THESIS

MOHAMED SAAD FATHY ABDELALIM

MSc of Agricultural Water Management Engineering

GÖDÖLLŐ

2023

Hungarian University of Agriculture and Life Science
Szent István Campus
MSc of Agricultural Water Management Engineering

MODELING LANDSCAPE EVOLUTION AT A SLOPE IN GÖDÖLLŐ

Primary Supervisors: István Waltner, University associate professor, Department of Water Management and Climate Adaptation, Hungarian University of Agriculture and Life Sciences (MATE), Institute of Environmental Sciences (KÖTI)

Gábor Halupka, University teaching assistant, Department of Water Management and Climate Adaptation, Hungarian University of Agriculture and Life Sciences (MATE), Institute of Environmental Sciences (KÖTI)

Independent Consultant: Ágota Horel, Senior Research Scientist; Department of Soil Physics and Water Management, Institute for Soil Sciences, Centre for Agricultural Research

Author: **Mohamed Saad Fathy Abdelalim**
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Gödöllő
2023

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1 Introduction

One of the mean aspects that dominate large number of natural processes that concern humanity is topography. Landscape topography is a major factor of natural hazards like floods or mass movements.

Weathering and erosion acting towards the heterogeneous lithospheric surface are some of the main reasons for the formation of different landforms. Landscapes are dynamic, markedly responsive to natural and artificial disturbances. Slopes could define landforms, so landscape evolution is best understood by studying of slopes and the multiple factors (e.g. meteorological conditions) taking control of slope development and its characteristics (Ghosh et al., 2021).

A landscape evolution model is a numerical model based on physical principles that simulates the changing terrain over time. Terrain change or evolution can be caused by glacial or fluvial erosion, sediment transport and deposition, regolith creation, the gradual movement of material on hillslopes, and more intermittent occurrences like rockfalls, debris flows, landslides, and other surface processes (Tucker & Hancock R., 2010). Many of these aspects are taken into consideration by a standard landscape evolution model (LEM). The overall goal of LEM is to get a better knowledge of landscape history by simulating land forming processes and process interactions. The primary goal of SaLEM (which is a specific tool of GIS-program System for Automated Geoscientific Analyses or 'SAGA') is to map regolith characteristics based on established physical correlations. In cases when limited trustworthy data are available for certain process variables, adequate parameterizations must be used.

1.1 Objectives

Our proposal involves the use of a lithological differentiated approach to model a soil and landscape evolution using (SaLEM), which can help explore the changes in soil parent material over time and space. This model will be powered by climatic data, including temperature and precipitation.

The validation of the model results can be difficult due to a lack of proper information on the characteristics of the regolith. To provide an initial impression, a collection of accessible drilling point data from soil surveys should be utilized to confirm the trend of the model's predictions about regolith thickness within our study area. Since soil qualities vary spatially and/or temporally, a relatively large number of samples must be collected and measurements must be repeated when conditions change or to assess if they are changing. These soil characteristics are usually evaluated in laboratories using field samples.

Besides, the statistical analysis of the data collected is an effective tool for providing quantitative information that may be used to guide background and site decisions. Therefore, some basic statistical evaluation should be applied for the available data such as field soil samples.

At the end, I would like to highlight that in this research the objective of the project was to simulate landscape evolution using the SaLEM model. Our model results showed up to 30 cm regolith production at the research site over 50,000 years, which might be an underestimation by the model based on available literature on the subject (Csillag, G., Rózsa, P., 2013).

Overall, we found the model to be a very useful tool to study changes in landscape over time; however, we found that this model might be especially suitable for larger scale studies, such as catchments. We also gathered field samples from different catena consisting of fourteen drillings of four meters deep to evaluate and validate the model outcomes using lab analysis. Although the SaLEM model is capable of simulating the changes in topography and sediment transport over a period of time, it must be used carefully and verified using reliable data such as our soil analysis findings. The difference between the predicted soil makeup and the output of the SaLEM model indicates that the input parameters or assumptions about soil erosion processes used in the model may require reassessment, particularly at a small scale.

2 Literature review

2.1 Landscape evolution

The surface of the Earth is constantly changing. While tectonic and volcanic activity aids in raising the Earth's surface, wind, sea, rivers, and ice work together to smooth out relief variations and reduce mean surface level. Today's continents, islands, and ocean bottoms feature a range of landforms due to the interaction of these opposing processes and its fluctuation across time and space (Kooi & Beaumont, 1996). The study of landscape evolution seeks to understand the processes that shape and modify the surface of the earth over time. These processes can be natural, such as erosion, weathering, and tectonic activity, or human-induced, such as urbanization and agriculture. Another important process in landscape evolution is tectonic activity, which can cause the earth's surface to uplift or subside over time. This can lead to the formation of mountains, valleys, and other landforms (Li et al., 2021). In addition to these natural processes, human activities can also play a significant role in landscape evolution. For example, agriculture can lead to the erosion of soil, while urbanization can alter the natural drainage patterns of a region, leading to increased flooding and erosion (Zhou et al., 2021). To better understand landscape evolution, researchers use a variety of techniques, including field observations, modeling, and remote sensing. By combining these approaches, scientists can gain a more complete picture of how landscapes change over time and how they may continue to evolve in the future.

Understanding the evolution of landscapes is a fundamental aspect of environmental management, with implications for conservation, protection, economic use, and ecosystem services. However, the current environmental changes that we are experiencing are unprecedented and profound, with far-reaching implications for our planet and societies. The global climate is warming and changing, resulting in the retreat of glaciers, melting of sea ice, rising sea levels, and more frequent and intense extreme weather events (Lee et al., 2018). These changes have significant impacts on landscapes worldwide. Additionally, the planet's population recently reaching eight billion people, with significant environmental impacts resulting from technological and economic changes (Brewer & Bonsall, 2021). The complex interplay between environmental, social, cultural, and political factors is leading to potential local, regional, and global turning points (Costa & Lee, 2019). Therefore, understanding landscape evolution and its impacts is crucial for addressing these challenges and promoting a sustainable future. Everything is interconnected, and the development of landforms, soils, ecosystems and hydrological systems are closely linked. Integrated approaches are therefore needed instead of the traditional semi-independent treatment of geomorphological, ecological, pedological and hydrological phenomena. Just as landscape elements do not vary independently of each other, few landscape phenomena can be attributed to a single cause (Phillips, 2018). Landscape responses to change are diverse, nonlinear, and characterized by feedback and complex reactions. Biotic and abiotic components evolve together, adapting to each other between and within them. Moreover, the living and non-living aspects of landscapes are often even more closely linked through ecosystem engineering, niche construction and extended composite phenotypes (Phillips, 2021).

There are many lessons to be learned from the study of landscape evolution. One of the most important lessons is that landscapes are constantly changing and evolving, driven by a range of physical, biological, and human processes. Understanding these processes and their interactions is crucial for predicting and managing landscape change, whether for conservation, resource management, or other purposes (Brewer & Bonsall, 2021). Another key lesson is that landscapes are complex systems, with interactions and feedbacks among different components such as soils, water, vegetation, and animals. This complexity can lead to unexpected outcomes and unintended consequences of management interventions, highlighting the need for holistic and adaptive approaches to landscape management (Liu et al., 2019). In addition, the study of landscape evolution can provide valuable insights into the long-term sustainability of human activities, including land use, resource extraction, and infrastructure development. By understanding how landscapes have responded to past environmental and human pressures, we can better anticipate and manage the impacts of current and future activities on the landscape and its ecosystems (Costa & Lee, 2019).

Lessons in landscape evolution understanding, or striving to understand, landscape evolution is crucial to basic human curiosity and understanding how our environment came to be, how it is changing, and what could happen in the future. An understanding of landscape change is essential for any environmental management endeavor, whether the objective is conservation, preservation, economic exploitation, maintaining human populations, ecosystem services, or any number of others (Zhou et al., 2021). However, we are witnessing significant and unprecedented environmental change: the global climate is changing in a variety of ways, including warming, glaciers retreat, sea ice melts, sea levels rise, and storms, floods, droughts, and wildfires become more frequent and violent.

2.2 Geomorphology

The study of landforms on Earth and the processes that shape them is known as geomorphology (Bledsoe & Watson, 2001). Geomorphology has always used a historical approach to comprehending landforms; the idea of landform evolution is deeply established in geomorphological philosophy. Landscape evolution is a phrase that contemporary process geomorphologists use to describe the interplay between form and process that manifest as quantifiable changes in landscapes over both geologic and human time scales (Pazzaglia, 2003). Geomorphology encompasses a wide range of topics, including the formation of mountains, valleys, rivers, and coastlines; the effects of climate change and tectonic activity on landscape evolution; the role of vegetation, soils, and water in shaping the landscape; and the impacts of human activities such as land use change and infrastructure development (Pike, 2000). One of the key goals of geomorphology is to understand the complex interactions between physical, biological, and human processes that shape landscapes, and to develop predictive models of landscape evolution. This knowledge is essential for a range of applications, from environmental management and resource conservation to hazard mitigation and infrastructure planning (Conrad et al., 2015).

Geomorphology and landscape evolution are closely related, as geomorphology is the study of landforms and the processes that shape them, while landscape evolution is the study of how landscapes change and evolve over time (Csillag, G., Rózsa, P., 2013). In addition, geomorphology provides a fundamental framework for understanding landscape evolution, as it describes the different types of landforms and how they form, and the processes that shape and modify them over time (Kooi & Beaumont, 1996).

The processes studied in geomorphology, such as weathering, erosion, sediment transport, and deposition, are all critical drivers of landscape evolution. For example, rivers erode their banks and beds, leading to the formation of valleys and gorges, and transport and deposit sediment, shaping floodplains and deltas. Similarly, glaciation sculpts mountains, valleys, and plains, and forms lakes and moraines, while tectonic activity creates mountains and rift valleys and changes the elevation and relief of landscapes (Ullah et al., 2019).

2.3 Geomorphological processes and technologies

Geomorphological processes refer to the physical processes that shape the Earth's surface, including weathering, erosion, transportation, and deposition (Temme & Vanwalleghem, 2016). Weathering is the breakdown of rocks and soils due to physical, chemical, and biological processes such as freeze-thaw, chemical weathering, and biological weathering (Gallen, 2018). Erosion is the process by which soil and rock particles are transported by wind, water, or ice from one location to another. This can lead to the formation of valleys, canyons, and other landforms (Zuffetti et al., 2018). Transportation refers to the movement of sediment by wind, water, or ice. Sediment can be transported by the wind as dust or sand, by water as sediment in rivers or oceans, or by glaciers as moraines or glacial till (de Lima et al., 2021). Deposition is the process by which sediment is deposited in a new location. This can occur when sediment is no longer transported due to a decrease in the energy of the wind, water, or ice, or when sediment is carried to a new location and deposited by wind, water, or ice (Temme et al., 2011).

Landforms were thought to be the result of single processes at the time, and they were described in mono-genetic terms. This category style of thinking is fundamentally at odds with modern numerical multi-process models where a landscape evolves and landforms arise due of the activity and interaction of multiple processes (Temme et al., 2011). The process of weathering can also contribute to erosion by weakening rocks and making them more susceptible to being eroded by wind or water (Sinha & Sinha, 2021).

Earth science investigations are increasingly utilizing geospatial technologies (Bishop et al., 2012). The rapid proliferation of geospatial technologies is related to advances in geodesy, photogrammetry, geophysics, computer science, statistics, remote sensing, geographic information technology (GIT), and numerical modeling, which have collectively revolutionized the field of geomorphology (Shroder & Bishop, 2003).

