Geographical Information Management and Applications

The relationship between moisture distribution on pedestal rocks and their direct topographic context in the Stołowe Mountains

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Abstract

The factors that shape pedestal rocks differ by climate zone and location. Pedestal rocks in the Stołowe mountains are thought to be shaped by selective weathering, where a major role is attributed to moisture absorption and evapotranspiration. These processes weaken the rock and speed up the weathering rate in the more vulnerable lower part. This study focused on the relationship between the moisture patterns on the rocks and the local environment, in an attempt to answer the question whether the terrain features surrounding the pedestal rocks have an influence on the moisture distribution inside the rocks. Structure-from-motion photogrammetry was used to model the surroundings of the pedestal rocks, which resulted in a 3D point cloud of the study sites. The moisture distribution was mapped using moisture measurement devices. The relationship between the environment and moisture was assessed using four factors (sunlight, wind, elevation, vegetation), with the main focus on the effects of sunlight. The sunlight modelling was accomplished in a point cloud environment using a Python script, which is an innovative way of approaching this type of analysis. Statistical tests proved significant correlations between wind and moisture (.72), and between shadow patterns and moisture (ranging from .28 to .8). No correlations were found between moisture and the remaining two factors (elevation, vegetation). A regression model explained 22.4% to 64.3% of the variance in moisture levels as an effect of shadow patterns on the rocks' surface. It was concluded that sunlight and shadows influence the moisture patterns on pedestal rocks. These results suggest that the weathering of the pedestal rocks might proceed at an accelerated pace in places where the rocks are more exposed to sunlight.

Contents

Disclaimer: All pictures in this report were taken by the author.

1. Introduction

A pedestal rock (sometimes called a mushroom rock) is a curious landform in the shape of a mushroom, with a smaller steel in the lower part and a larger hood or cap in the upper part (see Figure 1.1). They can be found in different places and environmental conditions around the world. There is a plethora of different theories on the origins of pedestal rocks. These rock formations seem to have different origins depending on the circumstances or environment in which they were formed (Twindale and Centeno, 1993). In the Stołowe Mountains the current theory is that the pedestal rocks are formed due to selective weathering (Duszyński and Migoń, 2022). The stem consists of a more porous sandstone which is less resistant to weathering compared to the hood (Migoń, 2021). The selective weathering of the stem can also be attributed to capillary action and moisture presence within the rock, which could additionally weaken it. There may be some external factors that influence the moisture patterns on the rock surface, for example, sunlight or vegetation. This study will attempt to combine moisture measurements with external factors modelled in a GIS environment to explain the dynamics between moisture patterns and influences by external factors. This chapter will first go through different theories surrounding the mechanisms that shape pedestal rocks, which will lead to the formulation of a research objective. Lastly, a short description of the study area will be provided.

Figure 1.1: An Example of a Pedestal Rock in the Stołowe Mountains

Theories on Pedestal Rocks

There is an abundance of literature covering the mechanisms that shape pedestal rocks. These rock formations can be found all over the world in different climate zones (Leonard, 1927; Twindale and Campbell, 1992; Twindale and Centeno Carrillo, 1993; Hong and Huang, 2001; Bruthans et al., 2014; Dorn et al., 2017), and their origins differ depending on the circumstances and climate in which they were formed. One of the theories on the origins of pedestal rocks is aeolian. It is presumed that the smaller steel is the result of erosion caused by little dust and sand particles which are carried by the wind at a certain height above the ground, which eventually results in the dual shape, with a smaller steel and larger cap (Cramer, 1963; Twindale and Campbell, 1992; Laity, 2009). While this theory was widely popular in the past, it is important to note that it is not the only way in which pedestal rocks can be formed. The aeolian origins may be true for some of the pedestal rocks, especially those which developed in an arid climate where aeolian erosion plays a fundamental role in the development of landforms (Goudie, 1989; Goudie, 2008). Pedestal rocks can also be found in humid climates, however, where this theory is not valid (Twindale and Centeno, 1993). There must be other mechanisms at play which shape these rocks in non-arid places.

One such mechanism which may be active in sandstone landforms is the negative feedback between stress and erosion, as described by Bruthans et al. (2014). The cap of a pedestal rock puts stress on the steel from above, but instead of weakening the structure the pressure acts as a stabilizing factor. The higher the pressure (heavier cap), the more resistant the steel becomes. They suggest that pedestal rocks (among other landforms) may be shaped by this mechanism, meaning that the force applied by the weight of the cap determines the size of the stem. Another possible mechanism is attributed to the hardening of the outer layer of the cap (Dorn, Mahaney and Krinsley, 2017). Due to weathering of the rock, a rind forms on the outer parts of the rock, which turns into a protective crust that makes the rock more resistant to weathering. This phenomenon is also observed on sandstone formations, where the sandstone is sometimes covered with a thin layer of silica (Thiry, 2005).

The current view on the evolution of pedestal rocks in the Stołowe Mountains is that they are of a dual origin, with selective weathering and capillary action being seen as the main causes (Duszyński and Migoń, 2022). The processes of selective weathering and capillary action are still ongoing, meaning that the pedestal rocks are still being shaped continuously. The stem of a pedestal rock consists of a more porous sandstone than the hood, which makes it less resistant to weathering, which in turn encourages faster weathering of the stem as compared to the hood (Migoń, 2021). The porous nature of the stem also encourages moisture circulation and increased capillary action in the lower part of the rock, resulting in heavier weathering. The part being played by moisture circulation seems especially important in this case. Sass (2005) confirms that spatial and temporal patterns of weathering can be explained by the moisture content of the rock. Water will be absorbed by the rock after rainfall, snowmelt, or by capillary action, where it will be soaked up into the stem from the ground. When it gets warm or when the sun shines on the rock, for example, the water will evaporate from the rock surface. These repeated cycles of absorbing moisture and evapotranspiration will weaken the rock (Thiry, 2005; Duszyński and Migoń, 2020). Additionally, when sub-zero temperatures occur, the water stored inside the rock will freeze and expand, which results in frost shattering of the rock (Sass, 2005).

There is another role being played by water content in the sandstone. Sumner and Nel (2002) compared Schmidt hammer rebound values for dry and wet rocks, among them two types of sandstone. They found that the Schmidt hammer rebounds (an indication of a rocks' strength) decrease when the moisture content of the rock is increased. The two types of sandstone that were used in their study seem to be especially susceptible to this phenomenon as opposed to other types of rocks, with the Schmidt hammer rebound values decreasing by almost 20%, compared to a 3-6% decrease for others. This phenomenon is also confirmed by Sass (2022), who observed that sandstone loses up to 25% of its strength when saturated with moisture.

Research Objectives

The dual origin theory along with the importance of moisture and moisture circulation in the weathering process present a direction in which this study should be directed. The moisture circulation can be affected by several different factors from the direct surroundings of the rocks. The main focus in this case would be on exposure to the sun and shadow falling upon the rocks. A northern or southern exposure of the rock face can be important in this case since the southern part of the rock will dry up sooner than the north due to more hours in the sunlight. Trees, bushes, and any type of vegetation surrounding the rock provide shadow, leading to a slower drying process. Aside from the shadows and sunlight, moisture presence in the direct vicinity of the rocks can also influence the moisture circulation within it. Some rocks are situated on dry ridges or higher patches of ground, where capillary action will be limited. Other rocks are located in small valleys or near (periodic) streams, which can also impact the moisture absorption from the ground.

The objective of this study will be to find out if the moisture content of pedestal rocks is influenced by their direct environment, and in turn if the surrounding environment is an additional factor determines the shape or weathering process of the pedestal rocks.

This objective leads to the following main question and sub questions that will be answered in this study.

Main question:
Do the local surroundings of pedestal rocks in the Stołowe Mountains have an influence on the moisture distribution inside the rock?

Sub-questions:

1. *What is the moisture distribution on pedestal rocks measured at 3cm and 30cm depth?*
2. *What is the spatial context of the pedestal rocks in the Stołowe Mountains as replicated in a 3D environment using photogrammetry?*
3. *Does the spatial context (shadows, presence of trees or creeks, etc.) have an influence on the moisture distribution inside the rock?*

Scope
The goal of this study is to find out if the moisture content of pedestal rocks is influenced by their direct environment, and if this can be seen as an additional factor that shapes these landforms. This study is not about finding the origins of pedestal rocks or determining how they were shaped 10.000 years ago. The surroundings of the rocks are subject to change over the years, the forest that is there today was different in the past, at some points there was no forest at all. This study will purely be focused on what happens at the present, if the moisture content can be influenced by the surroundings of the rock. An effort of monitoring the patterns of moisture on the rocks throughout the year is also outside the scope of this study. The focus is on (spatial) relationships between the locational setting of the pedestal rock and the moisture patterns on it.

Study Area and Objects

The study area is located in the Stołowe Mountains, which are part of the Sudetes. This mountain range spans across the German-Czech and Polish-Czech border. The Stołowe Mountains are located in the Polish province of Lower Silesia, near the border with Czechia (see Figure 1.2). The mountains are a sandstone plateau consisting of Late-Cretaceous sandstone (Duszyński, Migoń, and Kasprzak 2016). The plateau is defined by steep ridges from the northern and southern sides and contains summits up to 919 meters above sea level. The pedestal rocks can be found on the northern edges of the plateau, northwest of the town Karłów (see Figure 1.2). They vary in both shapes and sizes, but also their surroundings vary (see Appendix 1). Some are located in open areas, others are surrounded by sparse tree cover or a dense forest. This gives some freedom regarding the choice of study objects and enables comparisons between different local settings in which the rocks are located.

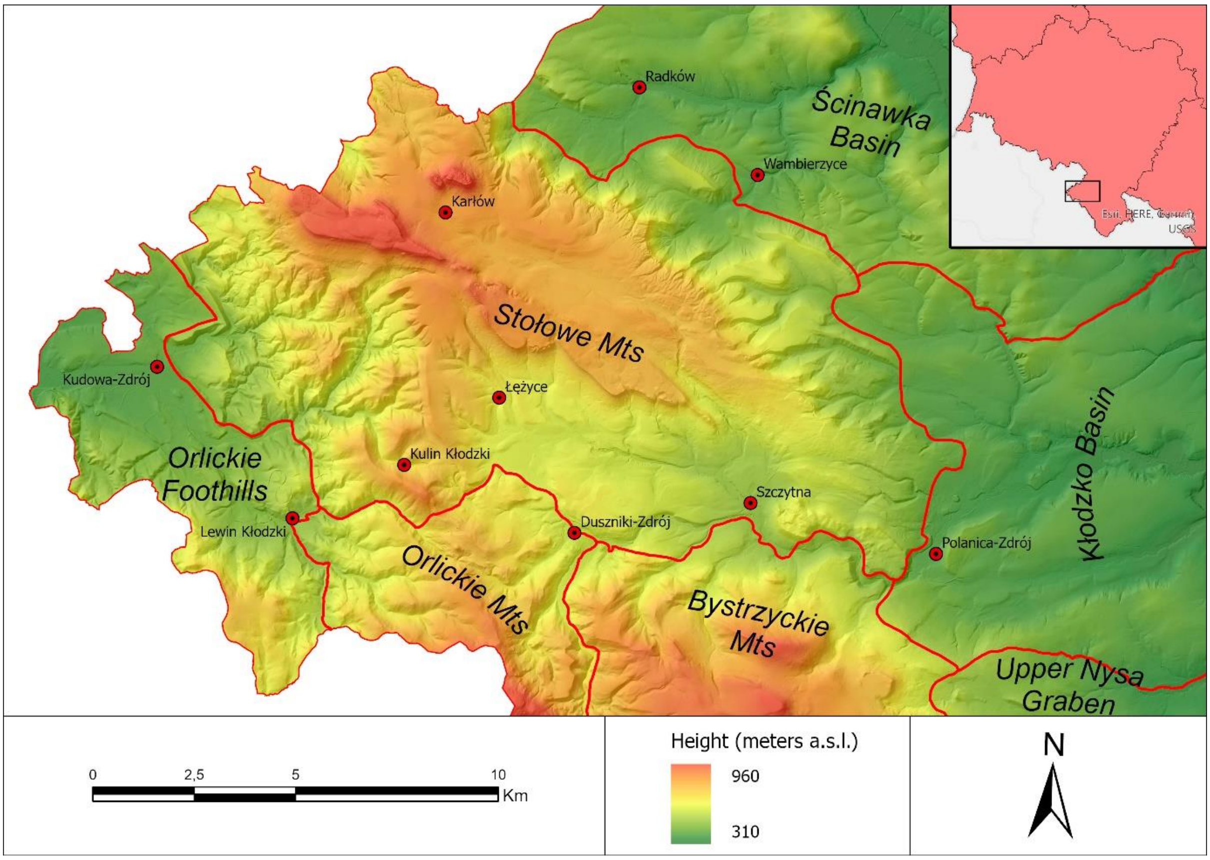

Figure 1.2: Location of the Stołowe Mountains within Lower Silesia

Contents of the Report

The report is structured as follows. First, in the methodology chapter a thorough description will be given of all the research methods that are used in this study, starting with the moisture measurements, the photogrammetric part, and finally the data analysis. Next, in the results chapter, the moisture patterns, maps, graphs, and statistical analyses will be used to show what results were obtained using the methodology. Afterwards, in the discussion chapter a deeper look will be taken at the results of the study. Finally, in the conclusion all the important findings will be described and research questions answered.

2. Methodology

The approach to conducting this research can be divided into three main phases. The first phase consists of carrying out fieldwork with the goal of collecting all the needed data. The required data consist of moisture measurements on the rock surface and pictures of the rocks and their surroundings. The second phase will include the photogrammetric aspect of the process, during which the pictures taken in phase 1 will be used in Agisoft (a photogrammetric program) for the creation of a 3D model of both the rocks and their surrounding environment. The third and final phase will be centred around using the 3D models of the environment for the purpose of modelling shadows and sunlight exposure on the rock surface. In the following section each step will be described in detail.

Phase 1: Field work, moisture measurements and taking pictures

The first step of the field work will be to conduct the moisture measurements on the rock surface. The moisture distribution will be measured with moisture measurement devices. There are two variants: the TROTEC 660 and TROTEC 610 (see Figure 2.1). The first one measures the moisture at a depth of 3-4 cm, while the second one can measure up to 30 cm inside the rock. This provides ground for an interesting analysis of moisture patterns at different depths, it will allow to see if the outside dries up quicker than the inside. Measurements will be conducted on the entire rock, but the question remains in what pattern the measurements should be made. Sass (2022) conducted moisture measurements on sandstone rocks using a grid of 40 x 40 cm, which resulted in differing numbers of measurements per sample plot. Sometimes 36 points, and 16 points in other cases. He concluded that this method was suitable for dampness assessment of the sandstone. A similar approach will be used in this study, measurements will be taken around 40cm apart, which should provide a good picture of the overall moisture distribution. The moisture measurements should be carried out 1-2 days after rainfall, because thanks to the increased moisture levels after rainfall (Sass, 2005) the moisture patterns on the drying sandstone will be more visible on the measurements.

