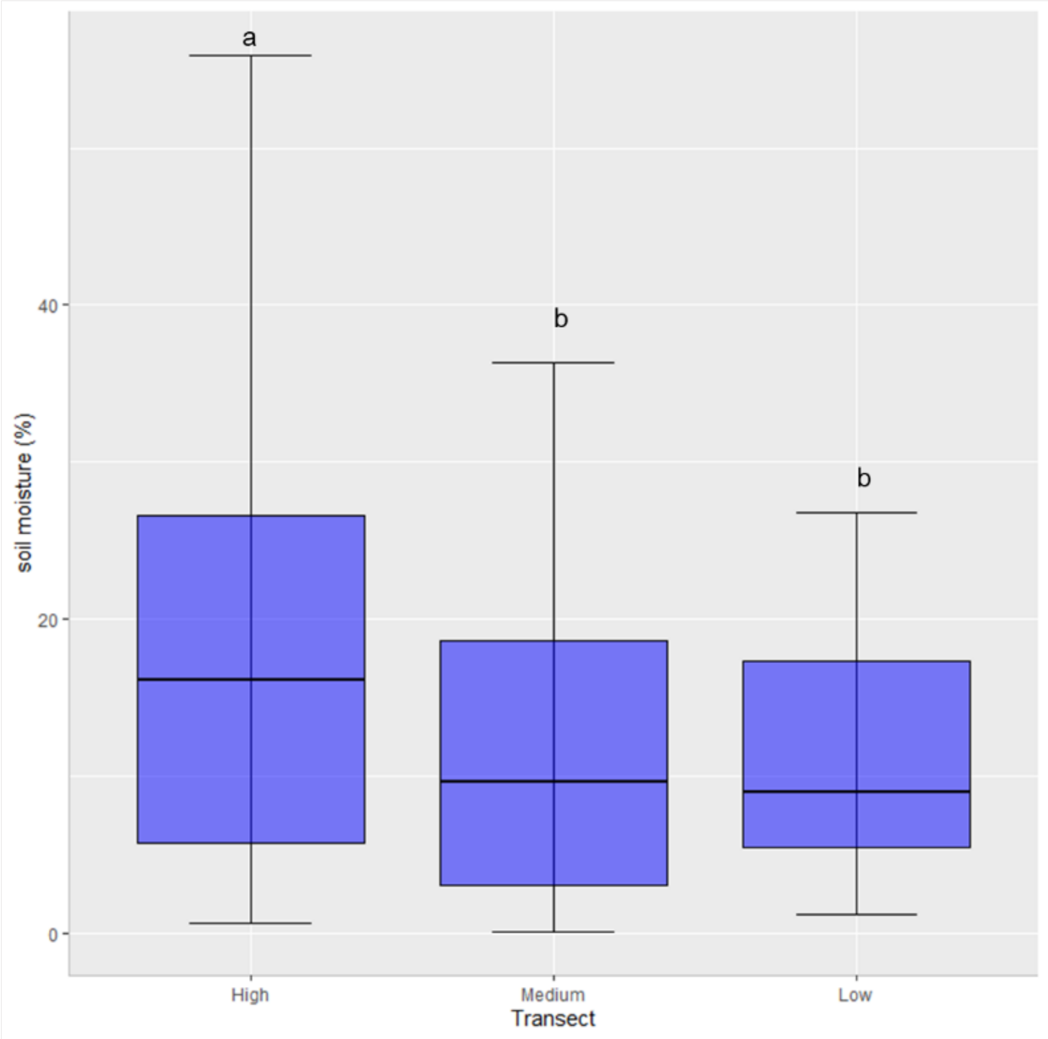

Figure 75. *SMC in transects of the TC treatment in the Aurora quarry. The box plot shows medians, 2nd and 3rd quartiles, and outliers. Different letters indicate different groups based on the Wilcoxon test.*

During the recharge period, the transects kept the trend of SMC as the previous analysis (Figure 76), the high transect had 3.7% higher than Medium transect and 4% than Low transect (Table 29), however, the data were not enough to run the tests.