Geospatial technologies are a group of modern tools and techniques used to collect, process, analyze, and visualize geospatial data. Geospatial data are information about the Earth's surface and atmosphere, including its physical features, land cover, natural resources, and human activities. Geospatial technologies include a wide range of tools and techniques, such as remote sensing, Geographic Information Systems (GIS), Global Positioning System (GPS), and digital mapping (Bishop et al., 2012). Remote sensing refers to the collection of information about the Earth's surface and atmosphere using sensors mounted on aircraft, satellites, and drones. These sensors capture data in different wavelengths of the electromagnetic spectrum, such as visible, infrared, and microwave, which can be used to create images and maps of the Earth's surface and atmosphere (Schwartz-Belkin & Portman, 2023). GIS is a computer-based system for capturing, storing, manipulating, analyzing, and displaying geospatial data. GIS allows users to combine data from different sources, such as satellite imagery, maps, and databases, to create maps and perform spatial analysis (Barruezo-Vaquero et al., 2022). Digital mapping involves the creation of maps using digital data, such as satellite imagery, GIS data, and GPS data. Digital maps can be easily updated, customized, and analyzed, making them useful for a wide range of applications, such as urban planning, emergency management, and environmental monitoring (Chiemelu et al., 2021).

2.4 Procedural studies

A decade ago, a substantial percentage of procedural research was devoted to investigating the influence of digital landscape representation (Pike, 2000). As previously stated, in landscape evolution modeling, there are essentially two options: regular grids (we use the more commonly recognized name DEMs as a stand-in for the more precise term Digital Terrain Models) and triangulated irregular networks (TINs). Using DEMs as a starting point, the LEM literature focuses on three issues: (i) the impact of the production or gridding process, (ii) the impact of the DEM resolution, and (iii) the impact and role of sinks and depressions (Hengl et al., 2004).

According to Hancock (2006), the use of different gridding approaches in DEM-derived topographical or hydrological parameters can result in slight variations. However, for example using the SIBERIA landscape evolution model, these differences are not significant over long timeframes, suggesting that the gridding method is not a critical factor for specific research. However, it is important to note that the model's resolution plays a vital role. Previous studies have discussed the limited research available on the influence of resolution on landscape evolution models (Schoorl & Veldkamp, 2001; Hancock et al., 2020).

2.5 Postdictive and predictive studies

Postdictive and predictive studies are two types of studies that are commonly used in scientific research, including in the fields of geomorphology and landscape evolution (Shroder & Bishop, 2003). Postdictive studies, also known as retrospective studies, are studies that examine events or phenomena that have already occurred. In other words, they look back in time to try to understand what happened and why it happened. Postdictive studies are often used to identify patterns and relationships in data and to test hypotheses (Shroder & Bishop, 2003). Predictive studies, on the other hand, are studies that make predictions about future events or phenomena. These studies use current data and trends to project what may happen in the future. Predictive studies can be used to inform decisions and policies that aim to mitigate or adapt to potential future changes (Korup, 2002). Although some descriptive studies used existing landscapes as a template or reference for their experiments, they were not characterized as postdictive since their goal was experimentation rather than exact modeling of landscape change. Almost all postdictive and, by definition, all predictive landscape evolution model studies work backward in time, from one well-known palaeo-landscape to another (often the present). Backward modeling has well-known conceptual and mathematical challenges. These issues are caused by equifinality, the idea that several palaeo-landscapes might result in one current landscape, and polygenesis, the idea that different processes can be responsible for the production of a landscape (Temme et al., 2011).

Both postdictive and predictive studies are important for understanding landscape evolution and help managing environmental concerns. Postdictive studies can help us understand how landscapes have changed over time and identify the factors that have contributed to these changes. Predictive studies can help us anticipate and prepare for future changes in the landscape, such as changes in sea level, changes in precipitation patterns, and changes in land use (Bledsoe & Watson, 2001). Because decadal, centennial, and millennial scale datasets are becoming more widely available for landscape evolution model calibration, our models of landscape development at shorter periods may be employed less descriptively and more predictively. As a result, their findings may be more relevant to policymakers (Korup, 2002). This necessitates a clear understanding of the value of forecasts. For this reason, sensitivity analysis and uncertainty analysis are becoming increasingly relevant. Temme et al., (2011) claimed that uncertainty analysis is one of the areas where environmental models may benefit the most, perhaps even more than model improvement.

2.6 Landscape evolution modelling

Landscape evolution modelling is a process of simulating the long-term development of landscapes based on a variety of factors such as geology, climate, vegetation, land use, and other environmental variables. These models use mathematical equations and computer simulations to predict how landscapes may evolve over time (Hancock et al., 2017). The purpose of landscape evolution modelling is to help researchers and policymakers understand the complex interactions between different environmental factors and how they affect the development of landscapes. This can help to inform decisions about land use planning, resource management, and conservation efforts (Dymond & De Rose, 2011).

Landscape evolution models come in two basic types, qualitative and quantitative, applicable to different spatial and temporal scales. Qualitative models are conceptual models that describe the physical processes and relationships between different components of a landscape in a qualitative way. These models are often used to provide a broad understanding of the mechanisms that control landscape evolution, without attempting to predict specific outcomes. They are useful for generating hypotheses and guiding research efforts, but they do not provide detailed quantitative predictions (Taloor et al., 2021). Quantitative models, on the other hand, use mathematical equations and computer simulations to predict the evolution of landscapes based on specific input parameters. These models are typically more complex and detailed than qualitative models, and they can provide more precise predictions of how landscapes will evolve over time (Tucker & Hancock R., 2010). There are many different types of quantitative landscape evolution models, each with its own strengths and weaknesses. Some models focus on specific processes, such as erosion or sediment transport, while others attempt to simulate the entire landscape evolution process. Some models are simple and easy to use, while others are highly complex and require specialized expertise to apply (Chen et al., 2014). Overall, both qualitative and quantitative landscape evolution models have an important role to play in understanding and managing landscapes.

Landscape evolution modelling has become an important tool for researchers in many fields, including geomorphology, hydrology, ecology, and geology. By using these models, researchers can gain insights into the past, present, and future of landscapes and make more informed decisions about how to manage and protect our natural resources (Hancock et al., 2020).

The overall goal of LEM is to better understand the history of the landscape through the simulation of terrain formation and handle interactions (Tucker & Hancock R., 2010). The main goal of SaLEM is to assess the properties of regolith according to known material relationships. In the absence of reliable data for certain process variables, they must be replaced with the appropriate parameters.

2.6.1 System for Automated Geoscientific Analyses (SAGA)

SAGA is a computer software used to edit geographical data in a geographic information system (GIS) (Conrad et al., 2015). It is free and open-source software that was created by a small team at the University of Göttingen's Department of Physical Geography and is currently maintained and enhanced by a worldwide development community. SAGA GIS is designed to provide scientists with a powerful yet simple framework for executing geoscientific methodologies. The application programming interface does this (API). SAGA includes a rapidly expanding collection of geoscientific methodologies packaged in interchangeable module libraries.

2.6.2 Soil and Landscape Evolution Model (SaLEM) tool

The SaLEM application is a special tool within SAGA for the spatiotemporal study of soil parent material evolution using a lithologically differentiated method (Böhner, J., & Anton, 2019). For the modeling of weathering, erosion, and transport processes, the model requires a digital elevation model and (paleo-) climatic data. User-defined functions control weathering in response to climatic conditions, local slope, regolith cover, and outcropping bedrock lithology. Lithology can be provided as a grid system, with each grid reflecting the top elevation of the underlying bedrock type. The purpose of SaLEM is to simulate weathering, erosion, transport, and deposition of unconsolidated material covering the bedrock during relatively shorter time periods (e.g. recent 50,000 years) using lithologically differentiated models. The simulation time is freely chosen and is only dependent on the availability of climatic data, which is regarded as critical for driving the model.

The inability to reproduce the original paleo-topographic state is one issue with LEM-based forward modeling. This is known as equifinality or landform convergence, and it has been addressed extensively in geomorphographic publications (e.g. Peeters et al., 2006). When modeling over longer geological time spans (several Ma), it must be regarded recognizable; but, for the time frame considered here (50000 years), it may be argued as less essential (Peeters et al., 2006). Therefore, for the initial topography of our modeling, we utilize the actual topography as described by the DEM.

The layer of unconsolidated material that covers the bedrock (regolith) now is the result of several natural processes that interacted over many thousands of years. Weathering processes degrade solid bedrock in two ways: physical weathering loosens the rock mass and chemical weathering rebuilds the mineral elements (Bishop et al., 2012). However, individual pieces are detached from the regolith and subjected to gravity transit downwards. This occurred under the effect of vegetation and produced several multi-material layers covering the solid rocks of the mountainous areas with a thin regolith coating. Its coat's thickness can range from a few centimeters to many meters (Chen et al., 2014). Because of its physicochemical characteristics, its ratio in regolith has a considerable impact on present properties of the soil.

2.7 Digital elevation model (DEM)

DEMs are widely used in various fields, including cartography, geology, geography, hydrology, and surveying. The traditional method for creating DEMs involves using data from surveying equipment, such as total stations or GPS units. However, the use of drones for creating DEMs is becoming increasingly popular due to their ability to cover a large area quickly and efficiently, and capture detailed images of the terrain from different angles. Recent studies have shown that drones equipped with sensors such as Lidar or photogrammetry cameras can generate high-resolution DEMs with improved accuracy compared to traditional surveying methods. Bennett et al., (2020) demonstrated an improved UAV-based DEM generation method using structure-from-motion and integrated relative orientation constraints. Jean et al., (2018) compared UAV-based and total station-based methods for generating DEMs of farmland, finding that the UAV-based method was effective. Xu et al., (2018) synthesized and looked ahead at the use of UAVs in landscape research. In addition to their accuracy, the use of drones for creating DEMs offers several advantages over traditional surveying methods. Drones are relatively inexpensive compared to traditional surveying equipment, making them a cost-effective option for creating DEMs. Drones can also cover remote or hard-to-reach areas that may be inaccessible with traditional surveying equipment.

2.8 Landscape evolution in a conclusion

Understanding landscape evolution is a complex and challenging task due to the interconnections, interactions, and adaptations among landscape components, as well as the presence of multiple causal relationships and non-linear complexity. Additionally, landscape evolution is often characterized by dynamic instability, contingency, divergence, and pathways, which further increase its complexity (Tucker & Hancock R., 2010). However, by adopting a systems perspective and analyzing landscapes as superorganisms, researchers can identify threshold-related state changes, apply selection principles to identify new phenomena, and utilize a law-place-history framework to identify commonalities and evolutionary trajectories while preserving their individuality and integrity (Phillips, 2021). Ultimately, the study of landscape evolution provides insights into the history, formation, and future of our planet's landscapes, and enables us to better manage and protect them for future generations.

3 Materials and methods

3.1 Study area

The study has been conducted at an experimental site located on campus at MATE University, Gödöllő, Hungary, (47°35′41″ N, 19°22′10″E) shown in Figure (1). The area of the experimental field is approximately 20000 m^2. The area has a slight slope toward the local erosion base of Rákos Creek (the creek is about 1 km far to the NE from the experimental field). Here we have selected exploration points (drilling points) which make catena downward on the surface of the slope of the research field.