Figure 2.1: TROTEC 660 (left) and TROTEC 610 (right)

The mapping of the 3D environment will be accomplished using photogrammetry. Terrestrial photogrammetry will be applied, which means that all the pictures will be taken from ground level. A successful approach to terrestrial photogrammetry in a forest environment is presented by Piermattei et al. (2019). They made 3D models of plots of forests in Slovakia and Austria using only terrestrial photogrammetry. They present a very detailed framework which will partially be used in this study. The proposed method for taking pictures of an area is to walk in a circular path around the area first while pointing the camera inwards, and then walking a smaller circle inside the area pointing the camera outwards (see Figure 2.2). For a plot with a diameter of 30 meters 338 pictures and 4 ground control points sufficed for creating a detailed model of the area. They suggest that if a plot is more complex, additional pictures should be taken in two perpendicular lines through the plot for more accuracy. Additionally, lighting conditions should also be noted when taking the pictures. Iglhaut et al. (2019) suggest that a high sun angle is preferable, overcast conditions provide an even lighting, and changing illumination (interchangeable sun and clouds) should be avoided. The 3D models of both the environment and rocks should be georeferenced as accurate as possible. The georeferencing will be accomplished using a local reference system based on reference points measured and placed in the field. Mikita, Janata and Surový (2016) used a white surface with a black cross as a reference point, and the same will be applied in this study.

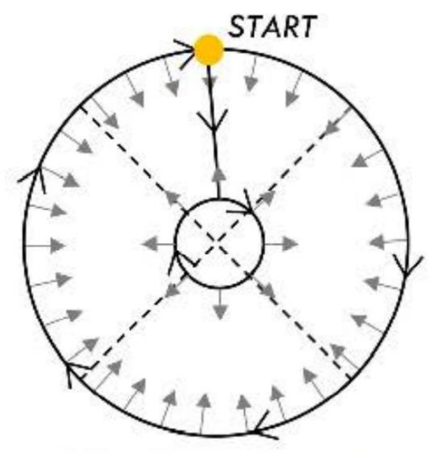

Figure 2.2: Schematic illustration of the photographic path, adapted from Piermattei et al. (2019)

Based on this information a basic protocol can be established for surveying each rock and its surroundings (see Table 2.1). Some additional notes regarding this protocol:

- The time estimates for taking pictures are based on Piermattei et al. (2019).
- The ground control points (GCP's) will be based on a local fabricated reference system. GCP's will consist of pieces of paper with a cross drawn on them to serve as the centre (see figure 2.3), the coordinates will be measured in the field.
- Area complexity (elevation, number and density of trees and bushes) can affect the time needed for establishing GCP's and the process of taking pictures.

Table 2.1: Fieldwork Protocol

What?	How/How many?	Time?
Establishing a measurement grid	Establishing a 40 x 40cm grid on all faces of each rock, starting from the bottom	5 minutes
Moisture measurements	Conducting moisture measurements every 40cm	Depending on the size of the grid 10-20 minutes
Establishing GCP's	Five per area, placed evenly around the place.	Depending on the complexity of the terrain 15-30 minutes
Taking pictures of the area	Picture layout in Figure 2.2, a minimum of 350 pictures per rock, diameter of 30-40m	Depending on the area complexity 30 minutes to 1 hour
Taking pictures of the rock	Walking around the rock, a minimum of fifty pictures per rock	10 - 30 minutes

Figure 2.3: Example of a Reference Marker Used in the Field

The procedures during the fieldwork are structured as follows. Note that the field work will be carried out by 2-3 people. Upon arrival at a plot/site the pedestal rocks are assigned as the center point of the plot. Then, a local coordinate system is set up on the site with the use of 5 coordinate markers. Each marker is placed on a tree within the plot and assigned its own local coordinates measured in centimeters with a laser measuring device. The north-south parallel will be used as the y-axis and east-west as the x-axis (see figure 2.4). After setting up the markers, measuring and writing down the coordinates for each marker, one person will measure a 15-20m line (depending on the on-site circumstances) from the central point of the plot towards the outside and place an orientation point in the form of a metal rod. This should be done 8-10 times to create a circle around the center point that would indicate the photographic path. Simultaneously, the other person will start taking pictures along the edge of the created circle, with a frequency of around 3 picture per meter. After finishing taking pictures all around the circle, the photographer will take a path towards the center point, and turn around at approximately 5m from it to take pictures from the inside towards the outside (see figure 2.2). Finally, close-up pictures of the pedestal rock can be taken to accurately model it in Agisoft later.

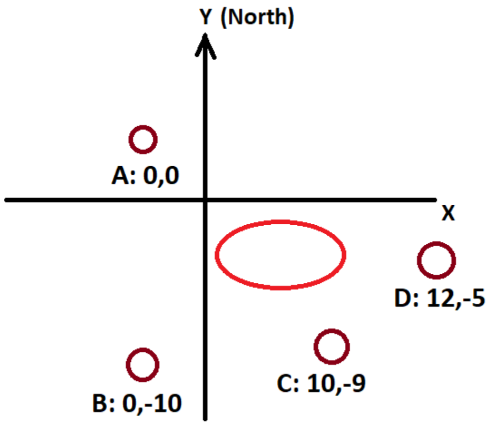

Figure 2.4: Schematic view of the Control Points System (the red oval resembles a pedestal rock)

The fieldwork can be divided into two separate steps, the moisture measurements and collection of pictures for photogrammetric processing. Since the first step is ideally done in specific weather conditions (1-2 days after rainfall) it is important to collect this data in a short timeframe for the sake of comparability between the rocks. The moisture measurements will take 30 minutes per rock at most, which would mean that the collection of data for 8 rocks would take 5 hours. Including walking and breaks, this should not exceed 8 hours of work, meaning it is doable within a day. The second step is more time-consuming, and therefore should be done separately. The process of taking pictures is estimated at around 2 hours per rock and surroundings, which would take an additional 3 days of fieldwork. It is not required to conduct the measurements and take photos on the same day, since the objects that will be captured in the pictures do not change. Therefore, the tasks can, and should, be done on separate occasions.

Phase 2: Photogrammetry

The methods in phase 2 are centred around photogrammetry. The photogrammetric technique structure-from-motion, SfM in short (Westoby et al., 2012), will be used to model the rock and its surroundings. A 3D model of the rock will allow for creating a moisture map on its surface, with the moisture measurements in digital form overlayed on the 3D model of the rock. The direct environment surrounding the rock can also be modelled using photogrammetry. This will allow for an insight into the surroundings of the rocks in a 3D environment and will help with understanding how the surroundings influence the moisture circulation. The 3D models will be constructed in Agisoft, a program that uses SfM for creating point clouds and digital terrain models (DTMs) from pictures. The steps that need to be taken to generate a 3D model using SfM are picture alignment, building a dense cloud, building a mesh, and after georeferencing the model, it can be exported as a DTM. The products created in this phase will be used for analysis in phase 3. The photogrammetric processing of the pictures has four main steps which will be explained below.

1. Image matching and camera orientation, resulting in a sparse point cloud
2. Importing the local coordinate system to scale the images
3. Improving the camera orientation with the help of control points and removing outliers
4. Building a dense point cloud

Image Matching

In step 1 a process is run to determine the camera alignment, which means the SfM program finds out where the camera was located for each taken picture. This process usually takes between 30 minutes and 1 hour for the number of pictures taken in this study. The highest accuracy setting is used with a key point limit of 100.000 and a tie point limit of 60.000. A successful run results in a sparse point cloud which already has some of the contours of the site features. There is still a lot of noise, however, which will be removed in step 3. The estimated camera alignment along with the sparse point cloud consisting of 450.718 points can be seen in figure 2.5. The three circular paths can be seen, with the outer circle facing towards the inside, the middle circle towards the outside, and the inner circle towards the inside again.

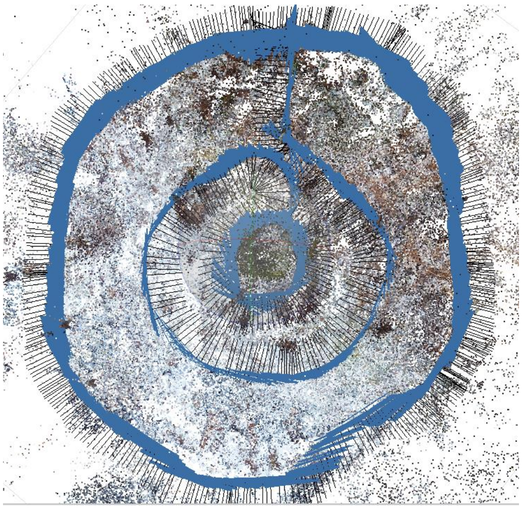

Figure 2.5: Photographic Path and Sparse Point Cloud at Site 2. The blue objects and lines indicate camera positions.

Importing Coordinates

Step 2 adds dimensions to the model. As the marker coordinates are imported and manually placed on the picture, it becomes possible to measure distances within the model. This step also helps with improving the camera orientation.

Improving Camera Orientation

In step 3 the added control points are used to optimize the camera alignment, resulting in a more accurate point cloud. In this step the outliers are also deleted. One of the methods is to delete all points that only appear in one image, which already results in a much cleaner point cloud. After this, the more difficult but obvious outliers are deleted manually for a further cleanup before step 4. A marked, filtered, and optimized sparse point cloud can be seen in figure 2.6.

Figure 2.6: A Filtered Sparse Point Cloud of Rock 2

Dense Cloud Generation

In the last step a dense point cloud is generated, which is the final product of the processing. This step takes a long time, usually between 1,5 to 2,5 hours at the high accuracy setting. This point cloud contains all the terrain features and makes for an accurate representation of the site, as can be seen in figure 2.7. The pedestal rock is modeled clearly In the center with some trees around it.

Figure 2.7: A Dense Point Cloud of Rock 2

Phase 3: Data analysis and shadow modelling

The final phase will be the analysis of the gathered data. The three sub-steps for this phase will be:

1. Creating a moisture map on the surface of the pedestal rock.
2. A quantification of the environmental factors that may influence the moisture content of the rock.
3. A statistical analysis of the factors and moisture data.

Creating Moisture Maps

In the first step the moisture measurements will be digitized in the form of points, and then interpolated to a raster. This will result in a moisture map which will make it easier to see what the moisture distribution on the rock is like. The data from these interpolations will also be used for further analysis.

Assessing Environmental Factors

Sunlight is the focal point of this study, but other factors will also be considered in the analysis to provide an even better understanding of the moisture patterns on pedestal rocks. The environmental factors that will be analyzed together with the moisture measurements have to be the ones that are most likely to influence the moisture level of the rock. Sass (2005) provides six findings regarding rock moisture levels:

1. Rainfall or snowfall are responsible for increased moisture levels.
2. Rock moisture is higher in summer than in the winter.
3. Geographic orientation of rocks influences their moisture levels, northern sides are wetter on average, but wind direction is also important, as wind carries precipitation in a certain direction.
4. Moisture levels are very variable in confined spaces .

5. Moisture levels are greatly increased at the edges of snow patches. In this case, a northern orientation also increases the area where elevated moisture levels are observed.
6. On average, rocks are wetter on the inside than on the outside.

The third of those findings can be split up into two measurable factors for this study, namely geographic orientation and wind. Rock surfaces exposed to the north have a significantly higher moisture content than those exposed in other directions. This would lead to the logical conclusion that exposure to the sun has a negative influence on the moisture levels, and so exposure to sunlight will be the first factor considered in this study. The other factor, wind, has a positive influence on moisture levels according to Sass (2005). This is due to the wind carrying the rain in a certain direction, making one side of the rock wetter than the other. This will be the second factor considered in this study.

According to Duszyński and Migoń (2022), the pedestal rocks may absorb moisture from the ground due to capillary action. This would mean that the soil moisture in the vicinity of the rock could influence the moisture absorption of a rock. Since soil moisture measurements are beyond the scope of this study, it will not be possible to use those for the analysis. The alternative is to use factors that are likely to influence soil moisture instead. Huang, Wu, and Zhao (2013) found that the most important factor influencing soil moisture is vegetation cover, followed by rainfall intensity, initial soil moisture, and finally slope aspect. Two measurable factors that can be used in this study are vegetation and slope. Vegetation increases the soil moisture retention and absorption. Moderate slopes and even ground are also good for moisture retention, while steeper slopes lead to increased runoff. This would give the third and fourth factor to be used in this study, namely presence of vegetation and slope aspect. Each of these four factors will have to be extracted into a measurable scale (see figure 2.8) to make a comparison between the moisture and factors possible. It should be noted that the main factor that will be studied is sunlight, with the remaining three factors being of secondary importance. This is because the data gathered for this study is most suited for a thorough assessment of sunlight, while the other three factors are difficult to assess accurately with the data at hand. The method for assessing each factor will be further explained next.

