Remote prediction of soil types

A working methodology to predict Unified Soil Classification System (USCS) classes based on total geological history

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Remote prediction of soil types:

A working methodology to predict Unified Soil Classification System (USCS) classes based on total geological history

by

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Abstract

The Dutch Ministry of Defence is interested in developing a tool or workflow that can be used to remotely predict Unified Soil Classification System (USCS) classes of any area to aid mobility-related decisions. Therefore, this study was initiated by Cohere Consultants in collaboration with NEO, a Dutch remote sensing company and Utrecht University to create such tool or workflow. This MSc thesis provides a study in how the total geological history (TGH) approach as proposed by P. G. Fookes, Baynes, and Hutchinson (2000) can be used for predicting soil USCS classes. This is done by implementing the core concept of the TGH into a decision tree model that makes use of many modules, sub-modules and supporting modules to characterise the tectonic, geologic and geomorphological setting of a soil unit. The modules are divided depending if the unit dealt with is a soil, rock or part of a mountain, whereby the soil module incorporates 7 sub-modules that characterize alluvial, lacustrine, coastal, marsh, aeolian, evaporitic and glacial/periglacial environments. The rock and mountain modules, on the other hand, attempt to determine the presence and characteristics of residual soils using a weathering grade system and a table with the weathering products of 23 common rock types. The performance of the decision tree model was tested using two pilot studies in Konna, Mali and Zamora, Spain and one validation study in 's Hertogenbosch. For each study, a map with the predicted USCS soil classes was generated for the study area. The pilot studies explored the possibility of combining the predicted USCS soil maps with topographic wetness index (TWI) and slope angle maps to make a qualitative prediction on the trafficability of the area. The pilot studies showed that the TGH-based decision tree model has potential for being expanded into a tool for aiding military mobility predictions. Next, the validation study compared the predicted USCS map for 's Hertogenbosch to 5 ground truth data points collected by the Dutch Ministry of Defence. The validation study concluded that the decision tree was in general able to distinguish between coarse grained soils and fine grained soils, however struggled with correctly predicting if a soil has high or low plasticity. Finally, the Mali pilot study was able to compare USCS soil predictions made using the decision tree model to those made by a classification of hyperspectral data (made by Flipsen (2022)). Based on the comparison, there seems to be promise for future works to integrate the two methods to benefit from the detail achievable by the hyperspectral method and the qualitative soil descriptions using the TGH-based decision tree. Future recommendations include fine-tuning the decision tree model so that is is able to incorporate more detailed geologic or soil maps (currently has been trained with maps of about 1:500,000), incorporating remote sensing data to create soil units, quantifying uncertainty and possibly automatising the workflow.

Preface

The undertaking of this thesis has been a valuable 11-month journey for me which led me down a path with many doors and possible directions. And behind each and every one of these doors lied an ocean of knowledge of which I could only attempt to scratch the surface.

For giving me the opportunity to take on this challenge, I would like to thank my company supervisor, Siefko Slob, firstly for believing in me to take on this challenge and providing a friendly environment to work on this project at Cohere Consultants. I am ever so grateful for the brainstorming sessions and for sharing your wisdom not only about engineering geology but also about presentation skills. I would also like to thank Eliam for always making a cheerful environment in the office.

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I would also like to thank Guillaume, my second university supervisor who was always kind and practical in his advice. Guillaume also motivated me to think further about how this model could be improved in possible future studies and brought up many interesting topics of discussion.

This acknowledgements will not be complete without thanking the SBIR HYSTA team, for giving shape to this project. This includes Eva Stierman and Paul Veldhuijzen from NEO BV, Prof. dr. Steven de Jong from Utrecht University who also kindly agreed to be a part of my supervising committee and has given useful feedback throughout the journey. And of course, Tom Flipsen with who was very helpful with sharing insights and results from his work.

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Nomenclature

AMC Army Material Command

ASRIS Australian Soil Resource Information System

ASTM American Society for Testing and Materials

ATV All Terrain Vehicle

BRGM French Geological Survey

CCM Cross-country mobility

CI Cone Index

DEM Digital Elevation Model

DoD Department of Defence

DTM Digital Terrain Models

DTW Depth to Water

ERDC Engineer Research and Development Center

ESA European Space Agency

ESD European Soil Database

FAO Food and Agriculture Organization

FEM Finite Element Model

GIS Geographic Information System

GMBA Global Mountain Biodiversity Assessment

HWSD Harmonized World Soil Database

IGME Geological and Mining Institute of Spain

ISRIC International Soil Reference and Information Centre

ITAcyl The Agriculture Technology Institute

LL Liquid Limit

LNEG Portuguese National Laboratory of Energy and Petroleum

MAGNA National Geologic Map

MGRS Military Grid Reference System

MPM Material Point Method

NATO North Atlantic Treaty Organization

NG-NRMM Next Generation NATO Reference Mobility Model

NRMM NATO Reference Mobility Model

NSDB National Soil Database of Canada

PI Plasticity Index

RADR Rapid Airfield Damage Recovery

RSG Reference Soil Groups

SOTER Soil and Terrain Database

SPH Smoother Particle Hydrodynamics

SRTM Shuttle Radar Topography Mission

SSURGO Soil Survey Geogrpahic Database

TGH Total Geologic History

TWI Terrain Wetness Index

USCS Unified Soil Classification System

USDA U.S. Department of Agriculture

VCI Vehicle Cone Index

WWI World War I

WWII World War II

WRB World Reference Base

1 | Introduction

The United States Department of the Army (2020) field manual defines mobility as the ability of military forces to move from place to place while being able to fulfil their primary objective. This includes the transportation of military personnel, weaponry and materials through various terrain conditions. As militaries often traverse off-road terrain, the mobility of their vehicles is dependent on factors such as the topography, soil type, local weather and other ground conditions. In terms of military mobility, problematic ground conditions include extremely sticky soils, soils with low bearing capacity, highly steep or rugged terrains as well as the presence of huge boulders. Problematic soils combined with unfavourable weather conditions can lead to unwanted complications to the progress of the military mission. For example, traversing an area with high plasticity clay during the wet season is extremely difficult as the soil tends to clump and get stuck between tyre grooves, leading to loss of traction. This can lead to the vehicles becoming lodged in the mud, which then costs time and money to remobilize, in turn affecting the success rate of the mission and creating difficult scenarios in an emergency situation. Hence, possessing a good understanding of the local ground conditions is vital for a successful mission.

Currently, the North Atlantic Treaty Organization (NATO) member countries use simulation programs such as the NATO Reference Mobility Model (NRMM) to assess ground vehicle mobility (Bradbury et al., 2011). To use the empirical model of the NRMM, it is important to know local soil types in terms of their Unified Soil Classification System (USCS) classes. This brings forth a problem for missions abroad. The current method for determining soil USCS classes based on the ASTM requires in-situ and lab tests to be carried out on the soil samples however, the time pressure of military missions do not allow for such tests to be carried out. Thus, the Dutch Ministry of Defence is specifically interested in developing tools that can be used remotely to estimate the most likely USCS class at any given location.