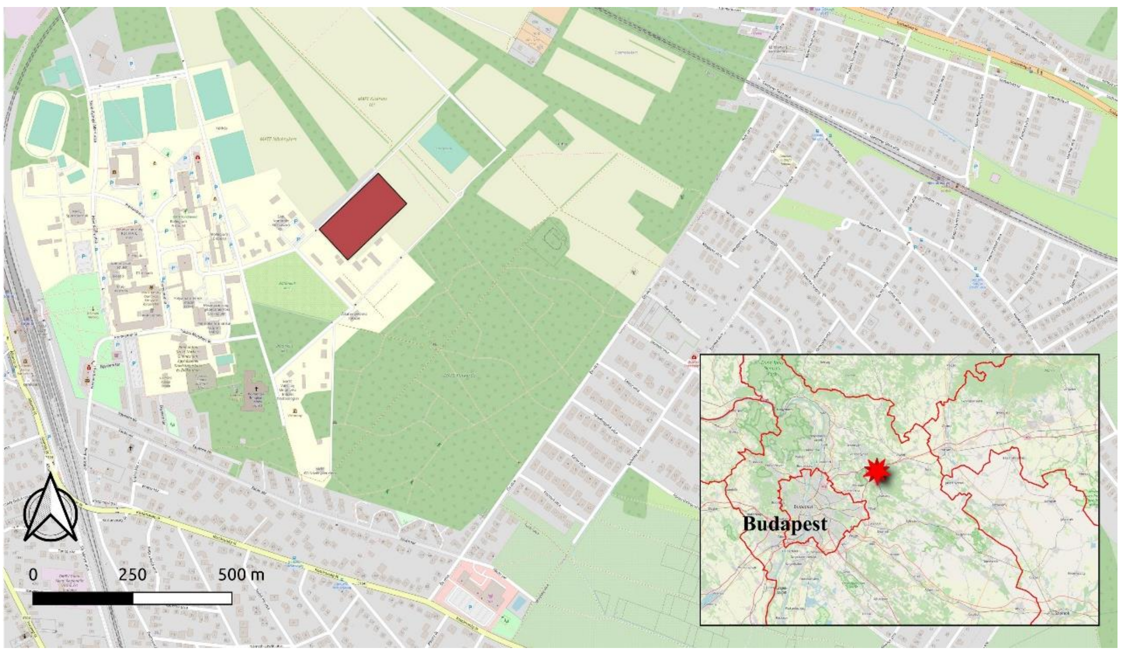


Figure 1. Local and wide regional position of the research field (MATE, Gödöllő)

3.1.1 Gödöllő's geography

Gödöllő is a town located in Pest County, Hungary, situated about 30 kilometers northeast of Budapest, the capital city of Hungary. The town is located in the Great Hungarian Plain, which is a large, flat area that covers most of the eastern and southeastern parts of the country. The Danube River flows just west of Gödöllő, and several smaller streams and rivers also run through the area. The town is situated on a slight incline, with the highest point being the hill where the Royal Palace is located (Helbrecht et al., 2017).

3.1.2 Gödöllő's geology

Gödöllő and the surrounding area is located on the Pannonian Basin, a large geological formation that covers much of central Europe. The basin is composed of several layers of sedimentary rock, including sandstone, limestone, and shale, which were deposited during the Miocene period, in an inland see. The area is characterized by its gently sloping terrain, with elevations ranging from 80 to 200 meters above sea level. The region was formed millions of years ago by tectonic activity and the shifting of the Earth's crust, which created a large depression that eventually filled with sediment and water. As a result, the area is known for its fertile soil, which is ideal for farming and agriculture (Horváth et al., 2014).

3.1.3 Climate: Present and past

The climate of Gödöllő is classified as humid continental, with warm summers and cold winters. In this response, I will provide a brief overview of the climate of Gödöllő in the past and present.

3.1.3.1 Historical Climate of Gödöllő:

Climate data for Gödöllő dates back to the late 19th century, with some records from as early as 1881. According to the Hungarian Meteorological Service ('OMSZ'), the average temperature in Gödöllő during the period from 1891 to 1920 was 9.1 °C, with an average annual precipitation of 641 mm. The warmest month during this period was July, with an average temperature of 18.6 °C, while the coldest month was January, with an average temperature of -2.6°C (https://www.met.hu/en/idojaras/).

3.1.3.2 Present Climate of Gödöllő:

Today, the climate of Gödöllő is still classified as humid continental, with some changes compared to the historical period. According to recent data from the Hungarian Meteorological Service (https://www.met.hu/en/idojaras/), the average temperature in Gödöllő from 1991 to 2020 was 11.1 °C, which is slightly warmer than the historical average. The warmest month during this period was also July, with an average temperature of 21.3 °C, while the coldest month was January, with an average temperature of -2.2 °C. In terms of precipitation, the average annual amount in Gödöllő from 1991 to 2020 was 620 mm, which is slightly less than the historical average. The wettest month during this period was May, with an average precipitation of 68 mm, while the driest month was February, with an average precipitation of 30 mm.

3.2 Soil sampling and analysis

3.2.1 Sampling tools

We used a 7 cm diameter hand auger set for drilling as shown in Figure (2) to get the soil samples, which is a great tool for manual auguring and sampling in a wide range of soil types. We found the augers to be lightweight and simple to use, even if working alone. What we appreciated about this set was that it included a combination of augers suited for practically every type of soil. We were able to drill to a depth of 4 m (except in 2 cases where the depth of the drillings were between 3 and 4 m, due to technical difficulties), liable on the water table, soil structure, and type of soil. The augers were easily changed during the procedure to fit the specific soil conditions we were working with. This made it a great tool for soil profiling, geology. A measuring tape or ruler was used to measure the depth of soil samples and to ensure consistency between samples. Small, metal containers with about 20 mL capacity were used to store soil samples, despite they are heavier and bulkier than other types of containers, which can make them more difficult to transport and handle in the field but they are sturdy and durable. In addition, a field notebook was essential for recording important information such as the location, depth, and characteristics of each soil sample. We also recorded the location of each drilling by using mobile application "GPS TEST". This app provides an acceptable precision of recording the position with using more global positioning satellite systems.

Figure 2. Auger set for hand-operated auguring with bayonet connection up to 5-6 m depth in heterogeneous soils (Source: https://www.royaleijkelkamp.com/products/augers-samplers/soil-augers-samplers/hand-augers/).

3.2.2 Sampling process

As part of a soil sampling survey for the evaluation of a GIS (SAGA) model, we conducted 14 hand auger drillings to obtain soil profiles as shown in Figure (3). Each profile was obtained by drilling a 4-meter deep hole (except in 2 cases where the depth of the drillings were between 3 and 4 m, due to technical difficulties) and collected 172 soil samples but we were able only to analyze 36 soil samples due to laboratories shut down by constructional works.

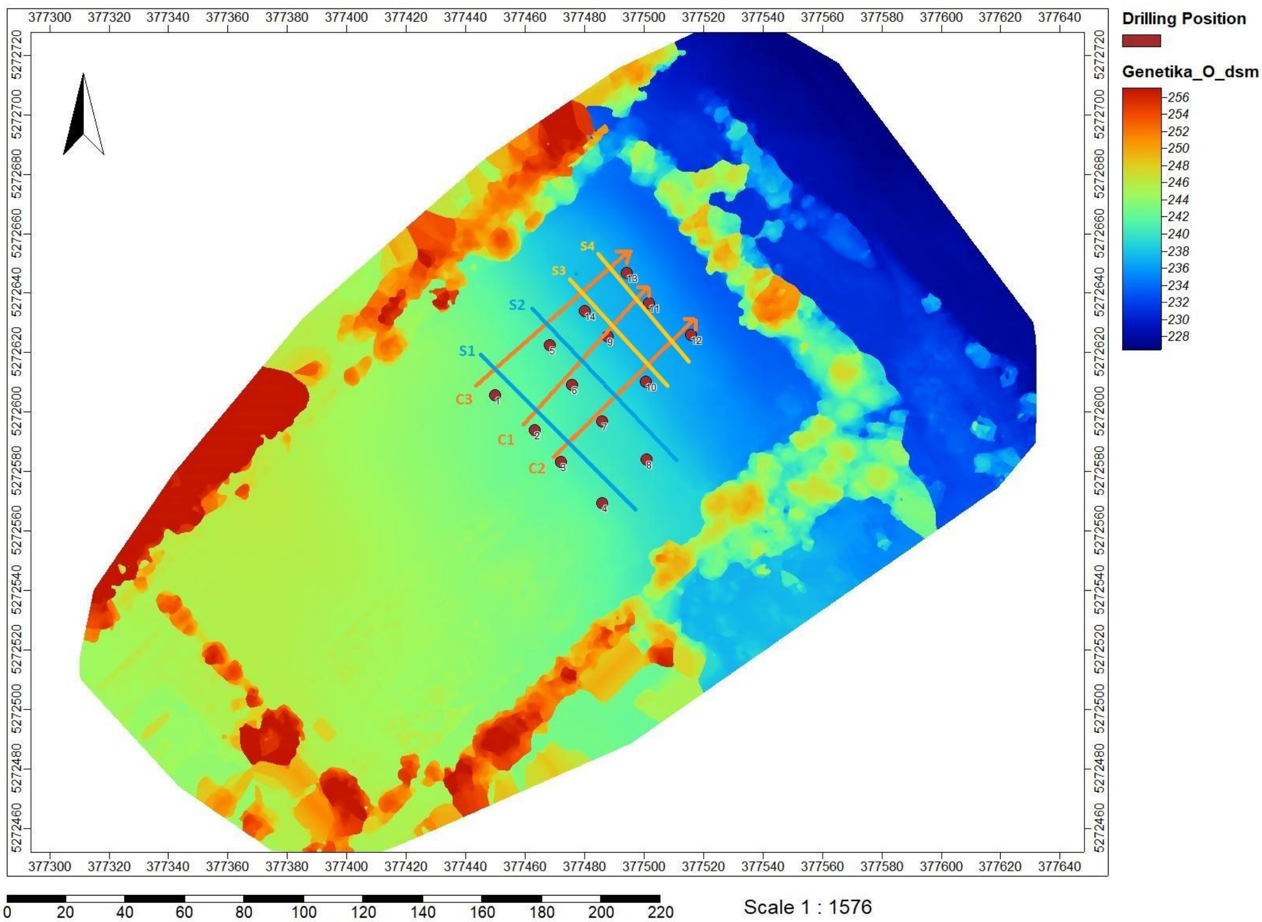


Figure 3. Soil sample collection points showing the different catenas (C1, C2, and C3) and slopes (S1-S4). The map was based on the digital elevation map provided by János Grósz, Dept. of Water Management and Climate Adaption, KÖTI, MATE.

The soil collection procedure is illustrated in Figure (4). The soil profiles were described based on various soil properties, including soil type, color, structure, texture, and horizon(s). Soil type was determined based on the dominant particle size and organic matter content, while soil color was assessed using the Munsell color chart. Soil structure was evaluated based on the arrangement of soil particles and degree of aggregation or clumping. Soil texture was estimated by feel, and later, in case of the selected samples, analyzed in a laboratory to determine the relative proportions of sand, silt, and clay.

Distinct soil layers or horizons were identified based on color, texture, and structure. The information obtained from the soil survey, including the calcium carbonate content, was used to better understand the soil properties.

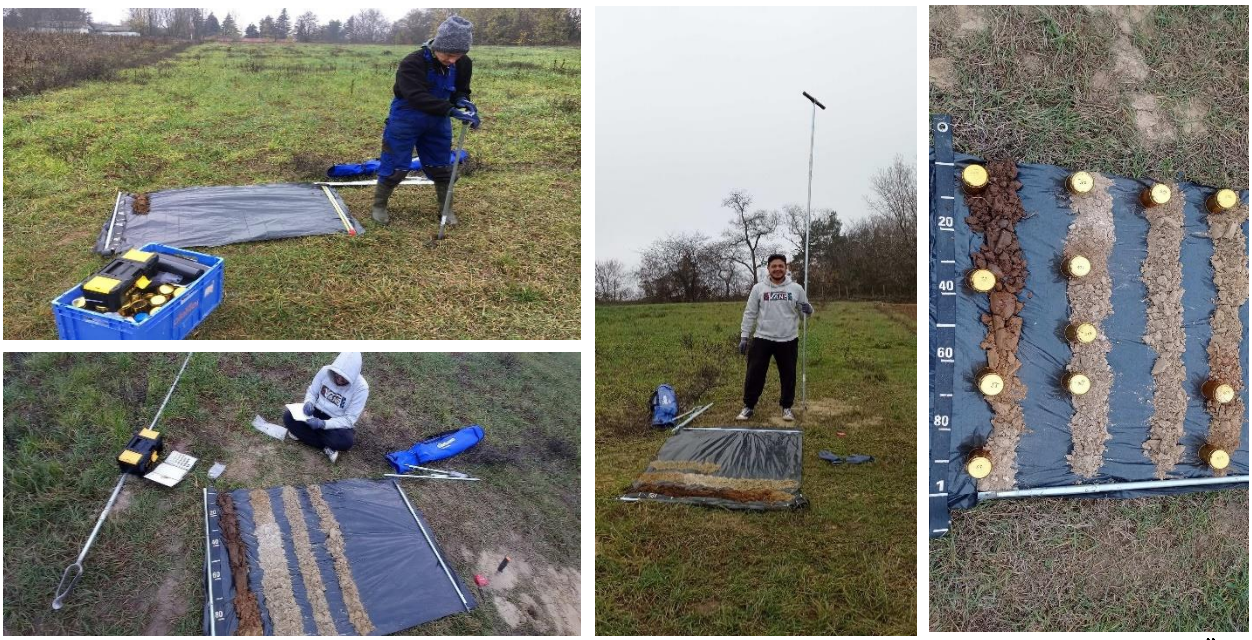


Figure 4. Sampling process by Halupka Gábor (Dept. of Water Management and climate Adaption, KÖTI, MATE) and myself in the study area. Photo: Gábor Halupka and Mohamed Saad

3.2.3 Laboratory analysis

The soil physical and chemical analyses were done in the ATK Institute for Soil Sciences laboratories. Below are the brief descriptions of the used methods.