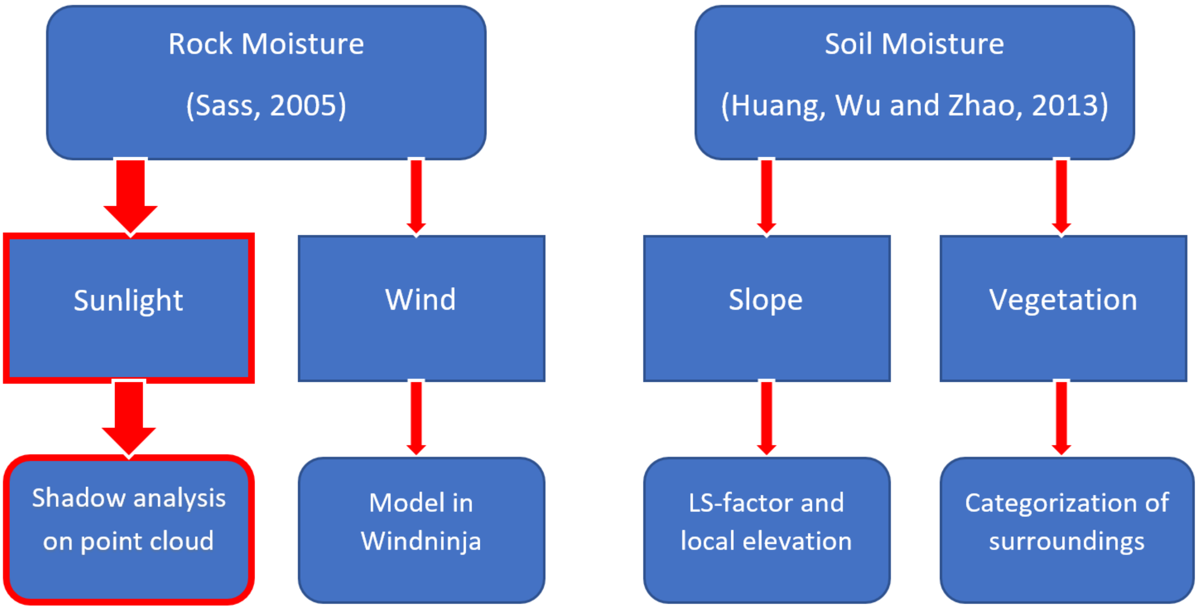

Figure 2.8: Factors Influencing Soil Moisture and Corresponding Analysis Techniques

Solar Radiation Modelling

The effect of solar radiation on the moisture content of a rock is obvious. More exposure to sunlight from a certain side means that this side will dry up quicker, due to heating and evapotranspiration. Therefore, it is important to know which sides of the rocks are well lit, and which are sheltered from sunlight by trees, slopes, or large boulders. There are existing tools for conducting this type of analysis in GIS. They are mainly used for modelling sunlight and shadow effects in cities. In this case, the 3D data will concern trees and forest features instead. The point clouds generated using SfM can be converted to a mesh and imported into a GIS for a sunlight simulation. The methods that use a mesh have its own limitations and problems, however. Among others, Song and Choi (2015) and Park, Guldmann and Liu (2021) showed the possibilities for solar radiation modelling with the use of meshes and tree models. Their research was focused mostly on urban environments, where the meshes are rather simple geometries, mostly cube shaped. The multipatch features (the ArcGIS version of a mesh) used in cities can have as few faces as five, which makes a solar radiation analysis relatively simple. Due to the more complex geometries used in this research, this tool did not work. The pedestal rock alone can have as many as 120.000 faces, with the whole model amounting to between 5 and 10 million. Another method that was tried was solar radiation modeling on a raster surface with the 'Area Solar Radiation' tool in ArcGIS Pro, which uses an algorithm based on Fu and Rich (2002). This works well for modelling the shadows cast by tree trunks in the model, but it does not take into account the more complex aspects of the surroundings, for example overhanging features such as branches and leaves or hollowed out features. This method worked, but was very clunky, yielding mediocre results, which is why a different method had to be used.

Instead of performing the analysis on a mesh or raster surface, it was chosen to do this in a point cloud. This gives three important advantages over the mesh and raster methods which were tried earlier.

1. A mesh is a solid surface, which means that even features that should let through some light, such as leaves, will be considered opaque in the analysis. In the case of a point cloud, solid, opaque objects are comprised of more points than semi-transparent objects, which allows for greater precision of the analysis.
2. A point cloud is able to account for complex geometries, unlike a raster, making the analysis more accurate.
3. Finally, a mesh surface is prone to interpolation problems when generating it from a dense point cloud. Some features which appear in the point cloud may not end up in the mesh if the algorithm decides they are too small to be left in, for example. The use of a point cloud will make sure that all features will be used in the analysis.

It is not easy to find a tool for sunlight modelling in a point cloud environment, however, which is why it was chosen to program a tool independently.

The tool was programmed using Python. The code can be seen in appendix 6, figure 2.9 gives a schematic illustration of the concept, which will be used in the following explanation to better visualize the working principle of the tool. The tool uses two input files, a file with start points and a file with the point cloud. The first step of the program is to set up a line from each of the start points in a desired direction. From the start point, which is element 1 in figure 2.9, the user can define a sun direction (2) and sun angle (3). Based on this user input, the program defines a line (4), which is supposed to simulate a beam of sunlight travelling towards the rock. The tool then calculates the distance from each point in the point cloud (6) to the line, and based on a user-input threshold (5), saves the points that fall within the desired threshold (indicated as hollow red points in figure 2.9). The output is saved as the start points along with a counter which counts how many points were encountered along the line within the specified threshold. The number of points encountered is a rough indication of how obstructed the start point is by objects in the surrounding area.

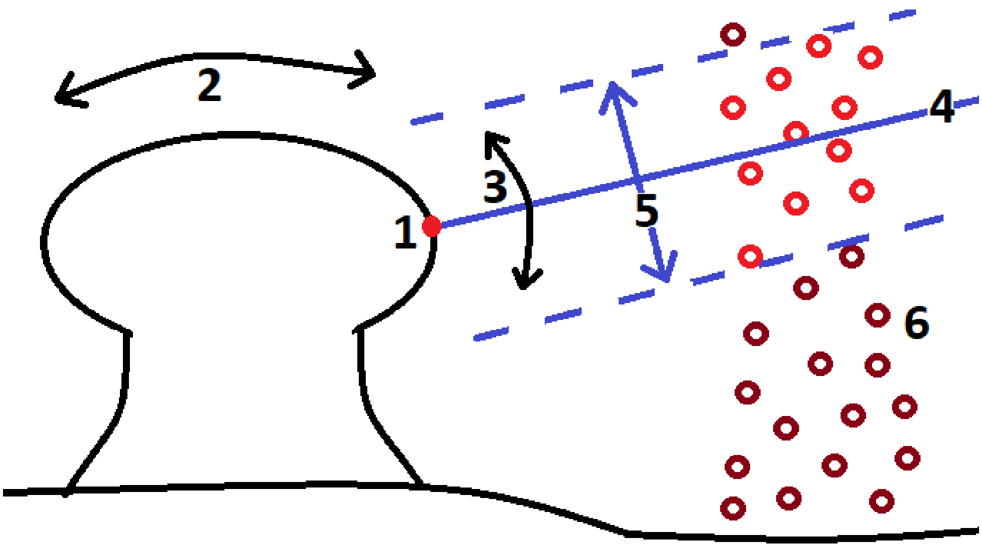

Figure 2.9: Schematic illustration of the working principle of the Python script.

1. *Start point on the pedestal rock containing xyz coordinates and unique ID*
2. *Horizontal sun direction (360 degrees around the rock)*
3. *Vertical sun angle*
4. *Line from start point as defined by the sun direction and sun angle*
5. *Threshold (indicated by striped blue lines)*
6. *Point cloud, red points fall within the threshold, brown points do not*

Wind Simulation

Wind may also play a role in the moisture content of pedestal rocks, as the wind can carry the rain in such a way that one side of the rock gets soaked, while the other remains mostly dry. Trying to model general wind direction and speed in complex terrain is fairly hard, most studies obtain wind data and then use mathematical models to predict the general direction. Some studies, however, use WindNinja (Brooks, 2012; Wagenbrenner et al., 2016), an open source program for modelling wind direction which uses an elevation model, weather data, and vegetation data as input. It was originally developed to predict forest fire spread. In this study it will be attempted to model the wind direction and speed for each site using WindNinja. The input wind data was taken from the Global Wind Atlas (2023). A DTM of the area, average wind speed and direction were also used as input for the model. The dominant vegetation type in the area is forest, and this was also selected in the parameters.

Vegetation

A third terrain feature that influences the moisture is the vegetation. To give an idea of the vegetation around the rock and how this may influence the moisture content, each plot will be divided into smaller parts of approximately 2x2m. For each sub-plot the dominant vegetation type will be decided based on four categories, namely trees, brush, grass, no vegetation. These features will be assessed for each plot and used in a statistical analysis later.

Slopes

The fourth and final factor is the terrain shape. Even though the influence of terrain characteristics on soil moisture varies for different regions and periods, there is still a clear influence of terrain types and characteristics on soil moisture distribution (Western et al., 1999; Beaudette, Dahlgren, and O'Geen, 2013). The terrain factor assessment will be done on two scale levels, on a small and large scale. The small scale will be based on the point cloud generated using SfM. The trees will be removed to leave just the terrain shape. This can then be converted to a DTM in the form of a raster for further analysis. It will be determined whether the rock is in a slightly higher or lower place compared to the surroundings, as this may influence the moisture content due to moisture accumulation in lower parts or better drainage if the rock is located in a higher spot. The slope will be measured over a distance of 2 meters away from the rock.

A similar analysis will be performed on the larger scale. This will allow for placing the rocks within the broader context of the Stołowe Mountains. The broader spatial context and the location of the rocks at the edge of the plateau or in the middle of it may have an influence on the moisture content as well. For the large-scale topographic assessment, the LS factor will be used, which is typically used for describing the effects of topography on soil erosion, with the L-factor measuring slope length and the S-factor slope steepness (Panagos, Borelli and Meusburger, 2015). In this case the LS factor will not be used for modelling erosion, but for assessing how water flows in the terrain. Since the LS-factor calculations are based around drainage areas and the water runoff along drainage lines (Desmet and Govers, 1996), it is also useful for assessing how water flows and where it may accumulate in the terrain. A low value of the LS-factor would indicate water accumulation, while a higher value will indicate drainage in the area, leading to less water retention. These values may correlate with the average moisture values of the pedestal rocks.

Statistical Analyses

After completing the sunlight, wind, vegetation, and elevation steps, the results can be compared with the moisture measurements. This will be a statistical comparison to see if there is a correlation between certain terrain/environmental aspects and moisture content on the rock. For factors that affect the rock differently from a certain side (such as sunlight exposure, for example) the rock will be divided into multiple segments based on compass directions and size of the rock. Each segment can then be compared separately.

Summary

The methods described in the steps above will make it possible to answer the questions formulated in the 'Research Objectives' section. Sub-question 1 *(What is the moisture distribution on pedestal rocks measured at 3cm and 30cm depth?)* is answered in phase 3, where the moisture distribution will be digitized and mapped. Sub-question 2 *(What is the spatial context of the pedestal rocks in the Stołowe Mountains as replicated in a 3D environment using photogrammetry?)* is answered throughout phase 1 and 2, where photogrammetry will be used for re-creating the surroundings using pictures of the area and SfM in Agisoft. Finally, Sub-question 3 and the main research question will be answered by the conclusions drawn from this study.

3. Results

Before conducting the fieldwork, it was required to obtain a research permit, as the research activities were planned inside a national park. This was accomplished at the end of October. After that it was possible to commence with the fieldwork. Seven sites have been chosen (see figure 3.1), containing a total of 10 pedestal rocks. These sites were chosen because the terrain was not too difficult for taking pictures. Some pedestal rocks are standing in the middle of a young forest, where trees are too dense to make photogrammetry work. There are 5 sites located at the edge of the plateau and 2 sites in the central part, where the terrain is mostly flat.

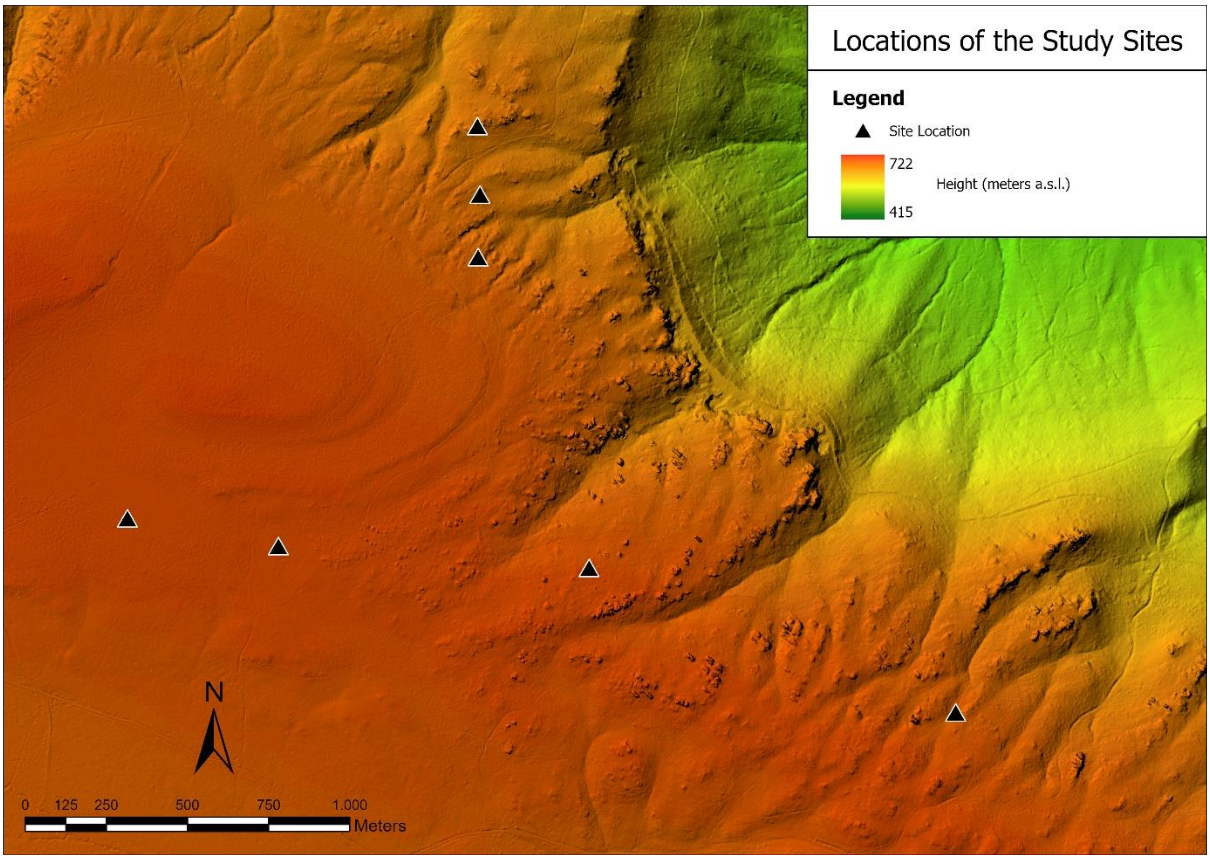

Figure 3.1: Locations of the Study Sites

Fieldwork

During the month of November 6 days were spent on fieldwork. The results are 4045 pictures across 7 plots and a total of 10 pedestal rocks inside these plots (see table 3.1). The estimated 2 hours of fieldwork for taking pictures was a correct assumption. Depending on the size and complexity of the terrain the work would take anywhere between 1 and 2 hours, with at least 2 people working on the plot.