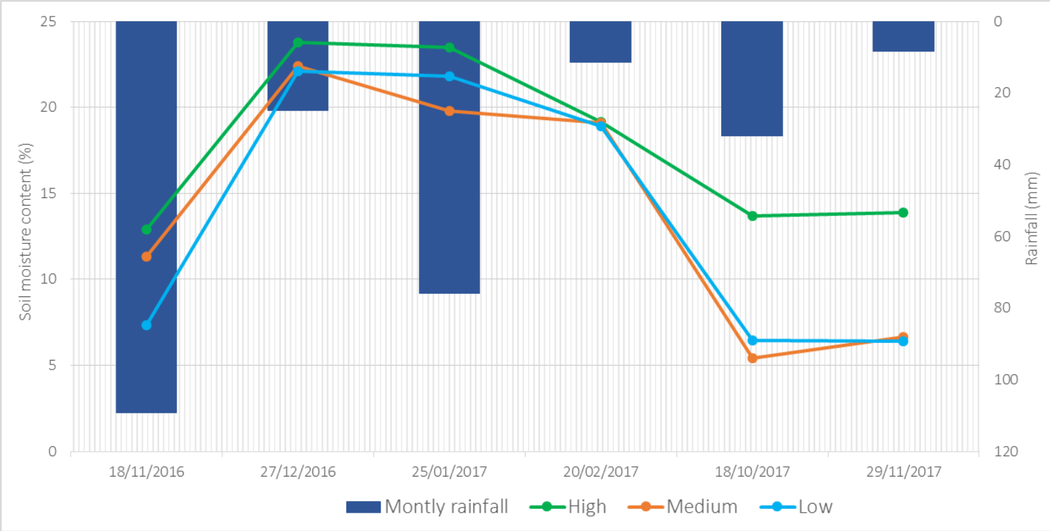

Figure 76. *Monthly rainfall amount and SMC in transects of the TC treatment in the Aurora quarry during the recharge period.*

Transects	Mean ± SD
High	17.8 ± 5.0
Medium	14.1 ± 7.3
Low	13.8 ± 7.9

Table 29. *The mean and standard deviation of SMC in transects of the TC treatment in the Aurora quarry during the recharge period. Data from 6 visits (n).*

7 Discussion

Runoff erosion and poor topsoil are the main barriers to the success of restoration practices in mining areas in Mediterranean environments (Zapico et al., 2018). The conventional reclamation approaches, based on slope and berm landforms, tend towards erosion, forming rill and gullies during extreme rainfall events (Martín-Moreno et al., 2018).

High rainfall erosion rates cause rill networks development, which allow runoff pathways that drive water out of the system (Moreno-de las Heras et al., 2011). Consequently, rainfall erosion decreases infiltration rates and reduces water availability, which is the main driver for vegetation development in Mediterranean areas (Nicolau, 2002).

Geomorphic reclamation designs stable topographies that reduce runoff volumes and improve drainage which reduces the formation of rill networks (Nicolau et al., 2012). Consequently, maximizes infiltration on the slopes providing a greater supply of water to plants (Balaguer *et al*., 2013). Moreover, this means lower sediment yield downstream (off-site effects) reducing the hydrological impact of mining.

This diploma thesis has compared SMC between conventional and geomorphic restoration approaches in two quarries under two different Mediterranean climate types in Spain. The main objective of this work was to observe which restoration approach offered more water to plants, which is the limiting factor of vegetation in the Mediterranean. Soil moisture content was used as an indicator, analyzing the data taken during the whole data collection period of each project and also, as a more accurate indicator of water supply to plants, analyzing the soil moisture content during the recharge period: from late autumn to early spring (October to February). At the Aurora quarry, it was possible to perform statistical analysis for this period since there was a sufficient number of observations, but in the Fortuna quarry, it was only possible to evaluate the trend without statistical testing.

Fortuna quarry has a Mediterranean continental climate, there geomorphic approach had higher SMC values than conventional one, during the whole collecting data period as well as during the recharge period. Indeed, the canonic example of the geomorphic approach -GFP unit- showed SMC values similar to the reference ecosystem (ER) and higher SMC (period average) than the conventional approach (TC). Indeed, the canonic example of the geomorphic approach -GFP unit- showed similar SMC values to the reference ecosystem (ER) and higher SMC (period average) than the conventional approach (TC).

A variant of the canonical geomorphic approach was also applied in the Fortuna quarry (GFG unit). It was an adaptation of the GeoFluv™ method in which tree planting was added, and micro-catchments were built on to collect surface runoff water into the holes of the planted trees (Constantini et al., 2015). In this case, SMC values in those inter-holes areas have been lower than in the canonic design (GFP) as was expected, since planting holes have collected a part of runoff.

In the Aurora quarry, the landforms from GF treatment showed higher mean SMC values for the recorded period than inter-rill areas, the only place where plant growth is possible in slopes of conventional restoration (Espigares & Moreno-de las Heras, M Nicolau, 2011). Therefore it might assume the geomorphic approach provides higher water availability to the plants than the conventional approach.

The geomorphic restoration includes the design of stable landforms but also the use of an appropriated substrate. In the Mediterranean mountains, soil erosion is very active and soil formation slow, so the topsoil layer is quite scarce. This is why restoration practitioners use some superficial formations, like colluvium, to cover the overburden in mining reclamation. Colluvium has good physical properties such as higher water infiltration, higher water holding capacity and lower erodibility than overburden. In our study site, it is composed of limestone fragments and a fine matrix of sand, silt and clay, with a loamy texture that allows a balance between optimum drainage and accumulation of water and nutrients, decreasing soil erosion. (Martín-Duque *et al*., 2010).