At present, USCS soil maps are unavailable for most parts of the world, or if they are available then they are not open to the public on the internet. However, there is a lot of data describing global geology, which can be used as a basis for understanding the factors at play in the formation of soil. In his book – Factors of Soil Formation, Hans Jenny

(1983) suggests a "functional relationship" between soil properties and their conditioning factors whereby a soil is a function of its climate, organisms that live in or via it, topography, parent material and time. Therefore, by understanding the factors at play in the formation of a soil, we should be able to predict its soil properties, which can then be linked to its USCS class. If successful, this approach can be used by the military as a way to leverage all the available soil, geologic and environmental data to make a prediction of the expected soil conditions in any given area. Thus, further supporting in-situ and laboratory soil tests.

By taking inspiration from the field of engineering geology, that for decades has been using the understanding of local geology to predict geo-hazards and geotechnical issues expected in a project site, we can use our knowledge of geology and the environment to understand the soil forming processes and in-turn predict the most probable soil cover type. This is where the Total Geological History (TGH) approach enters the picture. The TGH approach is a methodology proposed by P. G. Fookes et al. (2000) that incorporates a systematic study of the tectonic, geological and geomorphological characteristics of an area to predict the expected geo-hazards. The TGH methodology uses a combination of 3D models with example case studies to build a picture of the different possible settings. In this thesis, I create a methodology inspired by the TGH to predict the most likely soil USCS classes.

I believe that the total geological history of an area can be reconstructed using publicly available maps and geologic data. What is important here is how the various sources of information available are combined and what necessary steps should be taken to allow the soil USCS classes to be predicted. Furthermore, it is also beneficial to streamline this process into a reproducible model that can, in the future, be integrated with GIS programs as an automated tool for predicting soil USCS classes. The goal of this study is to produce a framework for such a tool.

2 | Research outline

2.1 Context

As mentioned in the introduction, the motivation for this research comes from the interest of the Dutch Ministry of Defence in being able to predict Unified Soil Classification System (USCS) soil classes for mobility simulations. As a response to this, an ongoing project is being carried out by Cohere Consultants in collaboration with NEO, a Dutch remote sensing company, and Utrecht University to create a tool or workflow that can be used by the Ministry of Defence to determine the USCS soil classes at any given location. As this project is still in its preliminary stage, the tools and workflows created are still proof of concept for a final product.

Under the supervision of NEO, Tom Flipsen, a master's student from the University of Utrecht made a study that uses the reflectance profiles of hyperspectral remote sensing data to classify soil into USCS classes. He also used satellite data and interpolation techniques to devise moisture and heat maps which can provide additional information about the soil in the chosen pilot study area.

At the same time, this study, under the supervision of Cohere Consultants and the Delft University of Technology, takes a more knowledge-based approach to determining soil USCS classes. The goal of this study is to take inspiration from the Total Geological History (TGH) approach in order to create a workflow that can make use of information available on the internet to predict the expected USCS soil class at any location.

These two methods, when used together provide a qualitative and quantitative prediction tool for USCS soil classes.

2.2 Research aim

From a scientific perspective, we are interested in knowing whether the TGH approach can be linked to what we know about how soils are formed, for example based on the soil forming factors by Jenny (1983), such that it is possible to predict the type and characteristics of the soil in an area of interest. This leads to the overarching hypothesis that will be tested out during the course of this project: with the TGH, it is possible to predict USCS soil classes.

While all the efforts made during this research must have some contribution towards the overarching hypothesis, the research questions break down the problem into smaller, quantifiable portions. The research questions investigated during the course of this thesis are:

1. How can the methodology of the TGH be implemented to derive USCS classes from multiple data sources?
2. Is it possible to have a generic classification system for the entire world?
3. Using the TGH approach, to what level of detail are we able to classify the terrain in terms of USCS soil classes?
4. Are the results of the TGH approach able to complement those of the hyperspectral method?

2.3 Scope and limitations

The scope of this research is to make a workflow to generate a USCS map of an area, that can be automated in the future. In order to achieve this, this study will present the steps needed to reach the predicted USCS classes in an organised an coherent manner. Furthermore, this study will also provide the user with the data sources used so that the final maps made within this study can be reproduced.

In order to ensure that majority of the efforts during the time frame of this thesis were focused on the main goals, some constraints were put into place. One of the decisions made was to use the total geological history approach as the basis for the workflow. This meant that the method would be knowledge-based, and other possible methods for classifying soils into their respective USCS classes such as empirical or machine learning methods were not considered.

The next constraint relates to the depth of soil that we are interested in. In the context of military mobility, most mobility calculations are made for the layer of soil called the critical layer. The U.S. Military Field Manual FM 5-430-00-1 (Department of the Army, 1994) describes the critical layer as the depth of soil which is able to support the weight of a specific vehicle. The depth of this layer ranges from 3 to 15 inches depending on the soil type, soil strength profile, vehicle type and weight as well as the number of passes the vehicle makes on the soil. More information about the critical layer is given in Appendix A. Based on the US Field Manual, the depth of soil the military is interested in ranges from 0.25 to 0.5 m. However, this study is not only interested in determining if a soil is able to support the weight of a vehicle but also in recognising other difficult ground conditions that might affect mobility such as collapsing of low density soils or the presence of many boulders. Therefore, the depth of soil of interest to this study is extended to the top 1 to 2 m of soil.

On the same note of military mobility, it should be mentioned that the type of military vehicles for which mobility is being studied are those which can only traverse on land. The military vehicles in this study are assumed to be non-amphibious and therefore are unable to traverse through water-logged areas.

2.4 Methodology and report structure

In order to answer the research questions, this study starts with a literature research to understand how the military makes decisions relating to mobility, the USCS soil classification system as well as the methodology of the TGH approach. Chapter 3 provides the reader with the relevant background information covering the aforementioned topics, as well as a short description of previous works that have been done using the TGH approach. Thus, laying the foundation for this study.

The next step is to make a framework that could be used to predict the USCS classes in any given location. Chapter 4 introduces the produced tool in the form of a decision tree which is made up of several modules and sub-modules. The next step was to test out and improve the decision tree model using pilot studies. Chapters 5 and 6 are pilot study chapters whereby Chapter 5 describes the first pilot study that was carried out on a town called Konna in Mali. Konna lies on the north-eastern border of the Niger river delta; a location which has a few different soil profiles within a small area. The second pilot study, discussed in Chapter 6, shows a slightly different landscape which is highly cultivated and has soil moisture data. This pilot study was carried out in the vicinity of Zamora in north-western Spain.

Through the first pilot study, I was able to explore the types of data that were easily available on the internet. The main question here was how to deal with the various data in an organised manner. Therefore, several methods were tried whereby the decision tree method showed a lot of promise but a second pilot study had to be included to give more perspective to the final framework. Through the second pilot study, the decision tree workflow was further refined and was expanded to accommodate different climate zones. Once the decision tree was made, it was then tested once again using the same two pilot studies.