3.2.4 Soil physics

Grain size distribution was determined using the sieve-pipette method—Hungarian patent number MSZ-08-0205-78, where sand, silt, and clay contents were measured. 25 g from air dried and sieved (<2 mm) soil samples were put in 1L cylinders. We added 20mL 0.5n Na-pyrophosphate solution and approximately 400mL DI water. The soil-solution mixtures were shaken for 6 hours prior to analysis.

3.2.5 Soil chemistry

The measurement of $CaCO_3$ contents of soil samples were done using Scheibler calcimeter (MSZ-08 0206/2-78). Depending on pre-check values of carbonate content, 1 to 10 g of soil sample was weighed in a reaction vessel and 15-20 mL of 10% HCl solution within small test tube was transferred into the reaction vessel. The reaction was initiated by tilting the vessel so the HCl solution could contact the soil sample. The reaction vessel was shaken for 5 minutes using a mechanical shaker to complete the reaction. The CO_2 volume was determined using a burette where the generated CO_2 displaced water.

3.3 Applied models

The SAGA and SaLEM models' input parameters used in this study were the following:

1) Initial surface elevation DEM of the research site.
2) Meteorological data (Minimum, maximum, and average temperatures and precipitation).
3) Initial regolith thickness (Default input)
4) Allochthone (Default input).
5) Bedrock parameters (Default input).
6) Tracers parameters (Default input).
7) Diffusive hillslope processes (Default input).

3.3.1 Digital Elevation Model (DEM)

In our study, we used a high resolution DEM that was generated by a drone that we could get an image dimension of 5286 pixels width and 4529 pixels height, horizontal resolution 96 dpi, vertical resolution 96 dpi and bit depth 32. The type of the drone was Yuneec H520e. The mounted sesor was E90 RGB camera on the UAV. The maximum flight level was 120 meters and the flight speed was 6m/s during the survey. Ground resolution of the images was 3.0 cm/pixel. The required license for the mission were A1 and A3. (In courtesy of János Grósz).

The airborne data recording by the drone was fulfilled in February 2022 by János Grósz (Dept. of Water Management, and Climate Adaption, MATE-KÖTI), who also provided the technical parameters of the drone measurement.

3.3.2 Climate data

Climate data parameters such as minimum temperature, maximum temperature, average temperature, and precipitation are major entries for the SaLEM module. In our study, first we used data from the automated meteorological station of the hosting department of this research (Department of Water Management and Climate Adaption, MATE-KÖTI) but the data series were not long enough to run the module essentially. Therefore, we used the National Aeronautics and Space Administration (NASA) climate data, which is shown in Figure (5). NASA has long funded satellite systems and research that provide data critical to the study of climate and climatic processes through its Earth Science research program (https://power.larc.nasa.gov/data-access-viewer/). Long-term climatologically averaged estimates of meteorological quantities and surface solar energy fluxes are included in this data. Furthermore, time series values of the underlying meteorological and solar data are presented. These satellite and model-based products have been demonstrated to be precise enough to offer reliable solar and meteorological resource data across areas where surface observations are few or nonexistent. The products have two distinguishing characteristics: the data is global and often continuous in time. Because of these two major properties, very massive data archives are generated. NASA's Earth Science Division Applied Sciences Program supports the development and release of user-friendly data sets formulated specifically for designated user communities, with access to these data via a user friendly web based mapping portal, to encourage the use of global solar and meteorological data.

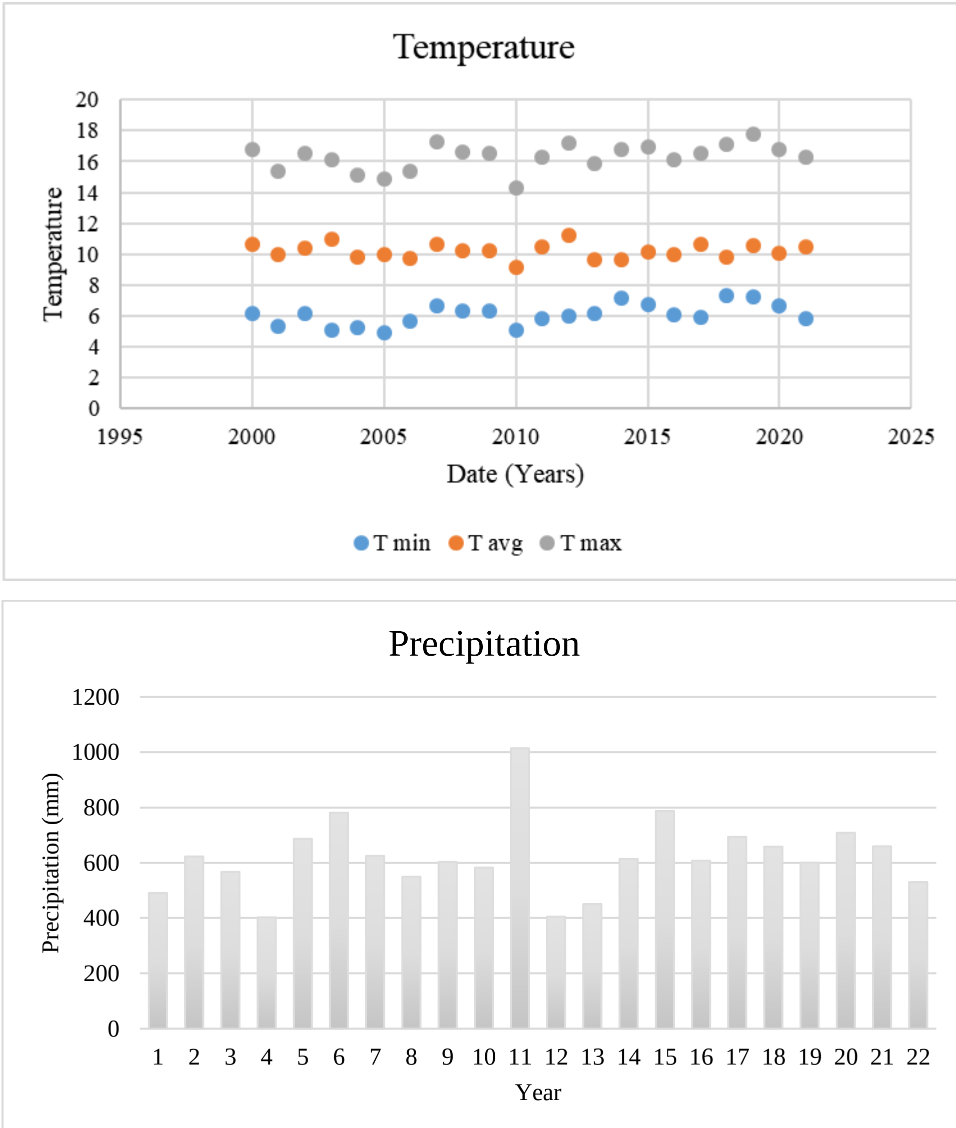


Figure 5. Minimum, maximum, and average temperatures and precipitation data for the last 22 years. (https://power.larc.nasa.gov/data-access-viewer/).

3.4 Statistical analysis

The effects of catena and slope positions on soil physical properties (particle size distribution) and $CaCO_3$ content were analyzed using nonparametric statistical analyses of the Wilcoxon test and Kruskal–Wallis ANOVA. Normality of the dataset was tested by the Shapiro-Wilk test. All statistical calculations were performed using the software package R (for the figures the ggplot2 and for the Wilcoxon test the ggpubr packages were used; R Core Team, Version 4.0.2). Statistical significance of the data sets was determined at $p < 0.05$.

4 Results

4.1 Soil analysis results

4.1.1 Soil profiles

We collected soil samples from 14 drilling locations within the study field to characterize the soil properties that could evaluate the landscape evolution using the SaLEM simulation. At each location, we collected a 4-meter soil core and we were able to create three series of drillings (Catena) down towards the slope and two series of drilling in perpendicular direction that we classified into four levels called S(1-4). The thickness of the organic layer is changing between 30 and 200 cm in the drillings. A brief description of the different sampling sites is given below.

4.1.1.1 Sampling site catena 1

It is characterized by a relatively thick layer of organic matter on top of a silty sand surface layer, with a sand subsoil underneath. The A level contains a low amount of plant debris and roots. The sandy surface layer allows for easy water infiltration and drainage. As we move deeper into the soil, the sand content increases. At this site, we only found a reddish layer in between two layers of high content of clay as shown in Figure (6).

4.1.1.2 Sampling site catena 2

Soil sample positions and soil color schematics of catena 2 is shown in Figure (7). This catena has a thinner organic layer than catena 1, and its sandy surface layer is much thinner with more clay subsurface layers. We noticed that it has more reddish layer than catena 1 and has more layers with high content of clay.

4.1.1.3 Sampling site catena 3

Soil sample positions and soil color schematics of catena 3 is shown in Figure (8). It is characterized by a thick organic layer as well such as catena 1, over 30 cm to 200 cm in depth. The surface layer is sandy with more coarse grain size; while surprisingly the subsoil has some dark layers much similar to the top layer. In addition, in two of the drillings (No. 1 and 13), we were not able to drill deeper and we stopped before we reached the four meters depth because of a very hard surface layer of the actual bottom of the ongoing drilling.

4.1.1.4 Slope positions S1, S2, S3 and S4

Soil sample positions along the study slopes and their soil color schematics are shown in Figure (9) and Figure (10).

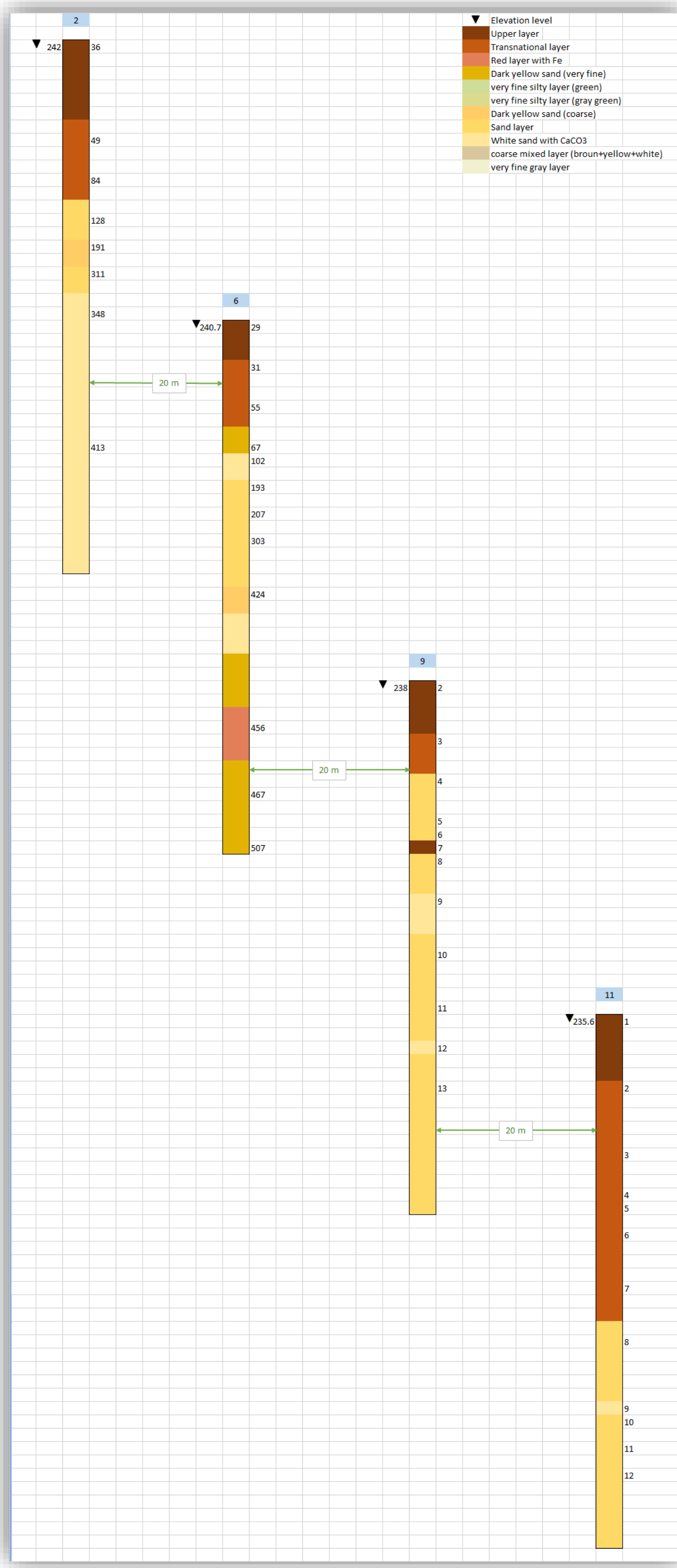


Figure 6. Catena 1 soil profile considering the elevation of drilling number (2, 6, 9, 11).