Table 3.1: Fieldwork Results expressed in Numbers

Plot nr.	Number of rocks inside the plot	Number of pictures taken
1	1	684
2	1	639
3	1	417
4	2	606
5	2	630
6	2	726
7	1	343
Total	10	4045

Site 1

The pedestal rock on this site was covered by forest from the north side but exposed from the south due to the presence of a road and freshly cut forest there. The first site was approached twice. After collecting the first batch of pictures and processing them using SfM it became clear that the program has some trouble with matching the pictures in difficult places where it was hard to spot tie points. This occurred in places with dense vegetation, for example at dense patches of young spruce trees, but also with pictures that were taken against the sun. Due to these difficulties, it was decided that a second trip should be taken to the site to correct the errors of the first run. It was ensured that there would be more overlap in pictures in the difficult spots, which resulted in successful matching later. Pictures that were taken against the sun were also taken in such a way to minimize the distortion and differences between the images. After successfully generating a point cloud for the first site, several conclusions could be drawn:

1. Sunny weather is sub-optimal for this type of activity. Like Iglhaut et al. (2019) suggest, overcast weather is ideal. This was not possible to accomplish at the first site however, because during the first half of November the weather was very sunny with almost no clouds.
2. More pictures need to be taken when the scenery is difficult for SfM to match.
3. If the terrain is uneven (with small hills or holes in the ground) an additional photographic path has to be taken to properly visualize these in the model.

Site 2

With the experience from the first site, the second site was approached when it was finally overcast during the second half of November. There was some snow on the ground, but it turned out that this was not affecting the generation of the model using SfM. The pedestal rock on this site is located on the edge of a field where the trees were freshly cut. To the east there is a sparse forest with trees spaced around 3-6 meters from each other. This site provided no difficulties, as the terrain was relatively easy.

Site 3

The third site is located on a flat stretch of terrain with some large dead trees around it, and small young spruce trees nearby. This site proved somewhat difficult, because of the density of the younger trees in some spots. It did not result in any technical difficulties later, though.

Site 4

The fourth site has two large pedestal rocks right next to each other, surrounded by a dense forest about 5-10 meters from them. The terrain is very difficult due to numerous height differences, a rocky ridge to the northeast, and the density of the trees in some places. The trees proved too challenging for SfM to match correctly, which resulted in an incomplete model. This could be fixed by taking some additional photographs the following day to ensure better image matching. This measure proved successful, and site number 4 had no additional problems.

Site 5
Again, on this site there are two pedestal rocks right next to each other. There is also a third rock about 10 meters from the two central ones, but this rock is not taken into consideration on this plot. The site is relatively easy, with no dense vegetation. There are a lot of large trees, however. The only difficulties are provided by some boulders situated on the site and very sparse water drops falling from the trees, which led to some pictures coming out as blurry. This did not result in any errors during the picture matching, however.

Site 6
This site had by far the most difficult terrain characteristics. There are rocky ridges at the south-east side, young trees below the ridges, numerous boulders on the site itself and to the north of it, the terrain descends relatively steeply towards the west, and there is a small valley on site. This site was approached very carefully, with 726 pictures in total. The picture matching using SfM was successful and the model itself turned out very promising, as all the difficult terrain features have successfully been mapped in the 3D model.

Site 7
The seventh site is similar to the third. Due to the dense spruce trees around the rock it was not possible (but also not necessary) to take pictures in a 20 meter radius. Instead, the site has a radius of about 10 meters. There were no difficulties with the picture matching.

In the end out of the ten rocks within the plots, only eight appear in the analysis phase. The reason for this is that the rocks at sites 4 and 5 are so close to each other that they have to be considered as a single object. There is a continuous pattern in the moisture measurements across the two rocks, which is why they have been treated as one.

Moisture Measurements

Depending on the size of the research object, between 60 to 90 measuring points per rock were established, each measurement roughly 40cm away from the previous one. The moisture measurements of the TROTEC 610 and 660 devices are displayed in indicative units, which cannot be converted to a true value, such as percentage of moisture. They can only be interpreted as indicators of wetness. A measurement of less than 40 means the surface is dry, between 40 and 80 it is moderately wet, and anything above 80 is wet (Trotec & Co. KG., 2014a; Trotec & Co. KG., 2014b).

Table 3.2: Descriptive statistics on moisture measurements

	N	Minimum	Maximum	Mean	Std. Deviation
TROTEC 660	580	37.00	80.00	59.17	8.2
TROTEC 610	580	37.00	100.00	61.64	9.14

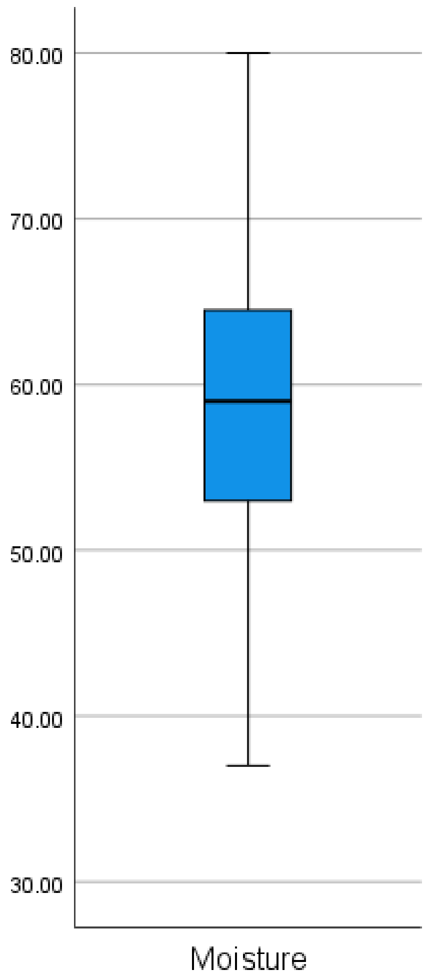

Figure 3.2: Boxplot showing the values of the TROTEC 660 moisture measurements

There were a total of 580 moisture measurements carried out across all eight rocks with each of the devices, the descriptive statistics can be found in table 3.2. The lowest recorded value for the TROTEC 660, which measures at 3cm depth, was 37. The highest value was 80. Most of the values fall within the 52-64 range, as can be seen in figure 3.2, meaning that most of them fall within the moderately wet category of the measurement units.

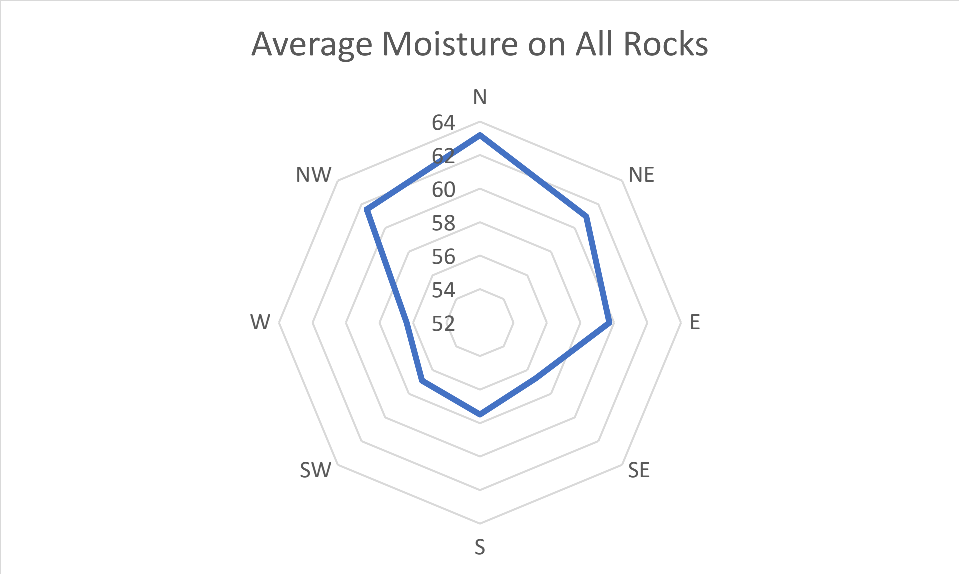

Figure 3.3: Average moisture values on all rocks divided per side

The moisture values for each side of the pedestal rocks were grouped together to see how the moisture patterns look when comparing the different sides of the rocks. The average moisture values are higher in the north and east, south is low, the west side is exceptionally low for some reason (see figure 3.3). This moisture distribution seems consistent with the general path of the sun, which should dry out the southern parts the most, and leave the northern parts with a higher average moisture content.

When comparing the surface moisture levels between rocks, it can be observed that there are some major differences between rocks 1, 2, 4, 5, and 6.1 which have a higher average moisture level, and rocks 3, 6.2, and 7. An interesting relationship here seems to be the fact that rock 3 and 7 are located farther away from the ridge. 6.2 seems to be an outlier, which may be caused by its small size, it is in fact the smallest rock measured in this study. Another thing to note is that rock 1 has an unusually large disparity between the min and max values. For a better look into the moisture patterns on the south side of the rock there are moisture maps in appendix 3. There, one can observe two different cases. The moisture map of rock 7 has a clear pattern, with higher moisture values in the lower parts of the rock and on the east side. Rock 5 on the other hand, has no clear pattern, with the moisture values appearing as random. These moisture patterns or the seeming lack thereof may be explained later with correlation analyses.

When looking at the moisture measurements from the TROTEC 610, which measures at 30cm depth, one can observe that the values are more uniform than the measurements at 3cm depth. When comparing the boxplots for both devices (figures 3.4 and 3.5) it becomes clear that the moisture levels in the deeper parts of the pedestal rocks are more constant, and table 3.2 shows that the mean value is slightly higher for the deep measurements. This would indicate that the inside of the rocks retains a higher moisture content, while the outside dries quicker. The values from the TROTEC 610 device will not be used in any further analyses, as the external factors likely have no effect at 30cm depth.

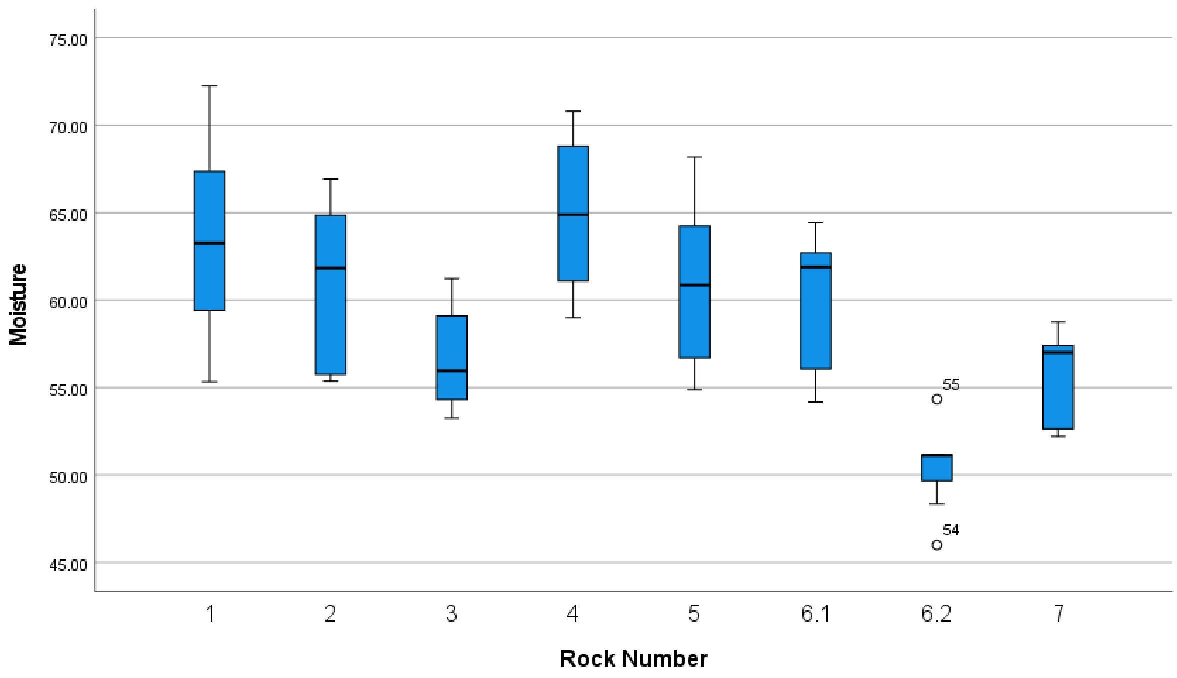

Figure 3.4: Boxplot showing the TROTEC 660 measurements per rock

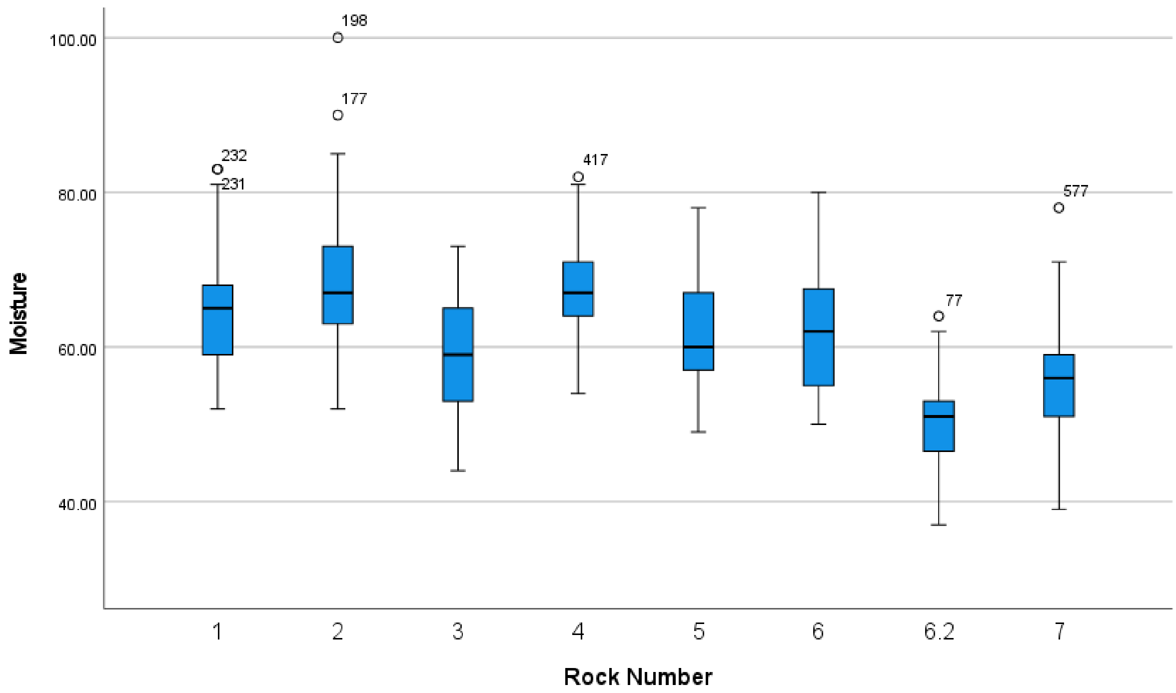

Figure 3.5: Boxplot showing the TROTEC 610 measurements per rock

Wind, Elevation, and Vegetation

The generation of the wind model using WindNinja was accomplished with no issues, the results of the model are displayed in figure 3.6. According to the generated model, the average wind direction is from the west and south-west, there are no places where the wind would change direction. The wind speed varies slightly across the sites, with sites number 3 and 7 being in an area where slightly lower windspeeds occur (around 14.5 km/h), with the remaining sites being slightly higher, between 16 and 18 km/h. The LS-factor was calculated using the Desmet & Govers method (Desmet and Govers, 1996), the results can be seen in figure 3.7.