A third and final study was made of a region in the vicinity of 's Hertogenbosch in the Netherlands and is presented in Chapter 7. As the Netherlands is well documented, as well as a USCS soil map and ground truth data is available for this location, this final study serves as a validation study for the presented methodology. Through this study, an evaluation was made on the progress of the tool and places for future improvements were identified.

Thereafter, Chapter 8 discusses the relevance of the model as well as how it adds to the existing work in the field. Finally, the study is concluded in Chapter 9 and some recommendations for future work is given.

3 | Theoretical background

Before a suitable methodology for remotely predicting Unified Soil Classification System (USCS) classes can be proposed, it is first important to understand all the different elements that play a role within this study as well as to get an idea of the progress that has already made within this field of study. This chapter provides the reader with the relevant information needed to understand the work carried out in this thesis, beginning with the way the military assesses mobility and the role of soil information in doing so. Section 3.1 describes the problem that a military may face with respect to mobility and gives examples of how the German and American armies approached mobility starting from World War I, and how this approach evolved over time. Next, as it is known that the Dutch Ministry of Defence uses the Unified Soil Classification System (USCS) as an input in their mobility simulations, Section 3.2 describes the USCS classes and how to tell them apart. Lastly, a comprehensive description of the total geological history (TGH) approach is given in Section 3.3 as this forms the cornerstone of the methodology that will be implemented during this research.

3.1 Mobility of military vehicles

As mentioned in the introduction, the United States Department of the Army (2020) field manual defines mobility as the capability of a military force to move from place to place with the aim of fulfilling their primary mission, whereby any obstacle that might hinder the military vehicle can result in mission failure, additional costs and risk to personnel and vehicle. A slightly different outlook on mobility is given by the Dutch Ministry of Defence (2021) National Plan for Military Mobility as it describes mobility to be a broad term that encompasses the domains of movement and transportation, logistic support and facilitating conditions such as infrastructure as well rules and regulations. These definitions bring to light the fact that mobility in a military context is a tool that can be used to achieve a military goal whereby good mobility does not only enable transportation but also enhances the safety of an army.

Starting with World War I, when the British Army introduced armoured vehicles to overcome the stalemate that trench warfare presented, the potential of using motorized vehicles on the battlefield was recognised. However, during this time tanks did not always work well as they were often bogged down by muddy and churned-up ground. When that was not the case, their slow pace made them an easy target for enemy artillery fire.(Canadian War Museum, 2008)

During World War II, military vehicles had improved a great deal such that they became a significant part of the ground forces. With this development, trafficability forecasts for an area of interest became an important factor in military planning. A paper published by the Geological Society of London called *"One hundred years of cross-country mobility prediction in Germany"* (Malm, 2018) describes how the German military geologists and engineers prepared cross-country mobility (CCM) maps for this purpose. The CCM maps were made using soil and geological maps aided by aerial photographs and topographical maps (an example map is shown in Figure 3.1). In ideal cases, a physical ground study was made at the end to verify the mobility recommendation. The German CCM maps from WWII were made under an immense time pressure and were subjective to the judgement of the military geologist preparing the map. Therefore, those CCM maps were not to be taken as absolute truths, but simply as general maps which represent the average condition of the terrain.

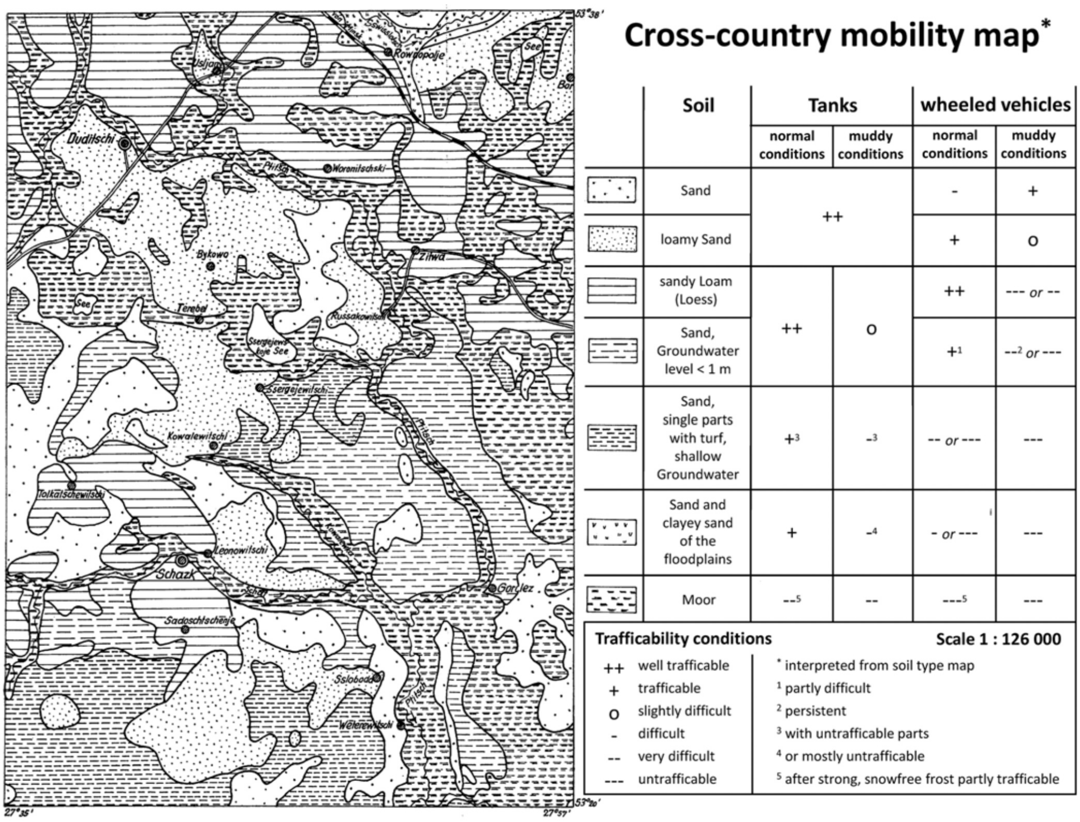


Figure 3.1: Cross-country mobility (CCM) map made by German army during WWII, based on a 1:126,000 scale soil maps of Belarus (Malm, 2018).

It was only after WWII that a scientific and systematic approach was developed for making trafficability predictions. The basis of this approach was to use in-situ trafficability tests such as soil cone index (CI) and vehicle cone index (VCI) whereby if the CI value of the soil is greater than the vehicle-specific VCI value, then the soil is considered to be trafficable. The CI of a soil represents its shear strength, measured by pushing a cone penetrometer in to the soil at a rate of 3cm/s such that the force per unit cone base area is the CI, whereas the VCI is a vehicle specific mobility metric that represents the minimum strength of a soil in the critical layer, that permits the given vehicle to successfully make a number of passes without being immobilised. The VCI value is calculated using parameters that represent the dimension and weight of the vehicle (Wong, 2022). It should be mentioned that the depth of the critical layer of soil ranges from 3 to 15 inches (<0.5 m), depending on the soil type, soil strength profile, vehicle type and number of passes made on the soil (Department of the Army, 1994). In short, the military is mostly interested in the top 0.5 m of soil. A table showing the relationship between the soil type, vehicle weight and critical layer depth can be found in Appendix A.