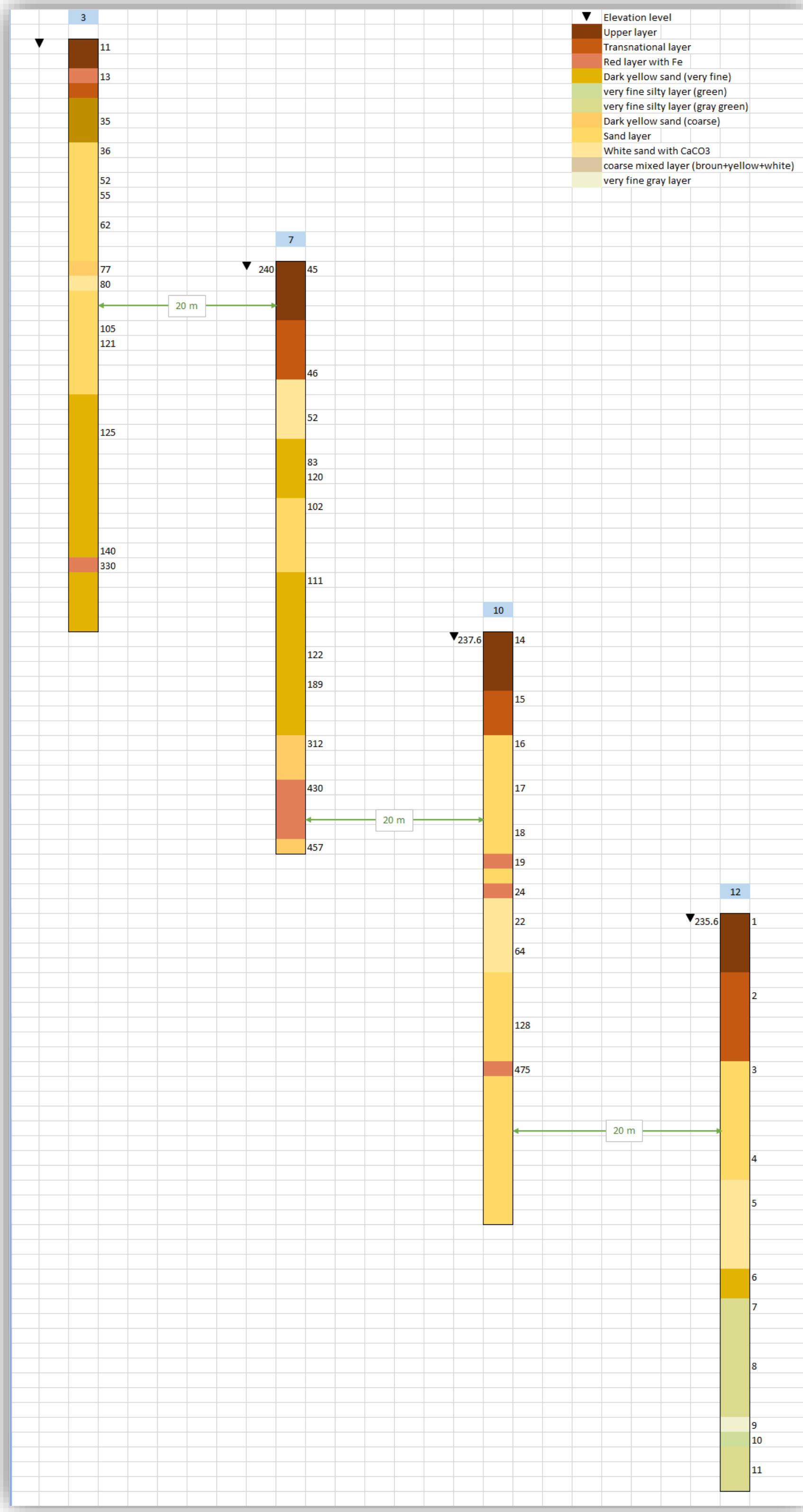


Figure 7. Catena 2 soil profile considering the elevation of drilling number (3.7.10.12).

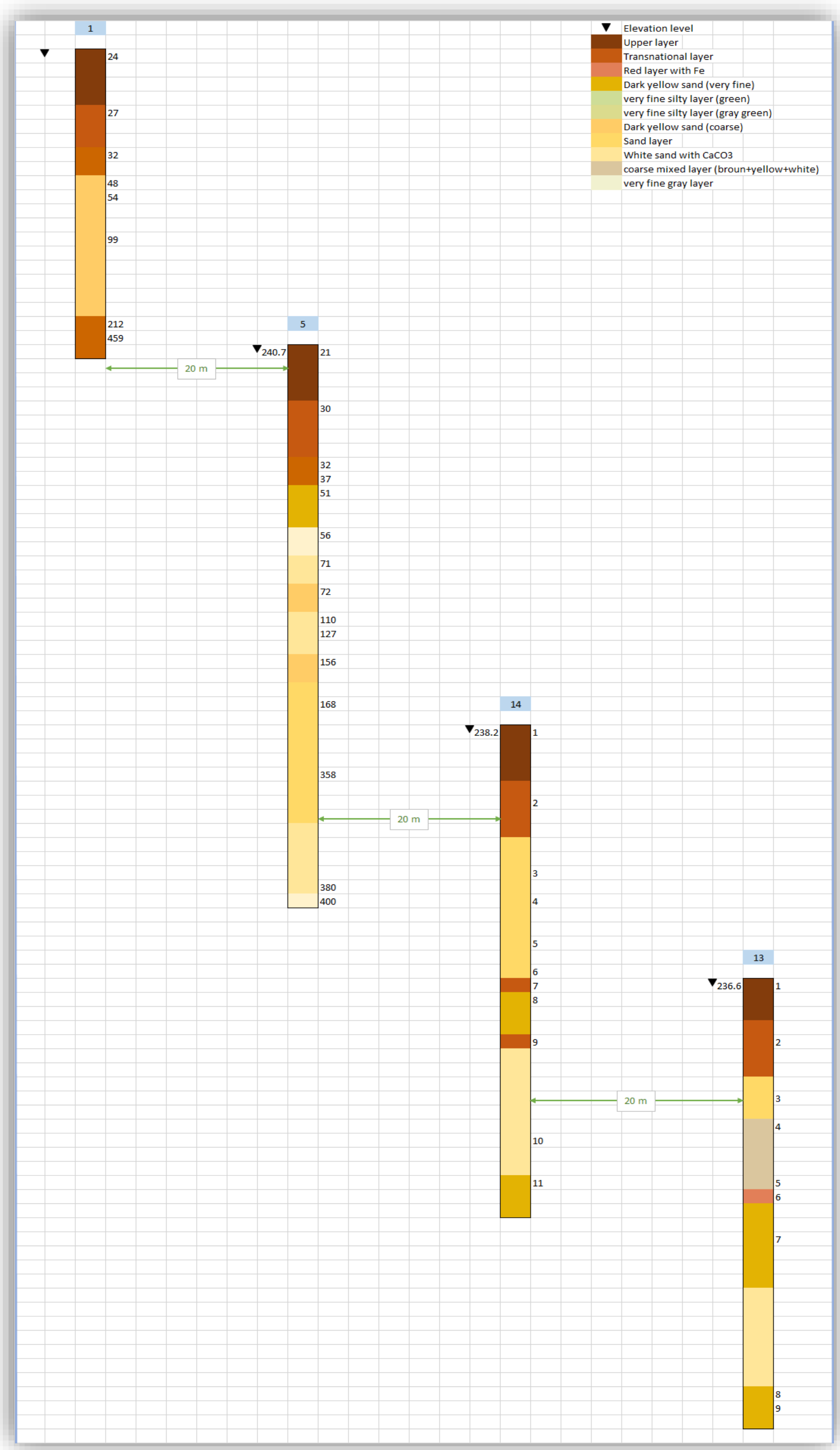


Figure 8. Catena 3 soil profile considering the elevation of drilling number (1.5.14.13).

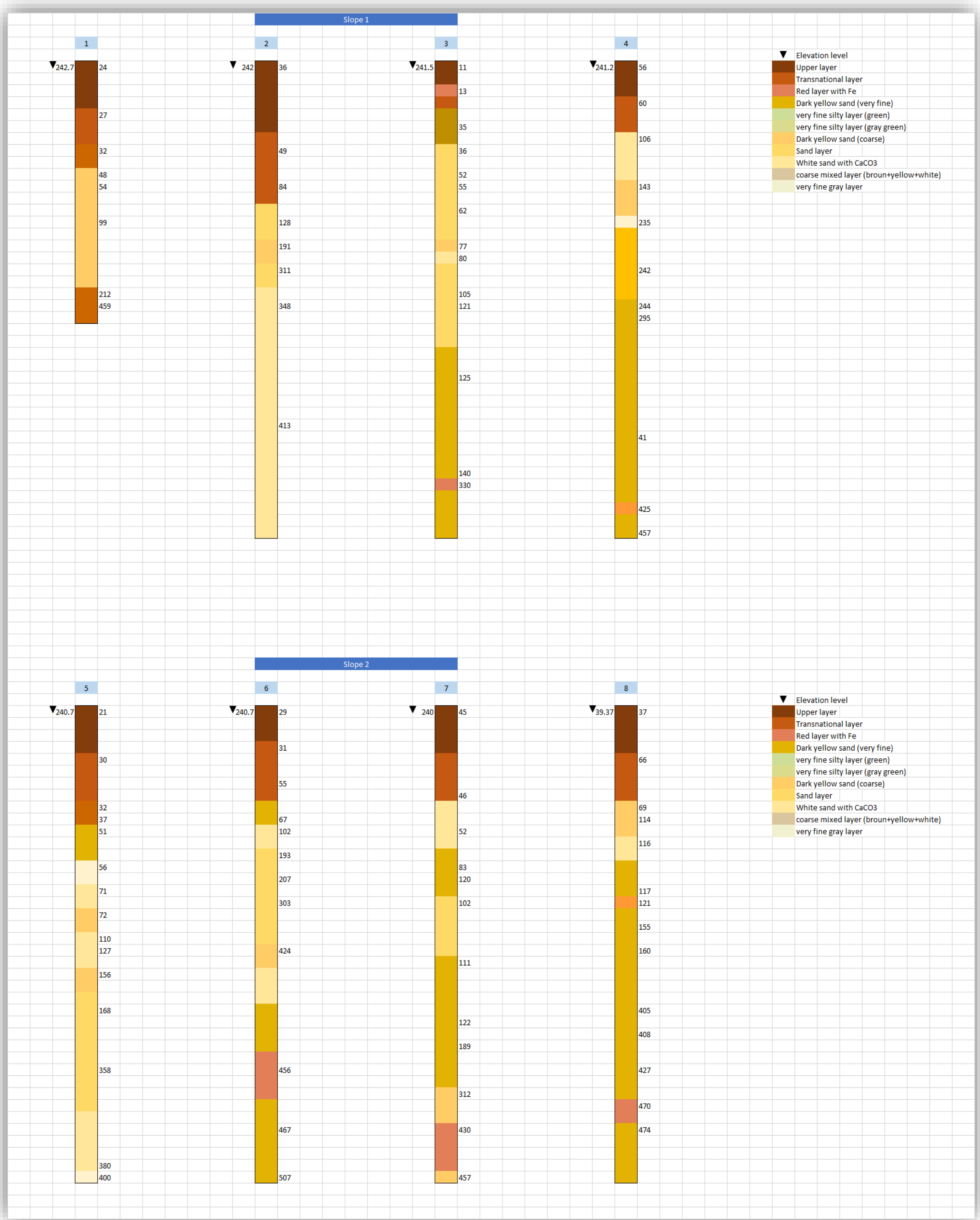


Figure 9. Soil profiles in two different levels, Slope 1 and Slope 2 (S1 and S2).