Table 3.3: Correlations between moisture, wind and large scale elevation

		Moisture	Wind	Elevation (large)
Moisture	Pearson Correlation	1	.72*	.41
	Sig. (2-tailed)		.04	.31
	N	8	8	8

*. Correlation is significant at the 0.05 level (2-tailed).

The first correlations that were looked for are on a larger scale, not comparing the sides of each rock, but rather the locations of each rock and the differences in wind and elevation (LS factor) between the sites. Two correlations were tried, one between the average moisture on each rock and the average wind speed per site, and another between the average moisture value per rock and the LS factor for each site. No significant correlation can be found between the average moisture values of a rock and the LS factor in the area. There is a significant positive correlation between the wind speed and average moisture levels per rock, however, at .72 (very strong correlation) This indicates that the wind could have an impact on the moisture levels of the pedestal rocks.

Table 3.4: Correlations between moisture, small scale elevation and vegetation

		Moisture	Elevation (Small)	Vegetation
Moisture	Pearson Correlation	1	-.03	-.06
	Sig. (2-tailed)		.82	.64
	N	64	64	64

The second set of correlations was run on the average moisture on each side of the rock on one side, and the small-scale elevation and vegetation type on the other. Vegetation was categorized as either no vegetation, grass, bushes, or trees. Denser or larger vegetation presence should correlate with higher moisture values. No correlation has been found between the moisture on each side of the pedestal rocks and the slope and vegetation type on the corresponding side. It seems that neither the drainage (be it small or large scale), nor the vegetation or wind have any relationship with the moisture distribution on the rock.

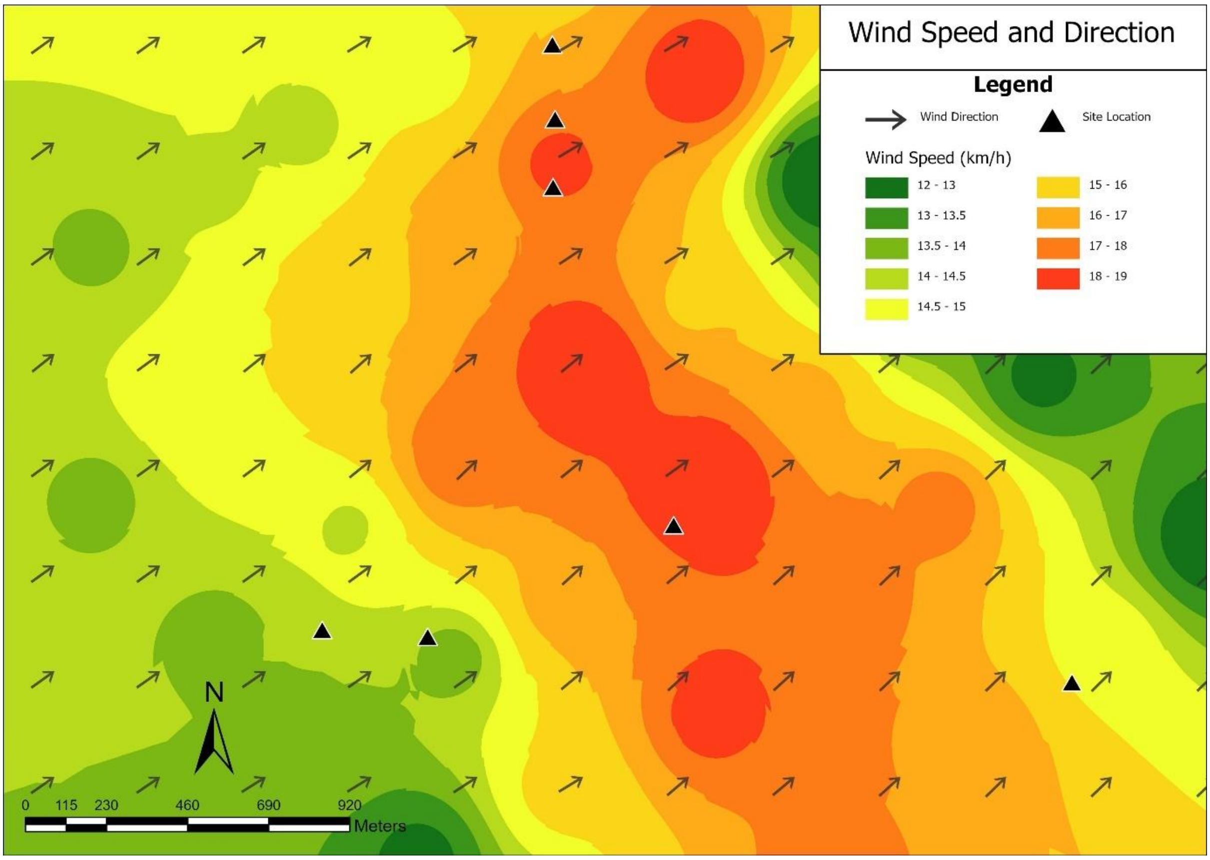

Figure 3.6: Wind Speed and Direction

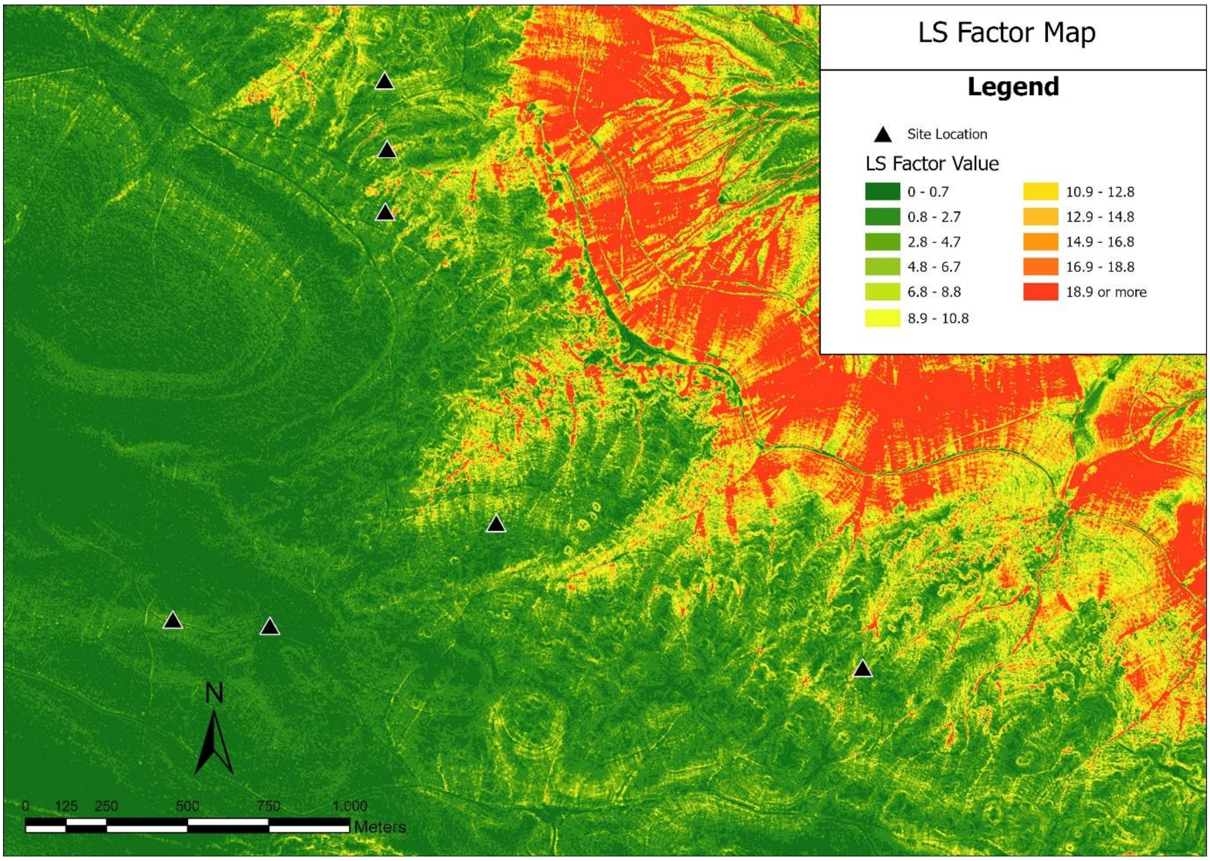

Figure 3.7: LS Factor

Sensitivity and Performance

The first runs of the script were used to test how it works and to visualize what the script exactly does with the point cloud. The result can be seen in figure 3.8, this figures demonstrates what the script does in practice. It was also necessary to run a few sample tests on one dataset to see how the output reacts to different input parameters. One of the ways this was done was by testing the same rock for 3 different sun directions, each for a different time of day. Around 11:30 the sun reaches zenith in November, which is why this was chosen as the first timestamp. The other two timestamps were 8:30 and 14:30, three hours before and three hours after the highest sun position. The input data for the sun positions was taken from SunCalc (2023). The visualizations of the results from the Python script can be seen in figure 3.9. The colors of the points correspond to the number of surrounding points encountered by sunlight on its way towards the rock. Darker colors indicate more points obstructing the way, exposing the places where shadows have a larger impact on the rock surface. It can be observed that the effect of sunlight changes over time, with the rock being more obstructed by shadow in the morning and at noon, while there is very little effect of shadows in the afternoon. This is because the rock is more exposed from the west side, there is a forest to the east of the rock which would block most sunlight. This shows that the influence of sunlight changes substantially during the day, which is why the choice for input parameters has to be the sun position for the warmest moment of the day. This is because at that moment the sun would have the largest impact on the evapotranspiration on the rocks. With this in mind, the parameters for the analysis were set to resemble the position of the sun at 13:30 on the day the moisture measurements were performed.

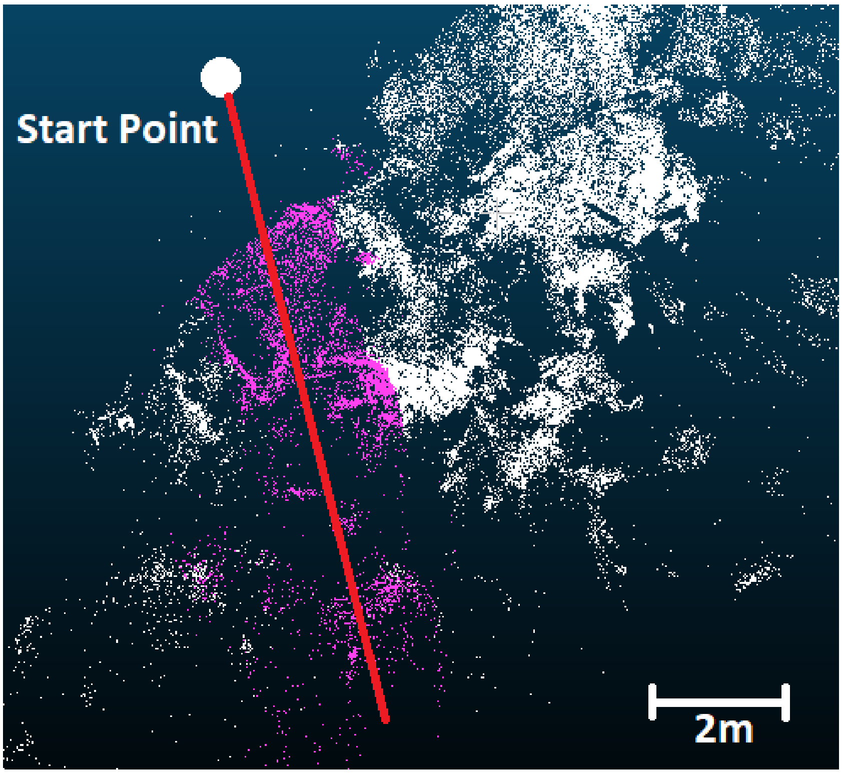

Figure 3.8: Visualization of how the points are selected from the point cloud. The red line is defined by the user, the pink points resemble the points that fall within the user-defined threshold.