The CI/VCI method was developed by the U.S. Army Corps of Engineers and was later shared with the North Atlantic Treaty Organisation (NATO) countries. The research carried out for the CI/VCI method eventually led to the foundation of the NATO Reference Mobility Model (NRMM), which is a computer-based model that takes into account all of the important trafficability factors (Malm, 2018). Nowadays, most countries are using simulation tools such as the NRMM for in-depth mobility analyses meanwhile simpler charts and look-up tables are being used for quick decision making.

3.1.1 NATO Reference Mobility Model (NRMM)

Currently, the NRMM is the only terrain traversability simulation tool of its kind to be recognised by NATO (Wasfy & Jayakumar, 2021). The NRMM was developed in the 1970s under the direction of the United States Army Material Command (AMC) (Haley, Jurkat, & Brady Jr, 1979) with the goal of developing an analytical procedure for quantitatively assessing the performance of a vehicle under specified conditions. The NRMM accomplishes its goal by introducing steady-state[1] empirical formulas which were made using data collected from military vehicles between 1960 to 1980. These empirical formulas were embedded within the *pre-processing* and *main* modules which required a broad and detailed list of input data in order to generate the output result.

The input data required by the NRMM can be categorised into four types: scenario data, terrain data, vehicle input and to a lesser degree the driver or operator actions. The scenario data usually entails the visibility conditions such as the amount of daylight, the

[1] dynamic processes were excluded

weather conditions as well as the presence of snow or ice. Next, the terrain data can be divided into on-road and off-road conditions whereby the off-road conditions account for the geomorphological features of the land, presence of obstacles as well as soil properties such as soil class, moisture content, density and cone index (CI) values among others. Finally, the vehicle data covers the dimensions and capabilities of the specific vehicle while the driver input takes into account the human reaction aspect of mobility. The aforementioned datasets are put through the empirical models of the NRMM, which in turn will output trafficability (go/no-go) maps, Speed-Made-Good data fields and motive efficiency data fields. The 'Speed-Made-Good' category describes the maximum speed a vehicle can traverse a given terrain going upslope, downslope and cross-slope whereas the motive efficiency data fields give a measure for the energy efficiency of a certain vehicle on a given terrain (Bradbury et al., 2011).

The drawback of using a tool that is based on empirical models is that the results are not always translatable to newer models of military vehicles, especially with the recent development of larger vehicles with oversized tires or tracks, small unmanned robotic vehicles, new suspension system designs and vehicle control technologies such as anti-lock braking (ABS). Therefore, from 2014 to 2015, the development of a Next-generation NRMM (NG-NRMM) was explored. The NG-NRMM overcomes the deficiencies of the NRMM by proposing 3D dynamic soil models capable of predicting the soil's reaction forces and is therefore not dependent on the studied vehicle type (Wasfy & Jayakumar, 2021). At the moment, the NG-NRMM only exists in the form of requirements and guidelines (NATO-S&T, 2019) that software vendors may use to develop compliant tools. Therefore, the NRMM is still being used by the alliance to predict the trafficability of military vehicles.

3.1.2 Terrain information used by the military

As touched upon in the previous sections, military mobility can be predicted to different levels of detail using simulation tools such as the NRMM, interpretations of aerial photographs and look-up tables giving a go, no-go or slow-go advice for different vehicles on different soil types. Each method takes into account the ability of the terrain to accommodate vehicle mobility. Malm (2018) categorises the terrain properties that have to be accounted for into static and dynamic parameters. The static parameters are slope, land cover, soil type and surface roughness which usually remain constant during the time frame of the military operation. Meanwhile, the dynamic parameters are related to the hydrology and climate of an area and are expected to change with time.

Looking closer at the static parameters, first, the slope of the terrain should be less than the maximum allowable value of both the tilt and the climb angle of the chosen vehicle. Thus, the acceptable slope depends on the type of vehicle being used. Next, in terms of land cover, the land could be either built up or natural. In places where civilisation has been built up, most of the area is untrafficable due to the presence of buildings. In natural areas, however, other aspects have to be taken into account. For example, the type of vegetation cover and the presence of water bodies. Forests are a tricky land cover as most modern military vehicles are only capable of crossing it if the tree spacing is >3m and the tree diameter is <30cm, whereas water bodies are considered to be obstacles as the military vehicles are assumed to be only for land.

If the vegetation does not pose a problem, then the soil type should be checked. The type of soil plays a large role in mobility as the soil should not be too soft or sticky as that can cause the vehicle to become bogged down and immobilised. This is where the Unified Soil Classification System (USCS) comes into the picture. Most militaries choose to use the USCS soil classes which categorise soils based on their grain size, organic content, liquid limit and soil plasticity. These characteristics of the soil determine how it will react when loaded under different moisture conditions. Thus, look-up tables can be made for trafficability recommendations based on USCS classes. An example of such a table is shown in Figure 3.2 which is taken from the Dutch Military Fieldbook (Koninklijke Landmacht, 2012) and shows the travel recommendation for a vehicle based on its VCI value with the soil USCS class and season for an area with a high terrain and wet season (groundwater level is deeper than 120 cm). A similar chart by the U.S. Army is shown in Appendix B.3.

USCS \ VCI	0.07	0.13	0.20	0.26	0.32	0.39	0.45	0.52	0.58	0.65	0.71	0.78	0.84	0.91	0.97	1.04	1.10	1.17	1.23
GW	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++
GP	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++
SW	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++
SP	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	+/-
GM	++	++	++	++	++	++	++	++	++	++	++	++	+	+	+	+	+	-	-
CH	++	++	++	++	++	++	++	++	++	++	++	++	++	++	+	+/-	-	-/–	–
SM	++	++	++	++	++	++	++	++	++	++	+	+	+/-	-	-	-	-	-	-
GC	++	++	++	++	++	++	++	++	++	+	+	+/-	-	-	-	-	-/–	–	–
SC	++	++	++	++	++	++	++	+	+	+	+/-	-	–	–	–	–	–	–	–
MH	++	++	++	++	++	++	++	+	+	-	-	-	–	–	–	–	–	–	–
CL	++	++	++	++	++	++	++	+	+	-	-	-	–	–	–	–	–	–	–
ML	++	++	++	++	++	++	+	-	-	-	-/–	–	–	–	–	–	–	–	–
OL	NO DATA																		
OH	NO DATA																		
PT	NO DATA																		

Figure 3.2: Table used by the Dutch military to determine trafficability based on VCI and USCS class, depending on terrain type, season and groundwater table depth. This table is made for an area with a high terrain, experiencing a wet season whereby the groundwater level is deeper than 120 cm.