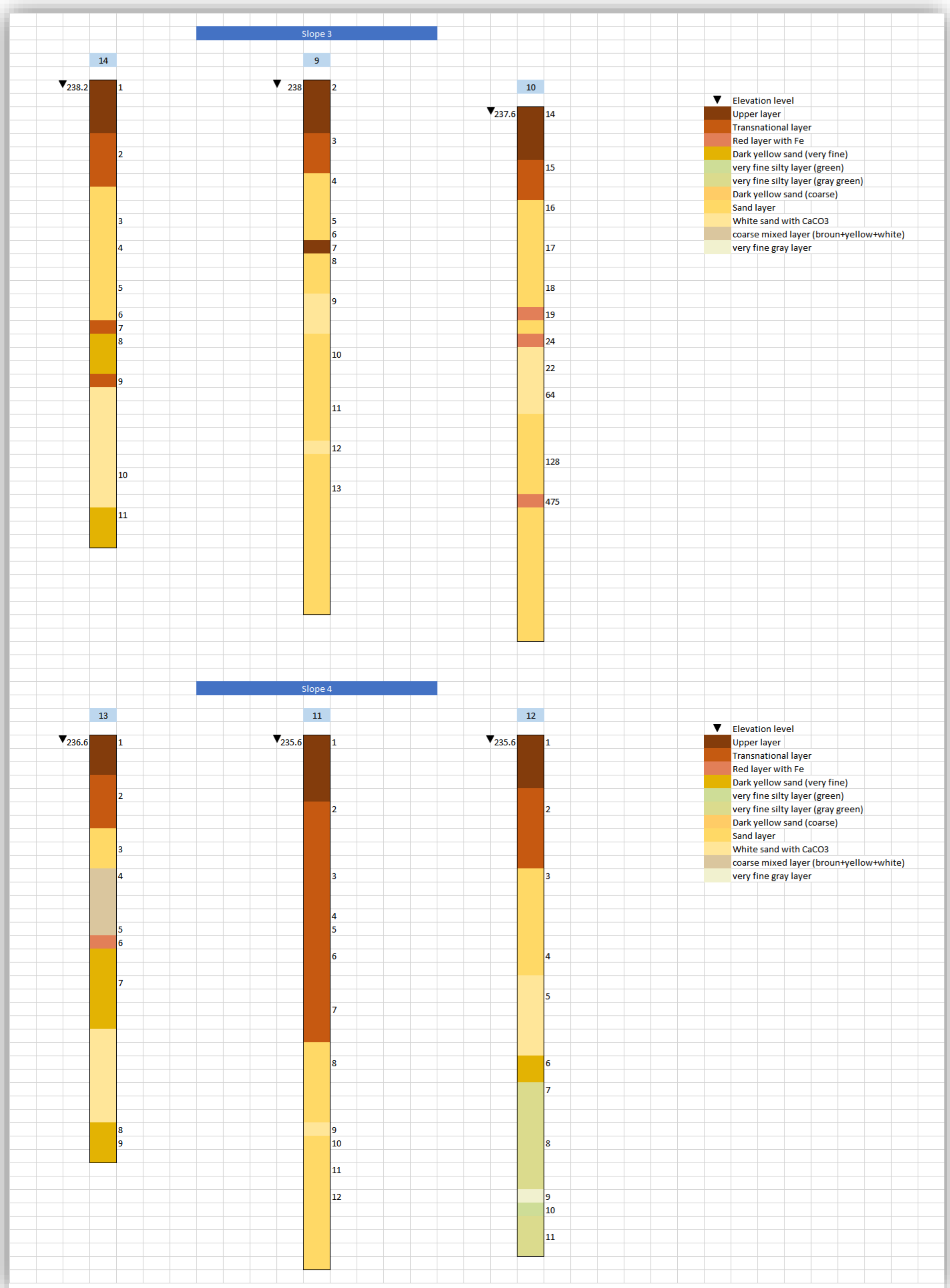


Figure 10. Soil profiles in two different levels, Slope 3 and Slope 4 (S3 and S4).

4.1.2 Particle size distribution and calcium carbonate ($CaCO_3$) characteristics

We analyzed soil samples for particle size distribution and calcium carbonate ($CaCO_3$) content in the laboratory (the data are summarized in Table 1, 2 and 3 for each sample point in Appendix 1). Due to limited resources, selected soil samples from catena 1, 2 and 3 were measured from 12 drillings, for a total of 32 soil samples. Our analysis of the particle size distribution showed that the soils in the study field were predominantly sandy loam, with a range of 42-91% sand, 6-50% silt, and 2-15% clay Figure (11). The soil texture analysis suggested that the soils in the study field well graded, with likely good permeability.

We also measured the calcium carbonate ($CaCO_3$) content in each of the soil samples, as this can have important implications for the soil's fertility and erosion potential, since calcium carbonate works as a kind of glue among the particles (Meng et al., 2017). Our analysis revealed that the $CaCO_3$ content varied across the study field, ranging from 0% to 59% by weight.

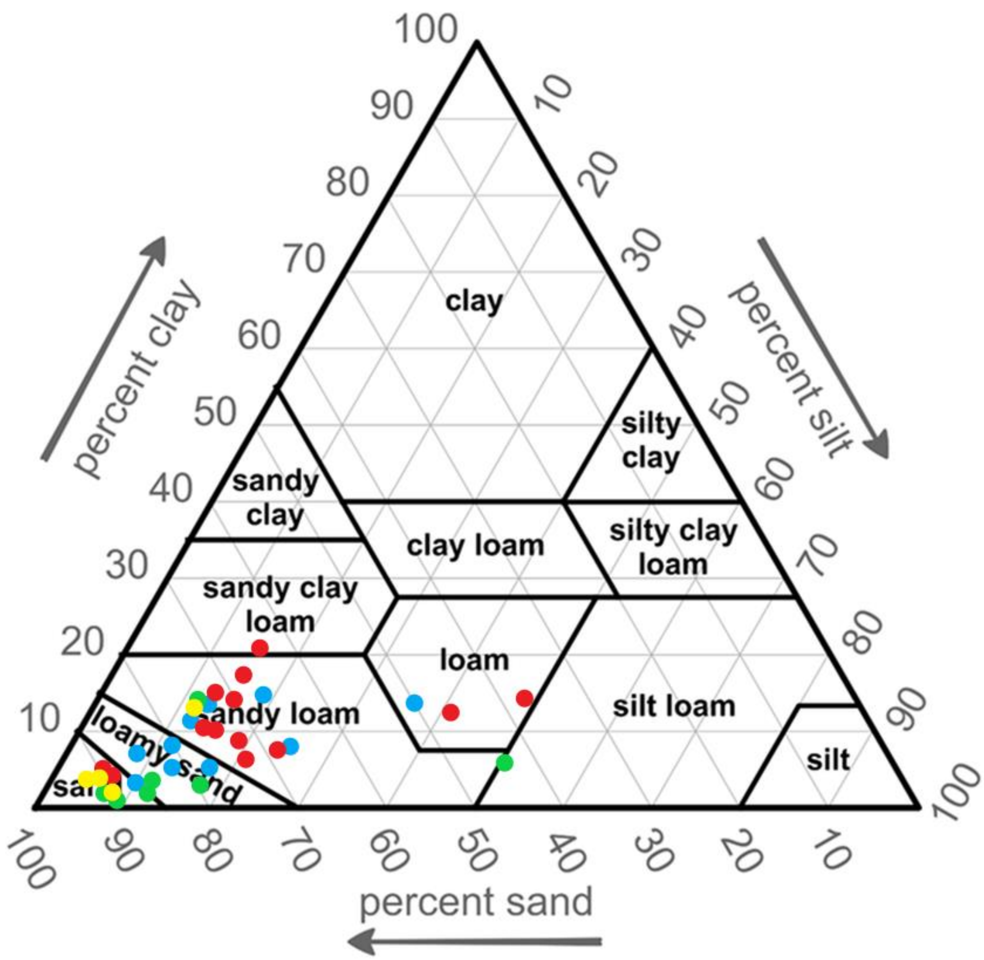


Figure 11. Soil texture determination based on the particle size distribution for selected soil samples of S1 (Blue), S2 (Red), S3 (Green), and S4 (Yellow).

4.1.3 Statistical analysis

The two chosen catenas (C1 and C3), the different drills, and the two slope positions (S1 and S2) were analyzed for differences in particle size distribution and $CaCO_3$ content. As the catenas were relatively close to each other, we did not find significant differences among the catenas for any of the investigated parameters ($p > 0.05$; Figure (12)). We also investigated if there is any difference among the 8 drilling data and found that most parameters are statistically not different, however, some drills showed significant differences in the field (i.e. $p < 0.05$ were for sand content between drill 5 and 14, 5 and 13, 6 and 13; silt content for drill 5 and 9, 5 and 13, 5 and 14; for clay drill 5 and 13, 6 and 13). For $CaCO_3$ content there were no significant differences among drills or slope positions. When the slope positions were independently studied Figure (13), some differences were observed for slope position 2 and 4 (sand and silt), slope position 1 and 4 (silt), and slope position 1 and 3 or slope position 2 and 3 (clay).

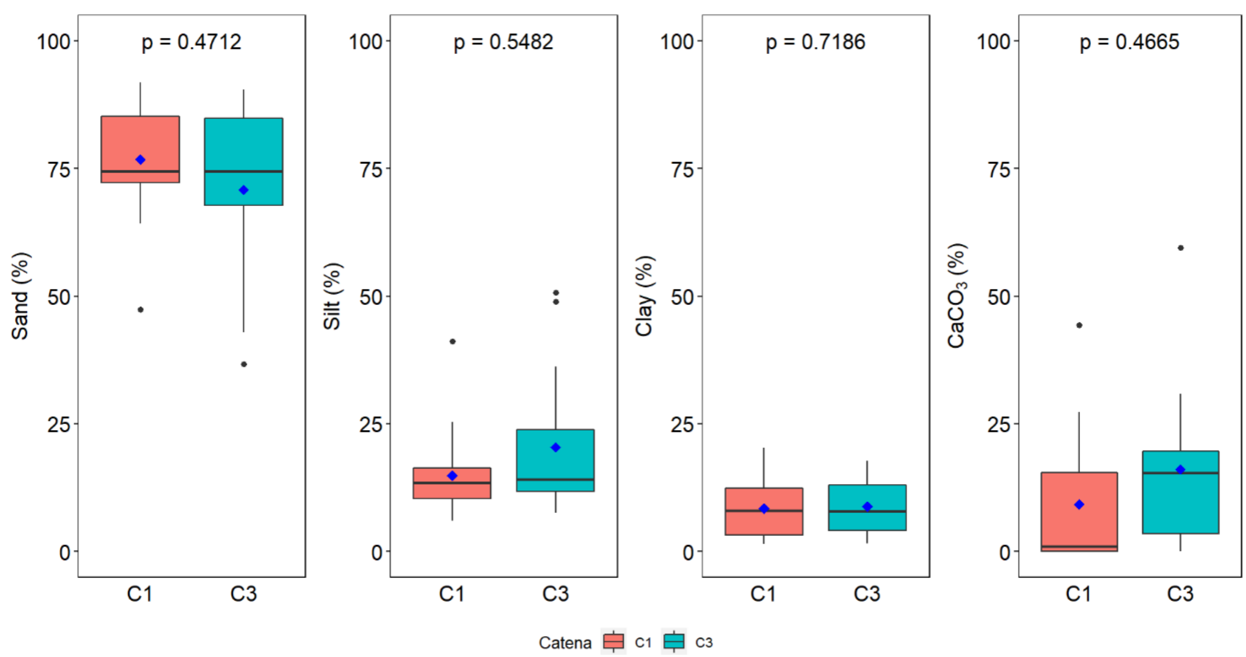


Figure 12. Soil physical and chemical properties of the two studied catena. Box plots show median (solid black line), mean (blue diamond), upper and lower quartiles, and minimum and maximum values (whiskers; data plus/minus 1.5 interquartile range). C1 and C3 represents catena 1 and 3, respectively. .