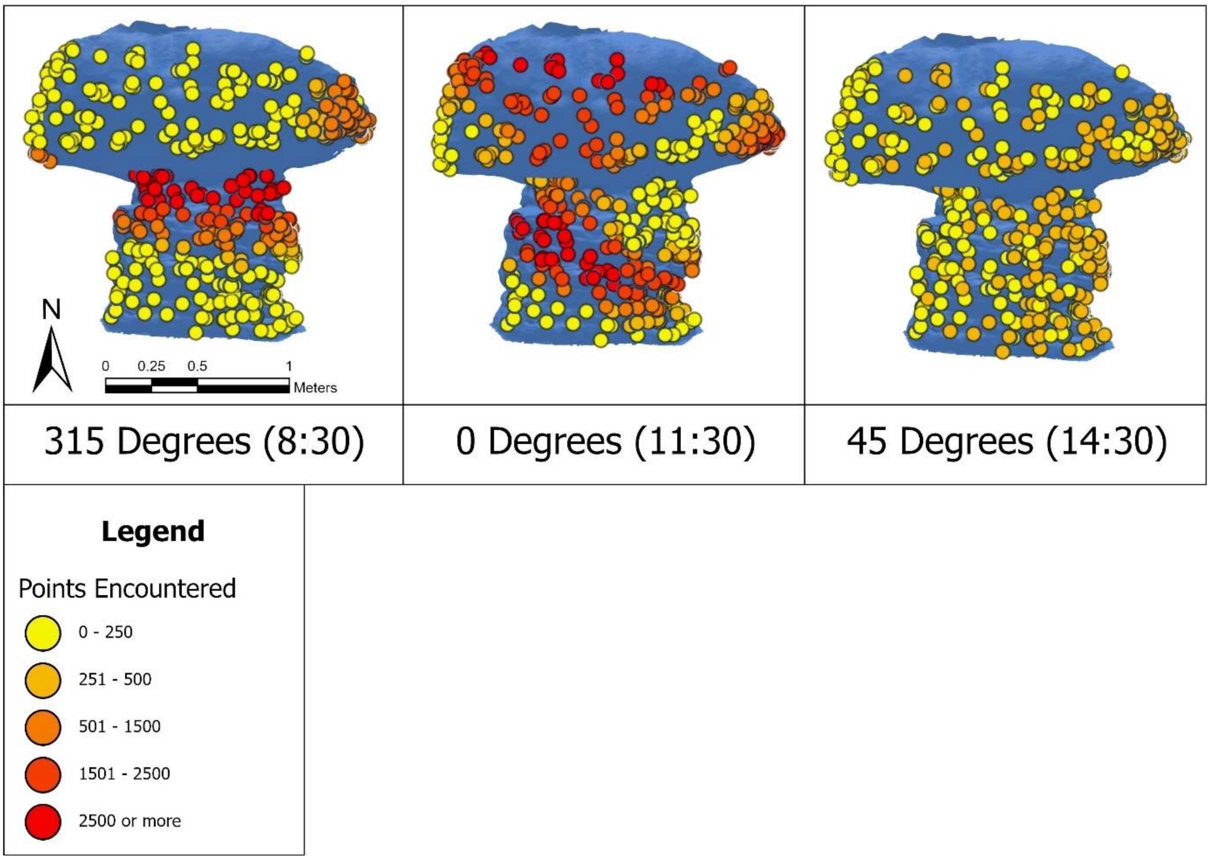

Figure 3.9: Comparison of three different sun settings for rock 2

The other sensitivity test was for the third input parameter, namely the distance threshold which is used to qualify points as an obstacle. This parameter was tested at 0.25m, 0.5m and 1m. The results can be seen in figure 3.10, which shows that the shadow patterns on the rock remain very similar throughout the three different parameters, albeit with different numbers. In the 1m variant the numbers range from 1800 to 9700, the 0.5m variant has ranges from 0 to 1976, while the 0.25m variant has numbers from 0 to 1142. Since the patterns remain the same throughout the three, the choice for the threshold value can be based on other factors. Looking at the numbers on the output files, the 1m variant picks up way too many points on its way with no zero values in the output, which would make it difficult to find unobstructed parts of the rock. The 0.5 and 0.25 versions seem better suited thanks to the presence of zero values. Since the analyses will be performed for one sun position only, it would be better to use a larger threshold, because in this way a larger catchment area will be considered in the analysis. This would result in a better approximation of the shadow patterns during the hottest time of the day. Considering these arguments, it was finally chosen to use the 0.5m threshold as the one to be used in the final analyses.

Regarding the performance side of the model, the running time largely depends on the size of the point cloud and the number of start points used. In this case, the number of start points was kept between 450 and 600, while point clouds contained between 460.000 and 600.000 points. One run of the model using the aforementioned numbers takes between six to ten hours. Higher numbers of points would considerably prolong the running time.

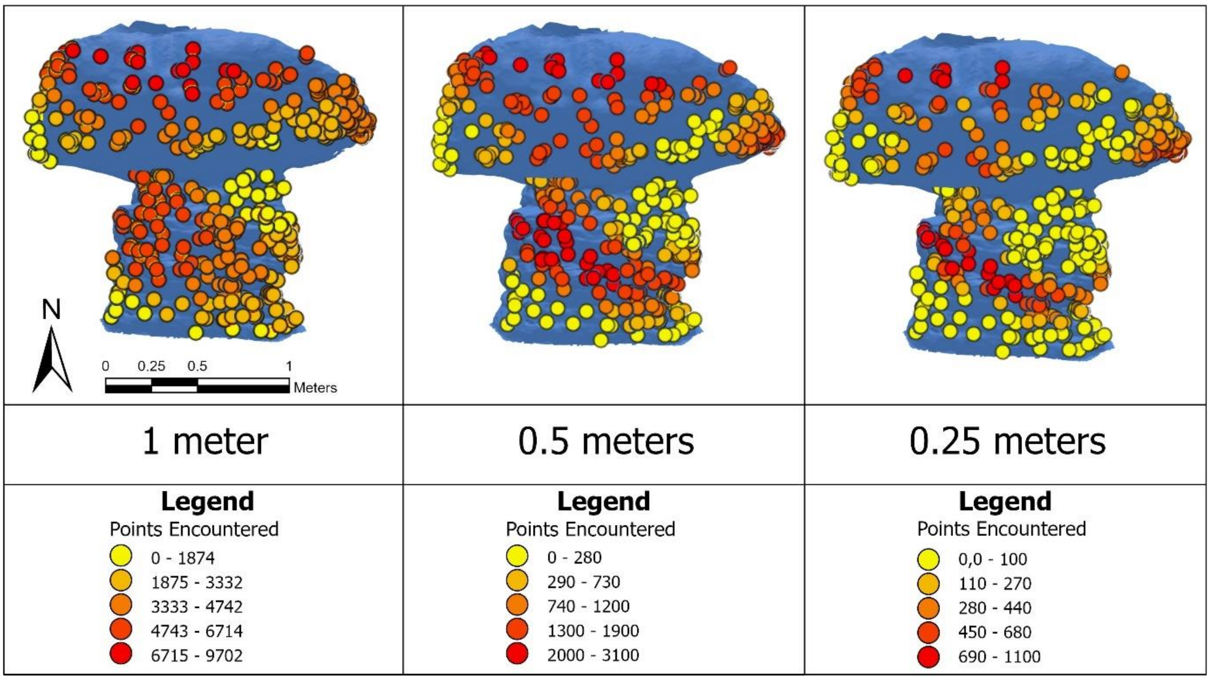

Figure 3.10: Comparison between the results of 3 different threshold values for rock 2. Note that the symbology is based on natural breaks for each of the rocks. The value ranges are different due to the number of points encountered for each threshold, which was done for the sake of proving that the patterns remain roughly the same, regardless of the threshold used.

Sunlight and Shadows

After determining which parameters should be used in the sunlight modelling phase, the Python script was run for each of the eight rocks. One of the outcomes can be seen in figure 3.11, where the shadow patterns are clearly visible on the east side of the rock. In this case there are several bushes nearby and young trees in the distance which are the cause of these patterns.

The results of the shadow modelling for each rock were coupled with the moisture measurements on the rocks. For each point for which the shadow impact was calculated, the observed moisture levels from the corresponding part of the rock were added to the point. Thanks to this, it was possible to look for correlations between the shadow impact on the rock surface and moisture levels in that same place. A Pearson's correlation test was run for each rock separately (see appendix 4). This was done because the moisture levels vary among the rocks, which could yield inaccurate results. A significant correlation has been found between the shadow impact and moisture levels for 7 out of 8 rocks (see table 3.5). In 6 cases this relationship was positive, meaning that a higher shadow level is statistically tied to higher moisture values. Only in the case of rock 1 this correlation was negative. It is difficult to say why this is the case. The other 6 rocks with a significant correlation all have positive coefficients, which suggests that this may simply be an outlier, or that a different unknown circumstance is at play here. Considering the outcomes of the other rocks, it is likely that the negative correlation in this case is caused by a factor other than the sunlight. Rock 5 is the only one for which no significant correlation can be found. The coefficient is very close to zero, which indicates that there is no correlation at all. This may be due to the fact that this rock is the only one which stands in the middle of a rather dense forest dominated by tall trees, which would lead to severely limited influence of sunlight.

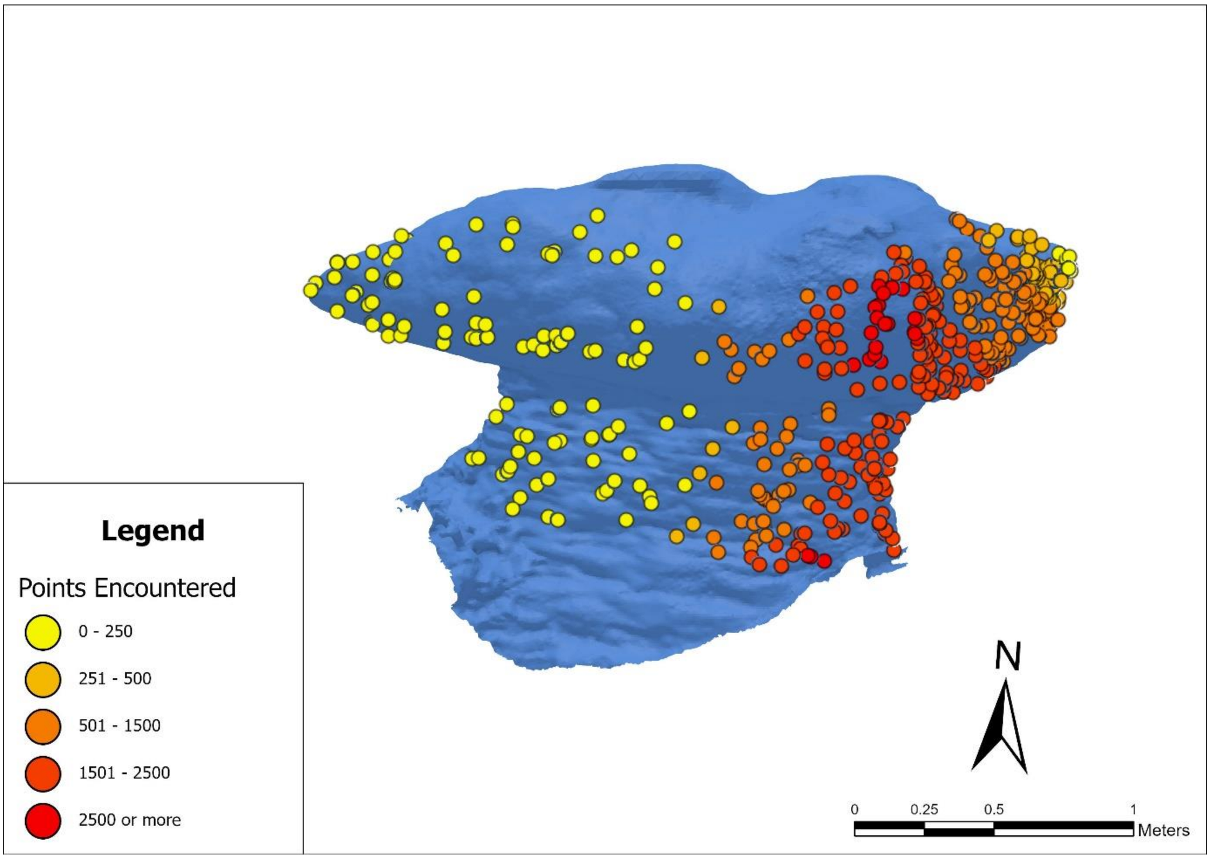

Figure 3.11: Shadow patterns on rock 7

Table 3.5: Results of the correlation tests between moisture and shadow patterns for each rock. All significant correlations are at the 0.01 level.

Rock nr.	Significant correlation?	How strong?
1	Yes	-.59
2	Yes	.8
3	Yes	.47
4	Yes	.28
5	No	.02
6	Yes	.7
6.2	Yes	.31
7	Yes	.68

When looking at the other six rocks, the correlation coefficients vary from .28 in rock 4 to .8 in rock 2. Rock 4 falls into the weak correlation category (.1 to .3), rocks 3 and 6.2 have a moderate correlation (.3 to .5), and the remaining three rocks have a strong correlation (.5 to .7). Figure 3.12 visualizes the similarities between the shadow and moisture distribution on the surface of rock 6. It can be observed that the middle side of the rock is predominantly covered with shadow, and the largest moisture values are also recorded there.

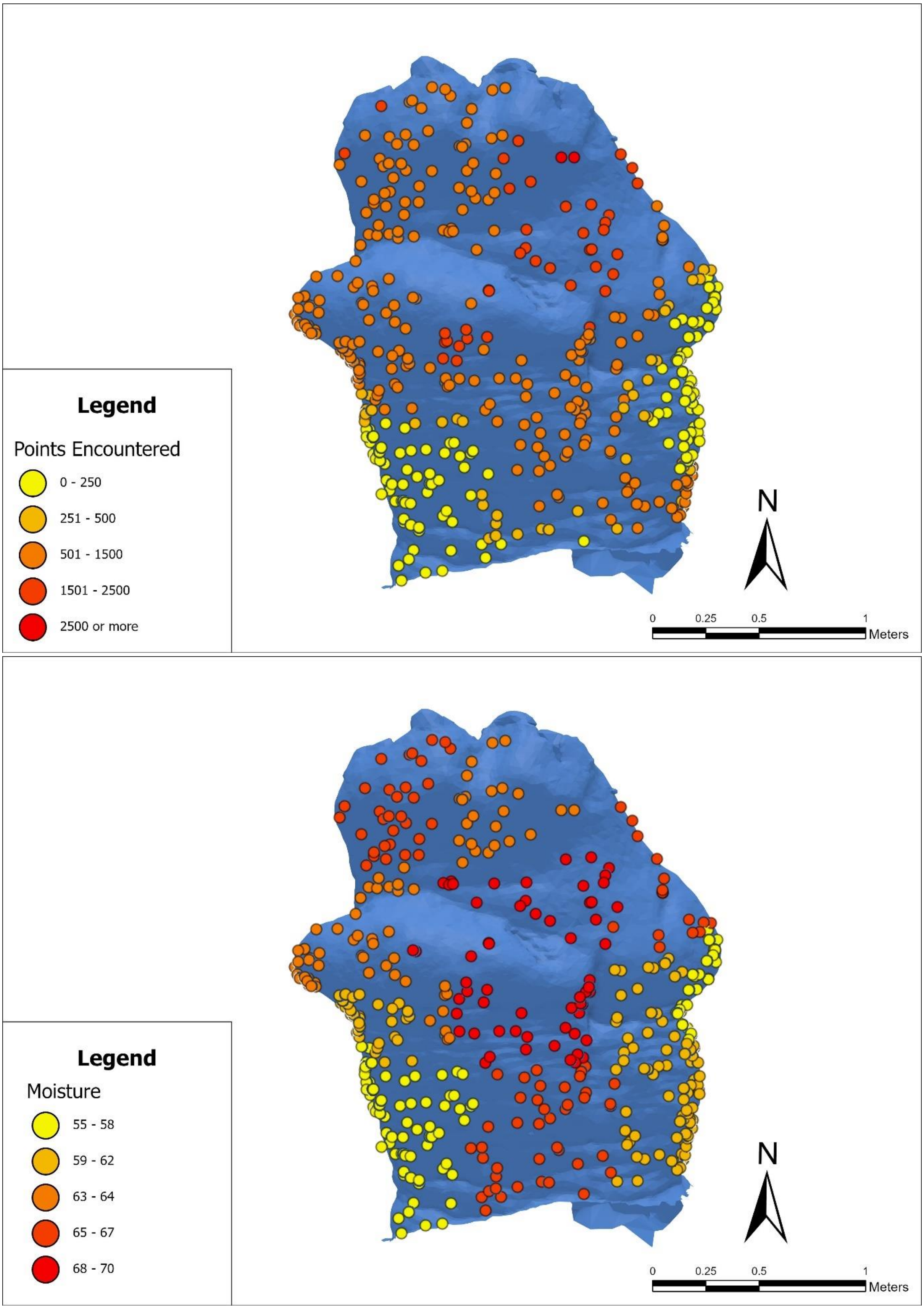

Figure 3.12: Comparison between the shadow patterns (top) and moisture values (bottom) for rock 6