The final static parameter accounted for is the surface roughness of a terrain. Features that can obstruct mobility are the presence of boulders and small sand dunes, however, this parameter is said to be difficult to determine without a local inspection.

Next, the dynamic parameters are parameters that are expected to change within the time frame taken into consideration. These parameters are precipitation, transpiration and evaporation as well as groundwater recharge. All of these parameters are affected by the local weather as it has a direct impact on the soil's moisture content (Malm, 2018).

By understanding the terrain conditions at the location of interest, the military is able to make an informed choice of the vehicle type to be dispatched for a specific mission, as well as plan the safest route. Most militaries simplify this problem by determining the USCS class of the topsoil at the location of interest, which can then be compared to simple charts that show the suitability of different vehicle tyres or tracks. As a result, the Dutch Ministry of Defence finds it important to be able to predict the USCS class of any given location in the world.

3.1.3 Solution of the U.S. Army

Akin to the Dutch Ministry of Defence, the U.S. Army Corps of Engineering faced a similar problem when it came to using the NRMM program. This was due to the limited knowledge of the USCS cover for any location in the world. As a response, the Rapid Airfield Damage Recovery (RADR) program looked into ways to create a database which could be used by the U.S. army (Zakikhani, Gidley, & Tingle, 2017).

Although the goal of the RADR program was similar to this project, the RADR program took a different approach; which was to compile information from various data sources and soil maps to generate a database. The data sources used by the RADR program were categorised into 3 tiers based on the quality and confidence level in the data. Tier 1 data sources contain the USCS classes of soils that have been measured and collected by the U.S. Department of Defense (DoD). This data source is the most trusted of the three tiers and is only available in their army database. Tier 2 data also has USCS soil classes, however this data has been collected from non-DoD sources such as other nations' reports, websites and published articles. The compilation for Tier 2 data is also found on the U.S. army database. Finally, Tier 3 data sources were converted from non-USCS data into USCS soil classes using scientific assumptions and formulations. Tier 3 data sources are the only ones for which the data is found openly (Zakikhani et al., 2017).

Data sources for Tier 3 data include the U.S. Army Engineer Research and Development Center (ERDC), U.S. Soil Survey Geographic Database (SSURGO), the National Soil Database of Canada (NSDB), Australian Soil Resource Information System (ASRIS) and the International Soil Reference and Communication Centre (ISRIC). Among the Tier 3 data sources, the ISRIC organisation has made a worldwide soil map to the scale of 1:5,000,000 under the Harmonized World Soil Database (HWSD) initiative. The HWSD is a raster database that has been made in 2012 with 15, 000 different soil mapping units from the Soil and Terrain database (SOTER), European Soil Database (ESD), Soil Map of China and Global Soil Profile Data (WISE). By using a standardised structure, the HWSD is able to combine selected soil parameters from multiple sources into a singular raster map.

For the purpose of this thesis, the main soil parameter of interest is the U.S. Department of Agriculture (USDA) soil textural classes because there are studies that show correlation between the USDA and USCS soil classes. The USDA has identified 12 soil texture classes based on the percentages of sand, silt and clay which are determined by the size of the soil particles. Therefore, converting USDA to USCS soil classes without knowing the Atterberg limit of a soil requires some assumptions to be made regarding the soil characteristics and mineralogy. Although there is no absolute translation from the USDA textural system to an equivalent USCS class, Zakikhani et al. (2017) presents four correlation methods from USDA to USCS soil classes, among which the method proposed by García-Gaines and Frankenstein (2015) is chosen to be used in this thesis as it is the only method that correlates USDA textural classes to its respective *'Most Probable'* and *'Possible'* USCS classes. The conversion table for this method is shown in Appendix B.4.

3.2 The Unified Soil Classification System (USCS)

The USCS is a system for identifying soils based on their textural and plasticity qualities, created with the aim of characterising how they would perform as engineering construction materials (Department of the Army, 2012). The USCS soil classification system has its origins in the 1948 Airfield Classification System which was created by Dr Arthur Casagrande upon being commissioned by the US military to be used in the construction of its military airfields (Waterways Experiment Station, 1953).

In the early stages of Casagrande's work, he realised that the existing soil classification systems were not made with the engineering capabilities of the soil in mind. For example, soil classification systems commonly used in the field of agriculture were based on their chemical and qualitative properties that said nothing about their mechanical behaviour. With this in mind, Casagrande's Airfield Classification System focused on characterising soils based on their physical properties that would also affect their engineering capabilities. This method of classifying soils was deemed to be useful and had been expanded and modified so that it would not only be applicable to airfields but also to embankments, foundations and other engineering features. As a result, in 1952, this soil classification method was adopted by the U.S. Bureau of Reclamation and the Corps of Engineers as the Unified Soil Classification System (USCS) (Kelechava, 2020).

The wide acceptance of the USCS led to its standardization into the American Society for Testing and Materials (ASTM) under the code ASTM D2487. In 1983, the ASTM D2487 underwent major changes to refine and cover the gaps in the classification creating a standard close to the ASTM D2487-17 used today (Selig & Howard, 1984). The ASTM includes the official definitions of each soil class as well as the specific procedures for identifying the USCS soil group based on laboratory tests (Kelechava, 2020). At the same time, militaries around the world have developed techniques to determine the soil USCS class by visual and simple field tests.

Table B.1 in Appendix B.1 shows how the American army classifies USCS classes on the field.

3.2.1 USCS classes

The USCS classifies a soil based on its particle size characteristics, liquid limit, and plasticity index (Kelechava, 2020) such that each soil gets a two-letter symbol and a corresponding name. Table 3.1 shows the letter symbols used in the USCS classification. The first letter in the class symbol represents the major soil division which consists of three categories: coarse-grained soils, fine-grained soils or highly organic soils.

Soil division		Soil modifier	
G	Gravel	**W**	Well graded
S	Sand	**P**	Poorly graded
M	Silt	**L**	Low plasticity
C	Clay	**H**	High plasticity
O	Organic		
Pt	Peat		

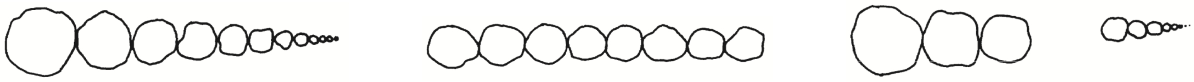
Table 3.1: Letter symbols used in the USCS classification.