In addition to the topography, the substrate is a key abiotic factor controlling the plant community assemblage, that is, the revegetation success. In both quarries, areas covered by Colluvium had higher soil moisture content that those covered by overburden. Although only in Fortuna differences were statistically significant. It is worth taking these differences into account when designing the restoration plan and we encourage the use of colluvium as the recommended substrate if its properties are good enough.

On the other hand, the slope aspect is an influential factor in soil moisture content as it is well known (Fan et al., 2020; Yu et al., 2018). The results confirm that the shady aspect (north) has higher values than sunny (south) orientations in both quarries, which can help to make the plant species selection for revegetation programs.

The hydrological functioning of geomorphic restored landscapes is still poorly understood, but it is of great interest to know the spatial distribution of soil moisture over time to improve the design of revegetation programs. Slopes designed by the geomorphic approach are not rectilinear but formed by convex (divides) and concave landforms (small valleys). It is expected the water to flow from the divides towards the small valleys (transverse pattern). Likewise, it is also expected a longitudinal pattern from the upper part (exporting zone) to the lower one (importing zone). In both quarries, this longitudinal pattern has been confirmed, in the GFP unit in Fortuna, the lower transect had 1.5% higher soil moisture content than the higher transect. As well, the GF unit in Aurora medium and low transects were significantly wetter/dryer than the high transect.

Additionally, there is also a water flow from the export convex zones (Divide) toward the import concave zone (Valleys). In both quarries, this longitudinal pattern has been confirmed in fact, the GFP unit in the Fortuna quarry showed significant differences between the Divide which has less soil moisture content than Valleys, the same trend occurred in the geomorphic approach of Aurora. Heterogeneity in soil moisture may benefit ecological heterogeneity (diversity) in geomorphic restoration(Garbarino et al., 2018) far from the uniformity present in conventional slopes (Rehounkova et al., 2011).

This SMC pattern in GeoFluv-canonical topography (GFP unit) is different from the pattern in the GFG unit, with micro-catchments that drive surface runoff toward planting holes. In this case no differences were detected between divides and valleys, which means that the micro-catchments has been successful in managing water. In fact, preliminary measurements carried out by the team from the CEAM (*Centro de Estudios Ambientales del Mediterráneo, who designed and carried out the planting experiment)* show a very high seedling survival rate (over 90%), which may indicate the effectiveness of this runoff control system. The micro-catchment system degrades with time hence might be no longer functional after several years, therefore, the flow pattern of soil moisture might reorganize at GFG towards a pattern similar to the GFP unit.

The expected increase of water downwards has been observed also in conventional slopes of the Fortuna quarry (TM and TC). However, another pattern has been found out in the conventional slope of the Aurora quarry: the higher transects are wetter than the lower ones. We hypothesize that it is due to the presence of an upper berm that provides water to the slope, increasing SMC in the higher parts. On the other hand, a lateral pattern occurs in this slope because of the formation of rill networks. Rills concentrate runoff showing higher SMC values than inter-rill areas. This pattern has already been observed in other mining restorations studies (Moreno-de las Heras et al., 2011). These authors, also found that plant cover was associated with SMC spatial distribution, with no plant establishment in the rills, because of erosion instability, low plant cover in inter-rill areas because of low SMC and higher vegetation establishment close to the rills, where soil water is available but no rill erosion occurs.

8 Conclusion

This study determines that the quarries restored under Mediterranean climate with a geomorphic approach have higher soil moisture content than quarries restored using a conventional approach. Therefore we might assume that the geomorphic approach provides higher soil water availability to the plants.

Colluvium substrate provides higher soil moisture than the commonly used overburden, hence we recommend to use colluvium substrate within the restoration activities.

North-facing areas have a higher SMC than south-facing areas, therefore it is important to take into account when selecting plant communities than north-facing areas.

The spatial distribution of soil moisture content in the canonical Geo Fluv ™ topography increases from the divides towards the small valleys (transverse pattern) and from the top (export zone) to the bottom (import zone) in a longitudinal pattern. However, having micro-watersheds alters the longitudinal pattern of water distribution by driving surface runoff into tree planting holes.

The spatial distribution of SMC in conventional restoration areas increases from top to bottom, however, this pattern may shift if the slope has an additional runoff inflow from an upper berm. Concerning the transverse soil moisture pattern, it is confirmed that the moisture content is higher in the rills than in the inter-rill, affecting the establishment of vegetation.

9 Resources

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