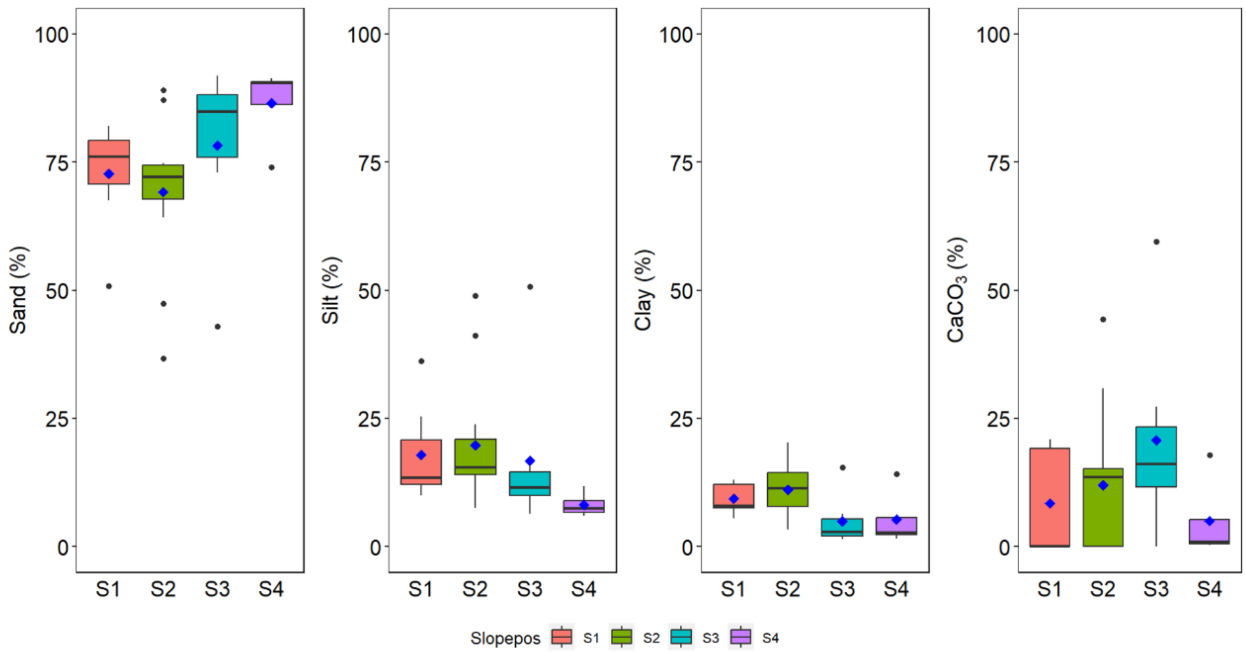


Figure 13. Soil physical and chemical properties of the different slope positions. Box plots show median (solid black line), mean (blue diamond), upper and lower quartiles, and minimum and maximum values (whiskers; data plus/minus 1.5 interquartile range). S1, S3, S3, and S4 represents slopes 1 through 4.

4.2 Landscape evolution model results

4.2.1 Landscape evolution model relationship to soil analysis

The soil analysis data was incorporated into the landscape evolution model, to find out if there are revealing significant correlations between soil properties and landscape features such as slope, erosion rates, and channel formation. Our SaLEM simulation produced a new DEM layers shown in Figure (14) that represented the predicted landscape evolution over a 50,000-year period that produced 0 cm to 30 cm of regolith thickness. Based on the soil analyses data we also estimated the soil moisture storage capacity of the study field using the SaLEM model, which is shown in Figure (15). By incorporating soil properties of particle size distribution data and $CaCO_3$ contents into our simulation, we can better capture the impact of soil erosion on landscape evolution as shown in Figure (16).

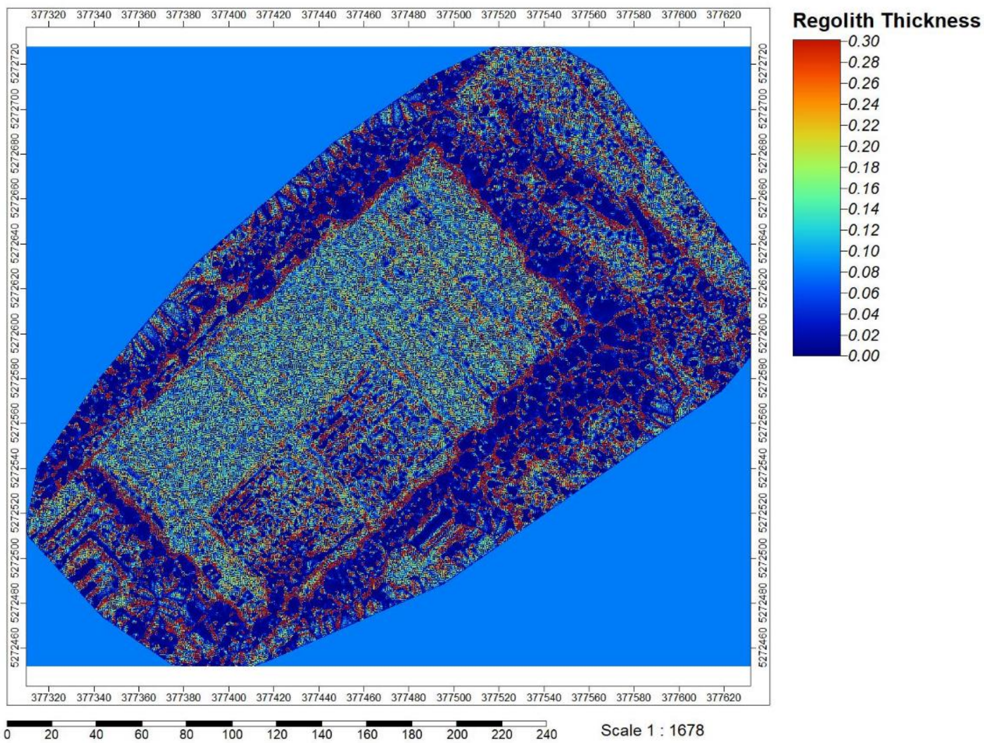


Figure 14. Generated DEM of regolith thickness by SaLEM model in SAGA.

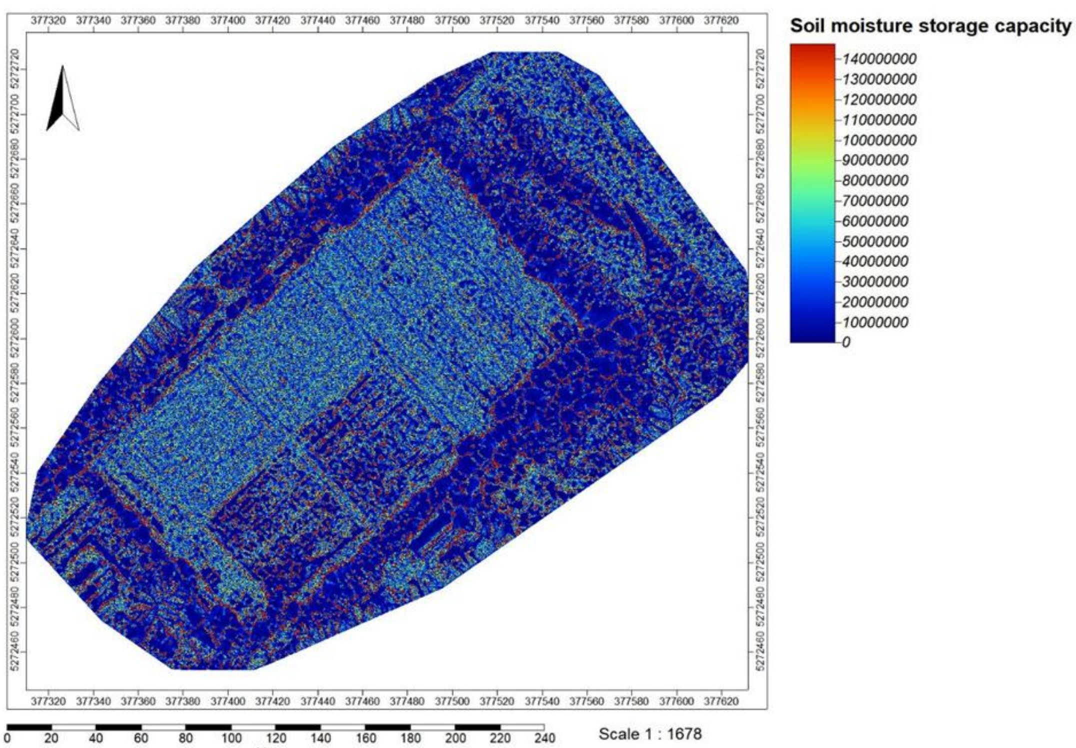
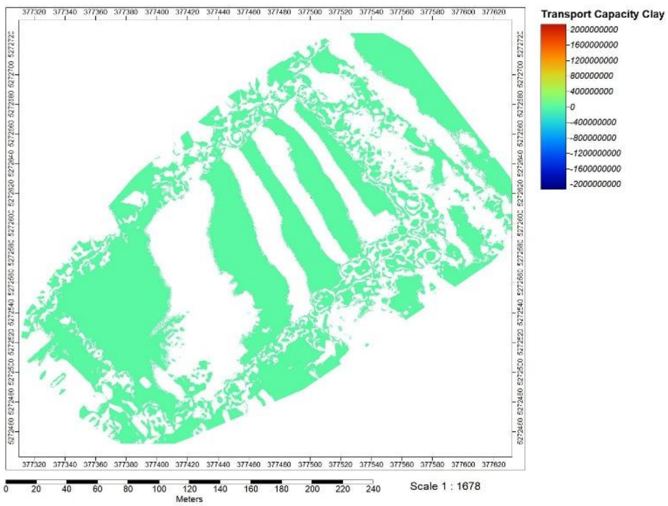


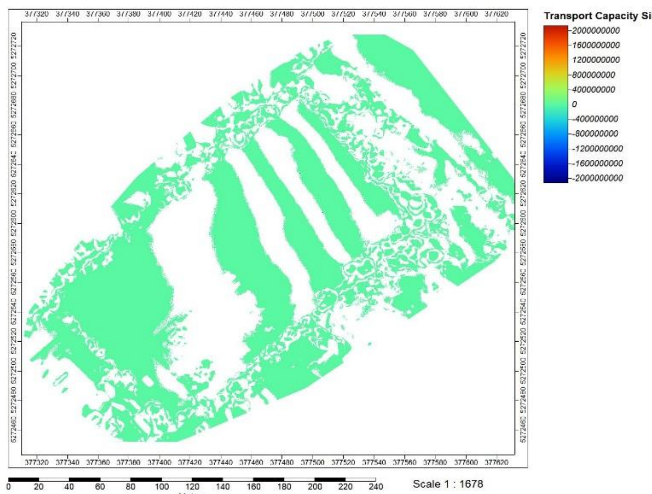
Figure 15. Soil moisture storage capacity in the study area estimated by the SaLEM model.