The ASTM D2487-17 standard provides a guideline for tests to be carried out to determine the soil USCS class. The first test that has to carried out on a soil is sieving, in order to determine the grain sizes present in the soil. Before sieving can be carried out, the soils first have to be prepared. The ASTM D2487-17 states that: "The wet preparation method is the preferred method for cohesive soils that have never been dried out and for organic soils" (Howard, 1988). This step ensures that soils whose naturally occurring structure has colloids, can be maintained. Dry sieving is used for all other soil types. It is important to note that the process of sieving itself can interfere with the particle size of the soil. Therefore, when dealing with residual or partially lithified soils, the uncertainty in the actual grain size of the soil should be accounted for by denoting such a soil as a secondary soil. More details on how to deal with secondary soils are given in 3.2.1.

To distinguish between a coarse-grained and fine-grained soil, the ASTM standard requires the soil sample to be put through a No. 200 U.S. Standard Sieve (opening size of 75μm). If more than 50% of the soil remains on the sieve it belongs to the coarse-grained soil class, otherwise, it is a fine-grained soil. The highly organic soils are a special class that can be recognised by visual methods. It is also the only soil class to not get a soil modifier letter. From here on, more lab tests have to be carried out to further divide the coarse-grained soils into gravel (G) or sand (S), and the fine-grained soils into silt (M), clay (C) or organic (O). A full list of the USCS classes used in the NRMM is given in Appendix B.1.

Coarse-grained soils

Once a soil is determined to be coarse-grained, the coarse fraction is then put through the No.4 U.S. Standard Sieve (opening size 4.75mm). If more than 50% of the coarse fraction is left on the sieve, then it is classified as gravel (G), if not it is sand (S). Once the first letter of the soil class has been determined, the second letter acts as a modifier to further define the qualities of the specific soil. For coarse-grained soils, two types of modifiers can be used depending on the amount of fines present within the soil. If less than 5% of the soil passes through the No. 200 sieve, then the soil exhibits non-plastic behaviour. Thus, the behaviour of such a soil is dependent on the gradation which is determined from the shape of the grain size distribution curve. Figure 3.3 illustrates the difference between well graded and poorly graded soils.



(a) Well-graded soil. (b) Uniformly graded soil. (c) Gap graded soil.

Figure 3.3: Grain size distribution expected in well graded soils (3.3a) and poorly graded soils (3.3b and 3.3c). Image taken from the U.S. Department of the Army (2012) Technical Manual.

A well graded soil (W) has wide distribution of grain sizes and is defined as a soil which has a coefficient of uniformity, C_u (Equation 3.1) greater than 4 for gravels and greater than 6 for sands. For both gravel and sand, the well-graded soil must possess a coefficient of curvature, C_c (Equation 3.2) between 1 and 3. On the contrary, a poorly graded soil (P) can either have grains that are all of the same size or have two dominating grain sizes.

$$C_u = \frac{D_{60}}{D_{10}} \tag{3.1}$$

$$C_c = \frac{{D_{30}}^2}{D_{60} * D_{10}} \tag{3.2}$$

According to shear strength tests carried out by Badhon and Islam (2017), gap-graded soils tend to have the highest shear strengths, followed by well-graded soils and finally uniformly graded soils have the lowest shear strengths. Kumar, Ohri, and Bansal (2007) show that well-graded soils tend to also have higher bearing capacities than uniformly graded soils. The results of these studies indicate that poorly-graded soils are a higher risk for mobility compared to well-graded soils as they are more prone to collapsing and liquefaction.

The second type of modifier for a coarse-grained soil is used when more than 12% of the soil passes through the No. 200 sieve. For these soils, the mechanical properties are determined to a greater extent by the plasticity of its finer-grained fraction. The liquid limit (LL) and plasticity index (PI) of the fine-grained fraction is then tested and plotted on a plasticity chart as shown in Figure 3.4. If the soil plots below the A-line then it falls under the low plasticity group (M) whereas a soil that plots above the A-line belongs to the high-plasticity group (C).

In some cases, the soil might fit the classification of more than one modifier class. These soils are termed *borderline soils* and they can be given dual symbols. For example, when a well graded gravel based soil is put through a No. 200 sieve, and between 5% to 12%

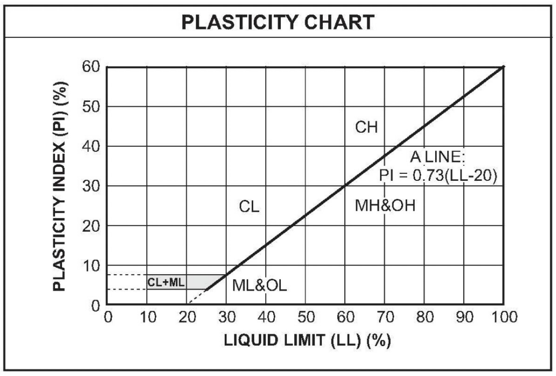


Figure 3.4: Plasticity chart showing the A-line, taken from a document published by the California Department of Transportation (CALTRANS, n.d.).

of the soil passes through, the soil can then be classified as either GW-GM or GW-GC based on the plasticity of the fines fraction (Department of the Army, 2012).

Fine-grained soils

A fine-grained soil can be further divided into the low-plasticity group (M), high-plasticity group (C) and organic group (O). The distinction between the M and C group is made using the plasticity chart as described in the previous subsection. For determining the modifier, the LL value is used. As can be seen in Figure 3.4, if a soil has an LL value less than 50, it can be considered a low compressibility soil (L) whereas if the LL value is more than 50, the soil is said to be highly compressible (H). If organic matter is present in the soil, then the soil can be categorised as OL or OH which fall into the same zone in the plasticity chart as ML and MH respectively. Lastly, if the fine grained-soil is on the boundary of two classes or is in the shaded region in the plasticity chart, it is considered a borderline class such as CL-ML.

In the USCS, ML, CL and OL are the low-plasticity soil groups, whereas MH, CH and OH are the high-plasticity soil groups. The main clay minerals present in low-plasticity soils tend to be kaolinite and sometimes illite, whereas high-plasticity soils tend to contain a larger percentage of smectite and montmorillonite. As a result of the different mineral composition, MH, CH and OH soils are stickier in nature than their lower-plasticity counterparts, and they often swell and compress easily with a change in load. Thus, these soils are the most difficult to traverse on when wet. However, when dry, the CH group exhibits the highest bearing capacity among the fine-grained soils (Department of the Army, 2012). Examples of CH soils are fat clays, volcanic clays and bentonite.

Highly organic soils

In order to recognise a highly organic soil, first a visual examination of the soil is carried out to determine if it has a fibrous texture comparable to that of peat, if so is given the symbol Pt. These soils usually have an LL in the order of a few hundred percent (Department of the Army, 2015) which causes these soils to be very sensitive and exhibit bog-like conditions which are hard to traverse (Yang & Dykes, 2006).

Special cases

Selig and Howard (1984) suggest that the presence of cobbles and/or boulders (particles greater than 75mm) is a special state that should be reflected in the name of the soil. For example, silty gravel with cobbles and/or boulders (GM). It should be noted that the military does not consider boulders larger than 600mm to be soils. Instead, these large boulders are called obstacles (Wasfy & Jayakumar, 2021).