For the pedestal rocks where a correlation coefficient of at least .4 was found between shadow patterns and moisture, a regression analysis was performed next, to check for causality between the dependent variable (moisture) and the independent variable (shadows). This selection was made because rocks for which a lower correlation value was found would not provide any meaningful results in the regression model due to the weak linear association between variables. The model outputs can be seen in appendix 5, a summary can be found in table 3.6 below. The percentage of variance explained indicates how much of the variance in moisture levels can be attributed to the effects of sunlight and shadows. The highest variance explained can be observed for rock 2, at 64.3%, the lowest for rock 3 at 22.4%, which still qualifies as a moderate association. Despite the negative correlation coefficient, Rock 1 is also considered in the regression analysis and the association appears to be strong. The case of rock 1 should be treated carefully however, as it is not clear why the relationship is so vastly different from the remaining rocks that display positive correlations between shadow and moisture. With this data we can conclude that for half of the pedestal rocks in this study the moisture patterns are influenced by sunlight. The strength of this influence or association varies between 22.4% and 64.3%.

Table 3.6: Results of the shadow-moisture regression model for selected rocks

Rock nr.	**% variance explained**	**Association strength**
1	35.6%	Strong
2	64.3%	Very Strong
3	22.4%	Moderate
6	48.3%	Strong
7	45.8%	Strong

4. Discussion

Some of the results of this study came out as anticipated and line up with the literature written on the topic of rock moisture levels, while other factors have come out inconclusive. In this section it will be discussed which results were to be expected, which were a surprise, and why this might be. At the end, the topic of shortcomings and possible fixes will be brought up along with recommendations for future research.

Results in the Bigger Picture

The measured moisture values were higher on the north and east side of the rock compared to the south and west. Additionally, moisture values measured inside the rock were higher on average than on the surface. Both of these findings are in line with the conclusions of Sass (2005). It seems that the moisture values are impacted by sunlight, which dries out the surface of the rock. There were several correlation tests performed on the data, which led to two main findings:

1. There is no significant correlation between elevation or vegetation on one hand and moisture on the other.
2. There is a significant positive correlation between the shadow or wind and moisture on the pedestal rocks.

With regard to the first finding, there may be several explanations as to why there were no correlations between the two factors and the moisture levels. Each factor needs to be looked at separately to properly assess why there seems to be no relationship. The same applies to the two factors that exhibited correlation, it must be determined what conclusions can be drawn from the positive correlations.

Elevation

The first factor, elevation, was tested on two scale levels. The small scale made use of the photogrammetric data and was supposed to show whether local height differences occur in the immediate surroundings of the rock. The large scale used the LS-factor, which was supposed to show the bigger picture, whether a rock was located in an area where water could potentially accumulate, or if it was in a drainage area. The lack of correlation on the small scale could indicate that the local height differences are simply too insignificant to have any impact on the soil moisture, and that moisture levels are perhaps similar across the plot. There is also a lack of correlation on the larger scale, however, which leads to two conclusions. The first, and most obvious, being that mapping soil moisture is too complex to be accomplished using the factors at hand. It would be required to conduct soil moisture measurements, which is beyond the scope of this study. The second conclusion is that perhaps the capillary action does not influence the overall moisture levels of the rock, but only the moisture levels in the lower parts of the rock. Increased moisture levels at the bottom of the rock can only be observed in case 2 and 7, which makes this hypothesis unlikely. Additionally, Qiu et al. (2001) confirm that soil moisture shows a significant correlation with slope gradient and aspect, which indicates that there should at least be some visible patterns on the larger scale. Western et al. (1999) also confirm the effect of slopes and drainage areas on soil moisture levels. In this case there are no correlations between rock moisture levels and elevation factors, however, which coupled with the fact that moisture at the bottom of the rock is not always higher, suggests that capillary action may not be as influential as thought previously.

As discussed, the question of soil moisture and its relationship with pedestal rock moisture levels is too complex to be derived from the method used in this study. If any relationship was to be found, this would have to be accomplished by an extensive study including soil moisture measurements and a comparison with rock moisture levels.

Vegetation

The vegetation factor is also supposed to influence soil moisture levels, which in turn could have an influence on overall rock moisture levels through capillary action. This factor also shows no correlation with the moisture levels on pedestal rocks. It would appear that the presence or absence of vegetation is not enough to significantly impact the soil moisture levels on such a small scale, but Western et al. (2004) suggest that even at small scales the soil moisture is related to different types of vegetation. They also noted however, that the smaller the scale, the more likely it is that two measurements will be more similar. It is difficult to tell whether the vegetation factor was insufficient to correctly portray soil moisture patterns, or if the soil moisture has a negligible effect on the moisture levels of pedestal rocks. The latter is reinforced by the apparent lack of relationship between the elevation factor and moisture, but further research would be required to answer this question.

Wind

The last of the three factors, wind, has a significant positive correlation with moisture levels of the pedestal rocks. The Pearson's correlation coefficient is quite high at .721, indicating a very strong correlation between wind speed and moisture levels across the eight rocks. Sass (2005) indicated that the wind carries rainwater in a certain direction, which would lead to one side of the rock getting wetter than the other. In this case the wind blew predominantly from the southwest in the days preceding the moisture measurements, which would result in the southwestern side of the rock becoming wetter than the other sides. This is not the case, however, as the west and southwest sides of the rocks hold the least moisture on average. This could mean two things. Either the wind was blowing from a different direction when it was raining in the days prior to the date of measurement, or the effects of sunlight are strong enough to quickly dry out the west surface of the rock. The overall average moisture levels of the rocks are higher at higher wind speeds, however, which could possibly mean the wind carries moisture even after the rain has subsided. The pedestal rocks are at a relatively high altitude of 700-720m a.s.l., and in the days preceding the moisture measurements it was cloudy at that altitude. It is possible that the wind plays a role in deploying small water droplets from the clouds onto the surface of the pedestal rocks.

It is important to note that wind modelling is a very difficult task, with many factors being at play. In this study it was possible to perform a simplified wind simulation using WindNinja, which only provides basic information on wind speed and direction across the research area. Exact wind behavior is a complex problem, which exceeds the capabilities of this study. The strong correlation coefficient between wind speed and moisture levels on pedestal rocks may be purely coincidental and more extensive research would be required to properly assess the impact of wind.

Sunlight

The outcomes of the sunlight simulations and comparisons with moisture measurements were the focal point of this study and yielded the most promising results. A significant positive correlation between shadows and moisture could be found for six rocks, and in four of those cases a regression analysis confirmed causality between the independent variable (shadows) and the dependent variable (moisture). There were two rocks that displayed a significant positive, but weak, correlation, which is why they were not considered for the regression model. For rock 5 there was no correlation, which, as discussed earlier, may be caused by the relatively thick forest surrounding it. Rock 1 on the other hand, displayed a negative correlation between the shadows and moisture, meaning that less shadows coincide with a higher moisture content. This is a curious finding and is contradicted by the remaining six subjects. It could be possible that a different unknown factor causes this. Nevertheless, it is difficult to explain this outlier. The fact that six rocks show a positive correlation stands in stark contrast with this single case of negative correlation, which is why the case of rock 1 should not disprove the findings of this study. Overall, it seems that there is enough ground to conclude that sunlight and shadows have an influence on the moisture distribution on pedestal rocks in the Stołowe Mountains. These findings are in line with the works of Sass (2005) and Sass (2022), who found relationships between moisture levels on rock surfaces and exposure to sunlight. In this case, six rocks display a positive correlation between shadows and moisture and four out of those display a moderate to very strong association between shadows and moisture, as concluded from the regression model.

Innovations and Shortcomings

This study has brought some innovative techniques and new insights, but there are also some shortcomings or elements that could have been executed better. The sunlight/shadow analysis performed in a point cloud environment generated by photogrammetry is an innovative part. The testing of different factors and using GIS to bring together moisture measurements and sunlight simulations gave a new insight on the moisture circulation on pedestal rocks. Aerial photographs could have improved the photogrammetric models of the forest, since the models suffer from the absence of canopy. Additionally, this type of study would be best performed during the summer to maximize the effect of the sun on pedestal rock surface. These points will be explained further in the following paragraphs.

Innovations and insights

Because of the problems with existing tools for sunlight analysis in GIS programs, it was decided to perform this in a point cloud environment using a script in Python. This way of approaching the sunlight modelling is something new, as the existing tools use meshes or rasters as input data. Thanks to this method it was possible to accurately model more complex geometries, which is not possible when using a raster. An additional advantage over the mesh is that the point cloud method can better account for semi-transparent objects like leaves or branches, for example. On a mesh surface these would appear as completely opaque, while in a point cloud environment they are represented as a point group of a lesser density than a solid object. The script that accomplishes the point cloud analysis may require some minor tweaks to improve its performance, as calculations can take several hours when using larger datasets. Despite long processing times, the output of the script is useful and provides an interesting alternative for sunlight modelling, which could be applied in other projects or studies.

Shortcomings

There are two shortcomings in this study that are caused by limited time and resources, namely the absence of aerial photographs to be used in photogrammetry and the time of the year during which the fieldwork was carried out. All data gathering for the photogrammetric process was carried out from the ground level, which results in a 3D model that is somewhat lacking when it comes to full models of trees. Most of the trees present in the model are only visible about 5-10 meters from the ground up, with their canopies lacking. This could be fixed by using an unmanned aerial vehicle (UAV) to take aerial pictures of the canopy to supplement the model made on the ground level, like in the work of Mikita, Janata and Surový (2016). This approach would result in a more accurate shadow model, as the canopy could play a major role in sunlight obstruction on certain research sites. It was not possible to do this, however, as this would require too much work, like getting a UAV flying license and obtaining a permit to fly above a national park, among others. Due to the limited time frame of this study this was not possible. The other limitation is the time of the year during which the fieldwork was carried out. Because the entire study had to be completed between September and February and the fieldwork window fell in November and December, it was not possible to obtain ideal weather conditions for conducting the moisture measurements. It was assumed that the sun would have a large influence on the moisture levels on the rocks, which is why it would be better to conduct these measurements during the summer, when the sun delivers more energy. Nevertheless, the results have been satisfactory, and it seems that the lower power of the sun did not affect the overall outcome of the analyses. If repeated during ideal weather conditions, perhaps even stronger correlations could be found between the sunlight and moisture levels. Finally, it should be mentioned that despite looking at four factors that may influence the moisture levels on pedestal rocks, an emphasis was put on the effect of sunlight. This was done because the data that was gathered was most suited for an accurate representation of this factor, while the remaining three factors (wind, elevation, and vegetation) were assessed through secondary factors or simplified techniques. This approach may have been the cause of the apparent lack of relationships between the factors and moisture distribution.

An additional note should be made regarding the accuracy of the point clouds generated using photogrammetry. Overall, the models were satisfactory, with a good representation of all major terrain features that are present at each site. Some models came out better than others, however. This has mostly to do with the light levels during the process of taking pictures. The most accurate models (site 2, 4, 6, and 7) were photographed between 11:00 and 14:00. The less accurate models (site 3 and 5) were photographed after 14:00, which resulted in more distorted models with less accurate features. Site 1 was photographed during a sunny day, which also resulted in some distortions. This is in line with the suggestions of Iglhaut et al. (2019), who indicate that good lighting is vital for this type of activity. Pictures should be taken around noon and overcast conditions are ideal. Nonetheless, they were accurate enough to correctly display the most important terrain features like trees, bushes and boulders.

Further Research

This study gives several opportunities for further research activities, which will be briefly discussed. The first, and most important, suggestion is to supplement the terrestrial photogrammetry with aerial pictures to model the forest canopy. It was discussed that the lack of a canopy representation in the 3D model is a shortcoming of this study, caused by resource and time constraints. The combination of terrestrial and aerial photogrammetry would result in a more complete model which would be better suited for a thorough sunlight analysis. Second, there is the possibility to perform the moisture measurements during better weather conditions at multiple timestamps during a day. Ideally, this would be accomplished during the warmer months of the year (for example May – September) when the effect of the sun is stronger. The measurements should be performed 1-2 sunny days after rainfall to have the best effect. Multiple timestamps during a day would help understanding how big the influence of the sun is over time. This effort could perhaps prove an even bigger relationship between sunlight and moisture, and provide clearer moisture patterns on the rocks' surfaces. Third, a more sophisticated approach could be taken with regard to the influence of capillary action on the moisture levels of the rocks. Duszyński and Migoń (2022) provided this phenomenon as one of the possible factors that influences the moisture levels inside the rocks, but it is not clear to which degree this is true, as the findings of this study regarding the influence of capillary action are inconclusive. The factors used in this study which related to soil moisture (elevation, vegetation) showed no correlation with the rock moisture levels. Additionally, there are no clear indications that the pedestal rocks hold more moisture in their bottom parts. To prove or disprove the role of capillary action, soil moisture measurements should be conducted along with rock moisture measurements on a larger scale. A comparison of these two elements would lead to decisive conclusions regarding the role of capillary action on the pedestal rocks.