4.2.2 Comparison with soil analysis results

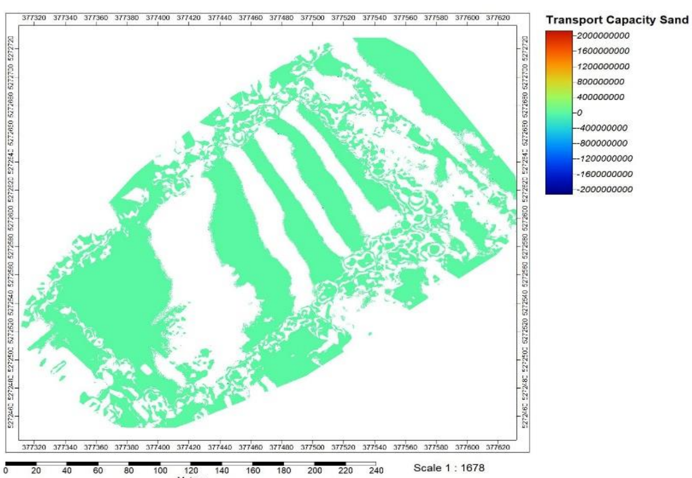
The results of the landscape evolution model (LEM) were compared with the soil analysis data, revealing areas of agreement and disagreement between the model predictions and the observed soil properties. The LEM shown in Figure (16) predicted higher erosion rates in areas with higher clay content, which was consistent with the observed data. However, the LEM predicted lower erosion rates in areas with higher sand content, which contradicted the observed data.



a)



b)



c)

Figure 16. Soil erosion modeled in SAGA by erosion tool for a) clay, b) silt, and c) sand.

5 Discussion

All weathering and transportation-related processes follow physical and chemical principles, which should be captured by the chosen SaLEM model. Even so, due to many factors, this can only be done as a rough approximation to real-world phenomena, such as input data for all elements of the associated processes are not accessible such as initial regolith thickness, the spatial resolution is insufficient to model all processes accurately, and physical modeling of some of the related processes would be too difficult and outside the range of SaLEM (Bock et al., 2018).

The results from the soil analysis and landscape evolution model were integrated to provide a comprehensive understanding of the study area, including the role of soil properties in shaping the landscape. The integration revealed that soil properties play an important role in determining erosion rates, slope, and channel formation patterns, and that these factors should be taken into account when developing and calibrating landscape evolution models.

The results of our soil analysis showed that the study field has predominantly sandy loam soils. The range of particle size distribution in the soil samples suggests that the study area is prone to moderate erosion rates. However, the grain size distribution and $CaCO_3$ content analysis revealed that the distribution of this mineral is not uniform across the field, some areas having significantly lower $CaCO_3$ content than others. The low $CaCO_3$ content in some areas of the field is a concern as it indicates a higher potential for erosion in those locations. Soils with higher $CaCO_3$ content are more resistant to erosion and tend to have better soil structure (Meng et al., 2017). Therefore, it is important to consider the spatial distribution of $CaCO_3$ content when designing erosion control measures and soil management practices in fields prone to erosion such as the present site. Furthermore, the variability in $CaCO_3$ content, beside the organic matter, the grain size distribution, across the study field also supports that there may be variations in the geological history of the landscape, which could have implications for landscape evolution processes. The presence of $CaCO_3$ can be an indicator of weathering processes, and variations in $CaCO_3$ content could be used to infer differences in weathering rates across the study area. Future studies should focus on exploring the link between $CaCO_3$ content and landscape evolution in the study area in more detail. In conclusion, our soil analysis revealed that the study field had predominantly sandy loam soils with possible good permeability. The $CaCO_3$ content varied across the field, suggesting localized areas of higher erosion potential. In spite of our efforts to improve the accuracy of the SaLEM simulation by incorporating the soil properties of the study field, the simulation results displayed some discrepancies with the expected values. The reasons for these discrepancies could be multifaceted, and further investigation is required to identify the underlying causes.

In addition to the soil analysis results, we used the SaLEM landscape evolution model to simulate the topographic changes in the study field over time. However, we observed that the model output did not match the measured soil composition, particularly regarding the absence of sand in the simulated soils. We believe that this discrepancy may be due to limitations in the SaLEM model's input parameters or assumptions about soil erosion processes. Therefore, while the SaLEM model provides useful insights into landscape evolution, it should be used with caution and validated with ground-truth data such as our soil analysis results. Also, based on the literature (Tóth, Á., Székely, B., & Kovács, 2011)(Csillag, G., Rózsa, P., 2013), we expected the change of regolith thickness in the Gödöllő region to be between a few centimeters to several meters depending on the location and type of bedrock. However, our simulation output revealed unexpectedly low regolith thickness-change during the modeling time-interval (50,000 years) ranging from 0 cm to 30 cm, which was not consistent with the previously reported values in the literature. According to Tóth et al. (2011), the thickness of regolith in the Gödöllő Hills can vary between 1 and 6 meters, while Csillag et al. (2013) reported that the thickness of regolith overlying the volcanic rocks in the area can range from 2 to 20 meters. However, it is important to note that these values are based on specific locations within the Gödöllő region and may not be representative of the entire area. Our unexpected finding of a relatively thin change in thickness of regolith layer suggests that further investigations are needed to better understand the geological processes and history of the study area. In general, our model yielded some unexpected outcomes, in case of thickness of the regolith. One possible explanation for these results could be in the variability of soil properties across the study area (Singh et al., 2023). Another possible explanation is the limitations of our SaLEM simulation. While SaLEM is a powerful tool for modeling landscape evolution and sediment transport, it may not be able to capture all of the complexities and nuances of agricultural land management (Böhner, J., & Anton, 2019). For example, the use of cover crops, which are known to be effective in reducing erosion and nutrient transport, was not explicitly modeled in our simulation. However, there might be a third, possible explanation. Namely in case of loose sediments as a kind of base rock under a specific soil, from geological point of view it's not always evident to define thickness of the soil profile, the regolith, and the underlying loose sediments (e.g. clay, sand, gravel).

It is possible that increasing the study area to a larger catchment may yield more reasonable results or outputs from the SaLEM model. The accuracy and reliability of the model's outputs are affected by several factors, including the size of the study area, the quality of the input data, and the assumptions made in the model (Böhner, J., & Anton, 2019). By increasing the study area, we may be able to capture more of the natural variability of the terrain, which could improve the accuracy of the model's outputs. However, it is important to note that increasing the study area may also require more detailed and comprehensive input data, such as higher-resolution topographic data and more extensive soil and geological information. This can be time-consuming and resource-intensive, and may also increase the complexity of the model. Therefore, it's important to carefully consider the trade-offs between increasing the study area and the resources required to do so such as number of soil samples for model validation, and to evaluate the potential benefits and limitations of the SaLEM model for the specific research question and study area.

6 Conclusion

The results of our soil analysis and SaLEM modeling provide valuable insights into the landscape evolution and soil characteristics of the study area. While the SaLEM model can help to simulate the topographic changes and sediment transport over time, it should be used with caution and validated with ground-truth data such as our soil analysis results. The discrepancy between the expected soil composition and the SaLEM model output suggests that the model's input parameters or assumptions about soil erosion processes may need to be revisited, especially in such a small scale. Moreover, the unexpected finding of a relatively small change in the thickness of the regolith layer coming from the SaLEM model highlights the need for further investigations to better understand the geological processes and history of the study area. Increasing the size of the study area may improve the accuracy of the SaLEM model's outputs, but this may also require more detailed and comprehensive input data, which can be time-consuming and resource-intensive. Therefore, the trade-offs between increasing the size of the study area and the resources required to fulfill a landscape evolution analyses of that should be carefully considered. Overall, our study provides important information that can help designing erosion control measures and soil management practices in the study field, and recommends avenues for future research to explore the link between $CaCO_3$ content and landscape evolution in the study area.

7 Summary

This research examines soil properties and topographic changes in an agricultural field in Hungary's Gödöllő region. The study utilized soil analysis and the SaLEM landscape evolution model to analyze the field's characteristics. The soil analysis revealed mostly sandy loam soils with varying calcium carbonate contents, indicating some higher potential for erosion in some areas. Although the SaLEM model provided useful insights into landscape evolution, caution is advised in usage of it due to some unexpected soil composition. Further investigation is required to comprehend the geological processes and history of the area, as the experienced thin regolith layer was unexpected. Expanding the study area and obtaining more comprehensive input data may yield more reliable results from the SaLEM model. The research concludes that the variability in soil properties emphasizes the importance of developing erosion control measures, and future research should investigate the connection between calcium carbonate content and landscape evolution in more depth at the research site.

Acknowledgements

I would like to take this opportunity to thank my great supervisors István Waltner, Ágota Horel and Gábor Halupka.

Also I would like to thank my professor János Grósz.

My research is funded by The Food and Agriculture Organization of the United Nations (FAO) and the Hungarian Ministry of Agriculture, which I would like thank for their support.

In addition, I would like to thank the Institute for Soil Sciences, Centre for Agricultural Research where I was able to conduct my analysis.

I would also like to thank my family, my wife and my daughter for their spiritual support and constant help.

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Appendices

Table 1. Particle size distribution and $CaCO_3$ content for selected samples of Catena 1.

Particle size distribution			$CaCO_3$
Sand	Silt	Clay	
2-0.05 mm (%)	0.05-0.002 mm (%)	<0.002 mm (%)	%
82.06	9.95	7.99	0.0
73.90	13.36	12.74	0.0
72.12	13.50	14.37	0.0
80.21	11.97	7.82	0.0
64.16	15.55	20.29	0.0
74.75	19.32	5.93	16.2
67.44	25.35	7.22	20.51
72.71	18.05	9.24	15.09
71.67	14.71	13.62	0.00
47.35	41.21	11.43	44.29
72.99	20.93	6.07	15.26
73.02	11.46	15.51	0.00
91.81	6.46	1.73	7.71
78.87	16.68	4.45	27.23
86.18	11.38	2.44	19.36
90.02	8.47	1.50	15.58
90.35	6.80	2.85	0.70
91.33	6.09	2.59	1.15

Table 2. Particle size distribution and $CaCO_3$ content for selected samples of Catena 2.

Particle size distribution			$CaCO_3$
Sand	Silt	Clay	
2-0.05 mm (%)	0.05-0,002 mm (%)	<0.002 mm (%)	%
80.60	12.72	6.68	0.0
85.41	10.67	3.91	13.66

Table 3. Particle size distribution and $CaCO_3$ content for selected samples of Catena 3.

Particle size distribution			$CaCO_3$
Sand	Silt	Clay	
2-0.05 mm (%)	0.05-0.002 mm (%)	<0.002 mm (%)	%
67.72	14.51	17.77	0.0
74.81	15.42	9.76	0.0
68.37	23.80	7.84	30.8
84.81	12.34	2.86	16.07
42.89	50.73	6.38	59.45
74.01	11.75	14.24	0.32
90.40	8.00	1.60	17.84
74.41	14.02	11.57	0.24
76.08	12.42	11.51	0.00
50.83	36.17	13.00	20.89
78.32	16.20	5.47	17.84
87.04	8.89	4.07	14.46
89.02	7.57	3.41	13.02

SUPERVISOR'S DECLARATION

As a supervisor of Abdelalim Mohamed Saad (Student's name) A5K2WO (Student's NEPTUN ID), I here declare that the master's thesis has been reviewed by me, the student was informed about the requirements of literary sources management and its legal and ethical rules.

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Signed below, **Abdelalim Mohamed Saad**, student of the Szent István Campus of the Hungarian University of Agriculture and Life Science, at the BSc/**MSc of Agricultural Water Management Engineering** declare that the present Thesis is my own work and I have used the cited and quoted literature in accordance with the relevant legal and ethical rules. I understand that the one-page-summary of my thesis will be uploaded on the website of the Campus/Institute/Course and my Thesis will be available at the Host Department/Institute and in the repository of the University in accordance with the relevant legal and ethical rules.

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