Next, a special clause is mentioned in the ASTM D2487-17 with regards to residual or partially lithified soils. This is because when carrying out laboratory tests to classify such soils, the sieving process can change the gradation of the soil. Examples of soils that can be affected by the sieving process are residual soils, weathered shales as well as some weakly cemented soil such as hardpan, caliche and coquina soils. The ASTM D6913-04 Standard Test Method for Particle Size Distribution (Gradation) of Soils Using Sieve Analysis (2009) mentions that the particle size distribution for such soils may be inconsistent between and within laboratories. This means that, although the USCS soil classification can be used for friable soils, it may not always represent the in-situ conditions accurately. Therefore, to test such soils, the test method must be adapted and standardised such that each specimen would be processed in a similar manner. The adapted test method requires the material to first be processed into a soil by either grinding or slaking in water for 24 hours. The soil can then be classified as a secondary soil (Bureau of Reclamation, 1991).

When denoting a secondary classification, the group name and symbol must be in quotation marks to distinguish them from real soils. For example, processed gravel and cobbles can be called "Poorly graded gravel (GP)" Selig and Howard (1984).

3.2.2 The future of soil classes

Currently, the NRMM uses empirical relationships between USCS soil classes, soil moisture content and vehicle cone index (VCI) values to predict how well the soil can support a chosen vehicle.

The newer NG-NRMM has plans of introducing micro- and macro-scale models to visualise the soil as a 3D system. In the micro-scale model, each soil particle is modelled with its actual size and geometry along with the interaction forces within particles whereas the macro-scale model lumps the soil together as one block which can be modelled using either the Finite Element Method (FEM), Discrete Element Method (DEM), Smoothed Particles Hydrodynamics (SPH) or the Material Point Method (MPM). For the use of the micro-scale models, the soil properties of interest are the particle size, particle size distribution, chemical composition, particle shape and surface roughness, soil moisture content, compaction state as well as soil temperature. These soil properties go beyond the information contained within the USCS soil classes and would require extensive tests to be carried out. On the other hand, the macro-scale soil model mainly requires the soil type (based on particle size distribution and chemical composition), soil moisture content and soil temperature (Wasfy & Jayakumar, 2021). Thus, the NG-NRMM RTG-248 committee agreed to keep using the USCS soil classes in the macro-scale models of the NG-NRMM, based on the committee members' experience and the fact that the USCS has already been in use in the NRMM for last few decades (Balling et al., 2020).

At the same time, the NG-NRMM RTG-248 committee also proposed a future research task to develop a soil classification system that is catered towards the way the soil behaves mechanically. The aim of this research task would be to refine the division of soil type relating to grain size and Atterberg limits, as well as, incorporate the grain shape and detailed chemical composition in the soil classification system. Such a soil classification system will allow for better calibration of the macro-mechanical soil models, such that the response predicted by the simulation of the soil test closely matches the response observed in the actual test (Wasfy & Jayakumar, 2021).

For the military, this will mean more accurate predictions of how the vehicle will move on the terrain, which in turn will allow for better decisions to be made in terms of vehicle and tyre type as well as choosing the most energy efficient option for traversing the terrain.

3.3 The Total Geological History (TGH) approach

In the previous two sections, the importance for the military to be able to predict USCS classes at any given location was explored. This was followed by a detailed description of the USCS classes and attributes that were used to classify soils into their primary or secondary USCS classes. The physical and mechanical qualities of the soils that would segregate them into different classes such as grain size, liquid limit, plasticity index as well as organic content are all qualities which are affected by the origin process of those soils. By understanding the parent material and how it interacted with its environment, we should be able to predict some features of the soil that we see today.

Here is where the total geological history approach comes into the picture. For many years, the field of engineering geology has been trying to achieve a similar goal that is: by understanding the parent material and how it was affected by tectonic and environmental forces in the past, we can predict the risks and quality of material we deal with today. The essence of this understanding has been formalised by P. G. Fookes et al. (2000) into the total geological history (TGH) approach, as expressed by the quote below:

> *"The ground conditions at any site are a product of its total geological and geomorphological history which includes the stratigraphy, the structure, the former and current geomorphological processes and the past and present climactic conditions."*

The above mentioned quote describes the principle based on which the TGH anticipates the ground conditions at a site, which is similar to what this thesis sets out to achieve. However, it should be kept in mind that the TGH works for a different goal than predicting soil properties for military mobility purposes. The TGH mainly focuses on planning the site evaluation for a construction project, and therefore places a larger emphasis on recognising the risks inherent to the tectonic, geologic and geomorphologic environment of an area. Although risk identification is also important for military missions, the main goal of this study is to predict the mechanical properties of the top 1 to 2 m of a soil. Hence, this thesis sets out to adapt the principles of the TGH approach into a framework for predicting the soil properties of an area.

3.3.1 Methodology of the TGH approach

P. G. Fookes et al. (2000) describe how the TGH approach can be used as a part of the preliminary desk study to make a checklist of features to be anticipated on the field. The TGH accomplishes this by providing the user with general tectonic, geological and geomorphological models, whereby the user can choose any number of models that apply to the location. Based on these models, the user can then form a checklist of questions to be asked on-site. In order to choose the relevant models and subsequently understand them, the user is required to have an appreciation of the history and formation of the Earth, which can be obtained from a geologic map of the area as long as it contains information about the age and lithology.

Firstly, TGH characterises the general regional structure by the means of a global-scale tectonic model. These models are presented as two-dimensional sketch sections of the large-scale area. The tectonic model focuses on the faulting patterns as well as the heterogeneity of the land based on the concepts of plate tectonics. There are 10 tectonic models which can be chosen depending if the area is in the middle of a tectonic plate or at a diverging or converging plate boundary.

Secondly, the TGH guides the user to zoom into the local geological setting. The local geological setting is characterised by three-dimensional block models which encompass the rock-forming environments and the tectonic modifications to the stratigraphy. There are 17 possible geological models which can be chosen based on whether the area is of igneous, sedimentary or of metamorphic origin, or if a structural feature such as faulting or a folding system is present. The geological models give an idea of the possible geological features that can be expected in an area as well as the degree of heterogeneity that is commonly associated with a specific geological setting. Along with this, the TGH also mention the geohazards and geotechnical issues that can occur in each geological setting. This is useful for the military, as the TGH can bring attention to the possibility of encountering problematic soils such as quick clays, migrating sand dunes, collapsible loess and large cobbles and boulders to name a few. As for the prediction of soil classes, the geological models can aid in dividing the terrain into units that have similar geotechnical properties, which can be used to streamline the soil classification workflow.

Finally, the TGH urges the user to complete the picture of the site by choosing a suitable local-scale geomorphological model. Similar to the geological models, the geomorphological models are also presented as three-dimensional sketch block models. These models show the surface processes which have modified or are currently modifying the local geology. The TGH presents 8 possible geomorphological models which are to be chosen based on the current or recent past (Cenozoic) climate. By anticipating the climate and important surface processes in an area, the main factors at play in forming local soils can be predicted.