5. Conclusion

This study brought together moisture measurements and terrain characteristics to explain moisture patterns on pedestal rocks in the Stołowe Mountains. For the purpose of mapping terrain characteristics, photogrammetry was used as the main tool. This ensured a 3D model of the terrain in the form of a point cloud or mesh, which could be used in the analysis. The answer to the first research question (*What is the moisture distribution on pedestal rocks measured at 3cm and 30cm depth?*) was provided by conducting moisture measurements with the two TROTEC devices. There are differences in the moisture distribution on 3cm and 30cm depth, with the moisture levels at 3cm differing more than the moisture deep within the rock. Additionally, the observed moisture at 30cm was higher on average than on the surface. The answer to the second question (*What is the spatial context of the pedestal rocks in the Stołowe Mountains as replicated in a 3D environment using photogrammetry?*) was provided by generating photogrammetric models of the study sites, which resulted in a relatively accurate representation of terrain features and objects on the sites. The answers to sub-question 1 and 2 ultimately provided the answer to sub-question 3 (*Does the spatial context have an influence on the moisture distribution inside the rock?*) and the main research question (*Do the local surroundings of pedestal rocks in the Stołowe Mountains have an influence on the moisture distribution inside the rock?*). Among four factors thought to influence the moisture levels (sunlight, wind, elevation, and vegetation), it was found that wind and sunlight have a significant positive correlation with moisture levels on the pedestal rocks. Elevation and vegetation displayed no correlation. Wind has a very strong correlation, with a Pearson's correlation coefficient of .72. For the sunlight factor, a significant positive correlation was found for six out of eight rocks, the correlation coefficient varies per rock from .28 to .8. A regression model proved a moderate to very strong association between sunlight and moisture for four rocks, with the percentage of variance explained ranging from 22.4% to 64.3%. It was discussed that the wind factor is uncertain, and further research would be required to confirm its effect. The sunlight factor, on the other hand, was proven to be influential. These results suggest that the evapotranspiration on the rocks' surface is greatly increased in places that are exposed to sun, which implies that the weathering process of the rocks might proceed at an accelerated pace in places that are exposed to sunlight. This is due to the repeated cycles of moisture absorption and evapotranspiration, which weaken the rocks, ultimately influencing their shape by the accelerated weathering process in certain parts or on certain sides of the rock.

The findings of this study lay a groundwork for further research and raised additional questions on the topic of how pedestal rocks in humid environments are influenced by moisture. The first question raised by the findings of this study is whether capillary action influences the moisture levels on pedestal rocks, as this theory could not be confirmed with the methods at hand. Further research into this topic with the use of soil moisture measurements would be required to definitely prove or disprove the influence of capillary action. The second, and most important, suggestion for further research is that it should be tried to generate a better 3D model of the terrain by modelling the forest canopy from aerial photographs. The terrestrial photogrammetry technique used in this study was successful in modelling terrain features on the ground, but the upper parts of trees and the forest canopy are lacking. The models obtained on the ground level could be supplemented by models of the forest canopy obtained using aerial photographs, which would result in a more accurate model of the terrain features. The approach of this study to sunlight/shadow modelling in a point cloud environment is a new way of tackling this type of analysis, which is traditionally performed on a mesh or raster. This study has proven that doing this in a point cloud environment is a valid approach when working with models generated by photogrammetry. Additional performance-oriented improvements could be made to further expand the possibilities of sunlight modelling in point cloud environments.

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Appendix 1: Examples of Pedestal Rocks in the Stołowe Mountains

Appendix 2: SfM Results

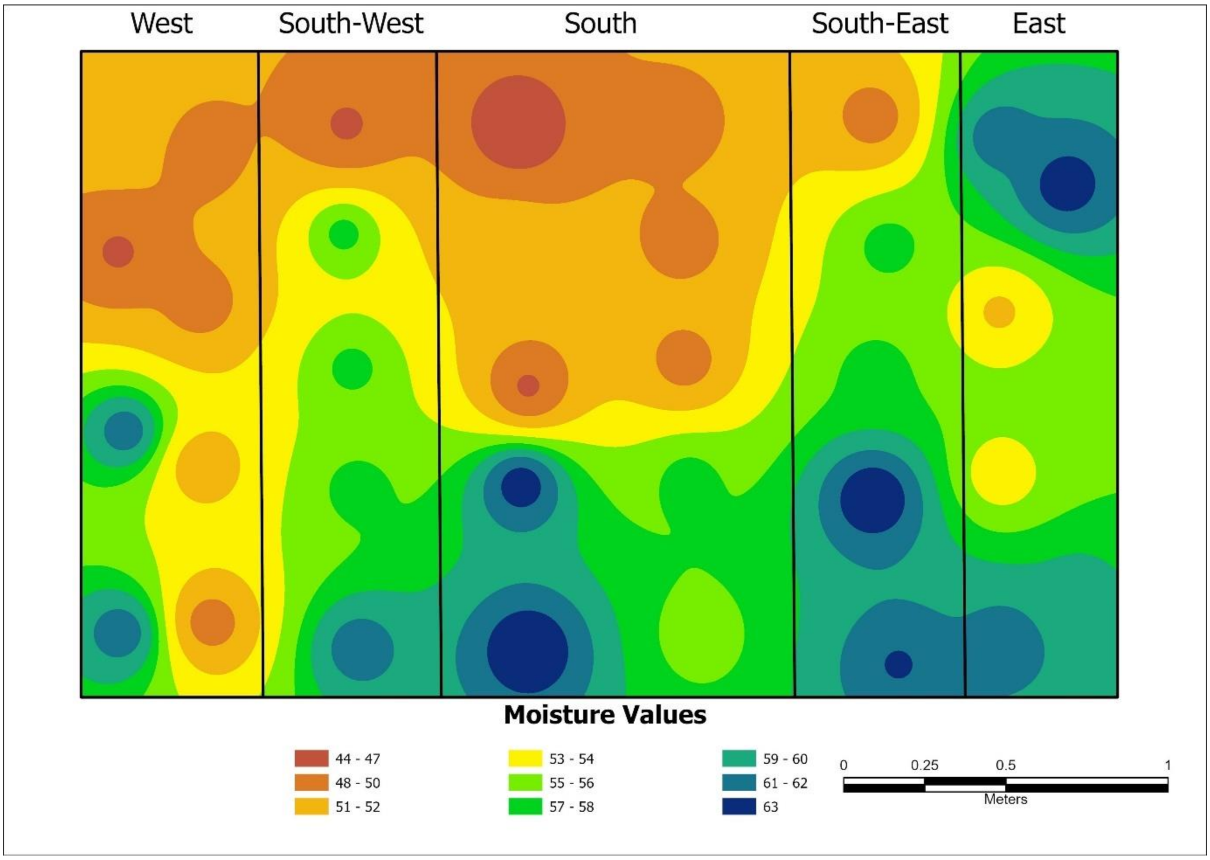
Rock 2 dense cloud

Site 7 dense cloud

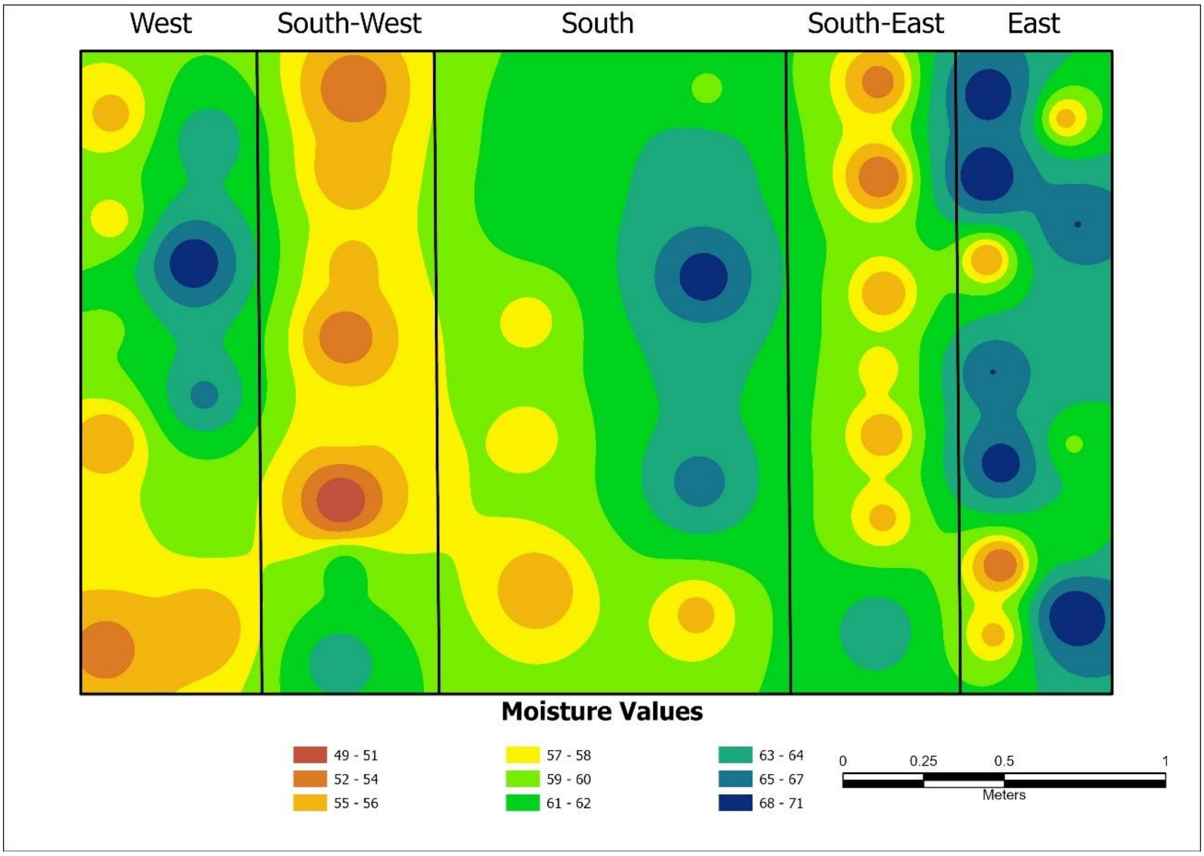
Site 6 sparse cloud

Site 6 dense cloud

Appendix 3: Moisture Maps at 3cm Depth



Moisture map of rock 7



Moisture map of rock 5

Appendix 4: Results of the Correlation Analyses

Correlation Rock 1

		Shadow	Moisture
Shadow	Pearson Correlation	1	-.597**
	Sig. (2-tailed)		<.001
	N	422	422

**. Correlation is significant at the 0.01 level (2-tailed).

Correlation Rock 2

		Shadow	Moisture
Shadow	Pearson Correlation	1	.802**
	Sig. (2-tailed)		<.001
	N	448	448

**. Correlation is significant at the 0.01 level (2-tailed).

Correlation Rock 3

		Shadow	Moisture
Shadow	Pearson Correlation	1	.473**
	Sig. (2-tailed)		<.001
	N	479	479

**. Correlation is significant at the 0.01 level (2-tailed).

Correlation Rock 4

		Shadow	Moisture
Shadow	Pearson Correlation	1	.284**
	Sig. (2-tailed)		<.001
	N	661	661

**. Correlation is significant at the 0.01 level (2-tailed).

Correlation Rock 5

		Shadow	Moisture
Shadow	Pearson Correlation	1	.018
	Sig. (2-tailed)		.694
	N	458	458

Correlation Rock 6

		Shadow	Moisture
Shadow	Pearson Correlation	1	.695**
	Sig. (2-tailed)		<.001
	N	448	448

**. Correlation is significant at the 0.01 level (2-tailed).

Correlation Rock 6.2

		Shadow	Moisture
Shadow	Pearson Correlation	1	.313**
	Sig. (2-tailed)		<.001
	N	463	463

**. Correlation is significant at the 0.01 level (2-tailed).

Correlation Rock 7

		Shadow	Moisture
Shadow	Pearson Correlation	1	.677**
	Sig. (2-tailed)		<.001
	N	472	472

**. Correlation is significant at the 0.01 level (2-tailed).

Appendix 5: Results of the Regression Models

Rock 1 Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.597[a]	.356	.355	2.76319

a. Predictors: (Constant), Shadow1
b. Dependent Variable: Moisture1

Rock 2 Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.802[a]	.643	.642	3.81851

a. Predictors: (Constant), Shadow2
b. Dependent Variable: Moisture2

Rock 3 Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.473[a]	.224	.222	5.69243

a. Predictors: (Constant), Shadow3
b. Dependent Variable: Moisture3

Rock 6 Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.695[a]	.483	.482	2.91346

a. Predictors: (Constant), Shadow6
b. Dependent Variable: Moisture6

Rock 7 Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.677[a]	.458	.457	3.61604

a. Predictors: (Constant), Shadow7
b. Dependent Variable: Moisture7

Appendix 6: Python Script

```
import numpy as np
import pandas as pd


df = pd.read_csv('points.csv', sep=',', header=None)
sp = pd.read_csv('start_points.csv', sep=',', header=None)
sp['3'] = 0
sp.columns = ["x", "y", "z", "Count"]
deleter = "final.csv"
f = open(deleter, "w+")
f.close()

Compass = int(input('Enter Compass (Sun Direction): '))
Azimuth = int(input('Enter Azimuth (Sun Angle): '))
Threshold = float(input('Enter Threshold (in meters): '))
for index, row in sp.iterrows():

    row = row.array
    LineOrigin = np.array(row)
    c = LineOrigin[3]
    for index1, row in df.iterrows():

        row = row.array
        Point = np.array(row)
        def Distance(LineOrigin,Compass,Azimuth, Point):

            Ax = Point[0]
            Ay = Point[1]
            Az = Point[2]

            Bx = LineOrigin[0]
            By = LineOrigin[1]
            Bz = LineOrigin[2]

            Cx = Bx + np.sin(np.radians(Compass))
            Cy = By + np.cos(np.radians(Compass))
            Cz = Bz + np.sin(np.radians(Azimuth))

            BA = np.array([Ax-Bx, Ay-By, Az-Bz])
            BC = np.array([Cx-Bx, Cy-By, Cz-Bz])

            distance = np.linalg.norm(np.cross(BA,BC))/np.linalg.norm(BC)
            return distance

        if Distance(LineOrigin, Compass, Azimuth, Point) <= Threshold:
            c = c + 1

    sp.at[index, 'Count'] = c
    print(int(c))

sp.to_csv('final.csv')
print('Done')
```