Once the relevant models have been chosen using the 2D sketch sections and 3D block models, questions about the site can be posed based on the list of site characteristics given. Furthermore, the TGH also supplies the reader with 31 case studies that are mostly about failures that occurred due to a lack of understanding of how the components within an environment interact. The case studies are classified based on the relevant tectonic, geologic or geomorphological setting.

As the TGH approach became accepted and widely known, other engineering geologists adopted and extended the models beyond the ones defined by Fookes. For example, engineering geologists have made block models to further illustrate different river regimes such as the braided, anastomosing and meandering river regimes. These 3D models show the various elements present in a river regimes which can lead to different soil types expected at different parts of the river. These block models are further described in 4.2.1.

Limitations of the TGH approach

Although the TGH approach is very useful for anticipating site conditions, there are some limitations to the TGH that should be kept in mind when using it. Firstly, the TGH requires the user to have a basic appreciation for geology in order to be able to choose suitable models for an area. Secondly, the conclusions made in the TGH were not based on any statistical evaluation of the causes (P. G. Fookes et al., 2000). Therefore, it is difficult to say the probability of a certain hazard manifesting. Thirdly, the TGH is also unable to pinpoint where exactly in an area a certain feature or condition is expected, only that it is expected. Finally, the TGH does not account for hazards or the evolution of a landform due to human action.

3.3.2 The TGH method used in other cases

Dambrink (2011) and Baynes, Fookes, and Kennedy (2005) are two papers that describe how the TGH approach can be integrated into projects within a geotechnical setting.

The first paper is a master thesis written by Roula Dambrink (2011) which incorporated the TGH approach in the making of geotechnical models for dredging projects. Her thesis was focused on the dredging of glacial till along the Finnish coast which is known to be difficult to work with due to the high variability in composition and strength properties. One problem commonly faced when dredging in glacial till is the occurrence of boulders of which it is important to know the content and size so that the right choice of dredging equipment can be made.

Dambrink incorporates the TGH into the construction of a site-specific geotechnical model which she later validates using field descriptions and test results. Dambrink's site-specific model was made by first describing the geological history in line from source to sink followed by a description of the glacial history with a focus on the last glaciation period. In order to understand the impact of the glaciation period, she uses the 3D models proposed by P. G. Fookes et al. (2000) such as the geomorphological model for continental glaciation, periglacial and coastal features. Dambrink then goes to describe the impact of the main features of each of the models on the environment and correlates them to rock mass properties such as block size. Based on this understanding, the advice given for the dredging method in Finland starts with an overall general recommendation to blast the bedrock. For some particular locations where the bedrock is heavily weathered, an exception is made such that blasting will not be necessary. In later chapters, this thesis captures the steps taken to make such a geotechnical model using flowcharts and figures.

The second paper that was studied was a report by Baynes et al. (2005) on the successful application of the TGH approach to several railroad development and improvement projects throughout Pilbara, Australia. This paper illustrates examples of the geological and geomorphological characteristics of a site can be expressed to effectively contribute to projects. First, a general appreciation of the region geology and geomorphology is gained based on literature study. The literature study looks into the bedrock stratigraphy and structure followed by how the landform evolved to the state which it is in now, including the climatic factors at play during this evolution. The paper presents this information in the form of a table which states the main geological events, geological environment and how these affect the engineering qualities of the area for each geologic age. Next, the paper advocates geo-mapping as an important strategy of the TGH approach. The engineering geological maps produced were made with the intention to differentiate units characterised by their engineering character. Another strategy proposed by the paper is to determine what they called *Reference Conditions* (shown in Figure 3.5) and to represent them in the form of evolutionary diagrams and 3D block models. By knowing the Reference Conditions to be expected on the site, the engineering geologist is able to identify features of interest, for which more attention can be paid on-site.

By using the TGH approach during the preliminary investigation stage, less geological efforts need to be expended during the main investigation phase. The TGH approach makes it possible to map out the site to a suitable degree such that the need for more extensive subsurface investigations can be decreased. Thus, providing a less expensive solution compared to the traditional approach to understanding the site. Furthermore, the TGH also allows the Observational Method to be implemented into the project, making the main investigation and construction stage more time effective.

Similar to railroad projects, the military can also benefit being able to make a preliminary prediction of the characteristics of the soil before being able to go on the site and carry out in-situ and laboratory tests.

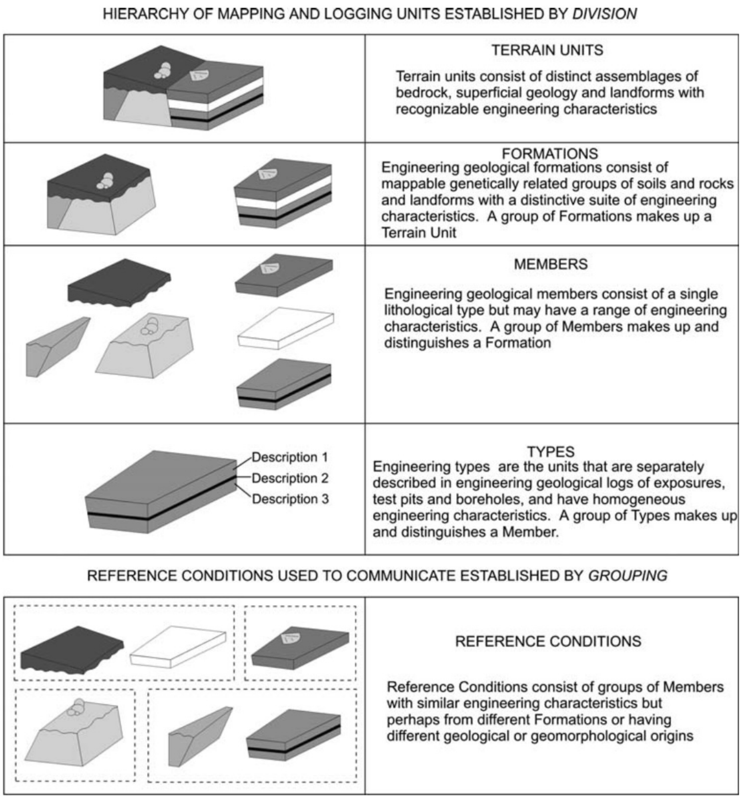


Figure 3.5: *Reference Conditions* used as part of the TGH approach in railway projects in Pilbara, Australia.

4 | Model description

The objective of this thesis is to present a framework that uses the inherent knowledge in the total geological history of an area to predict the most likely soil Unified Soil Classification System (USCS) class. During the literature study phase, some similarities were noticed between what we are trying to achieve here and soil classification systems made by soil scientists in the past.

For example, in 1927, K. D. Glinka proposed that the first step to classifying a soil should be understanding how much the soil is affected by its external environment (Glinka, Marbut, et al., 1927). Glinka categorised soils either as similar to their parent material (endodynamorphic) or strongly modified by their external environment (ektodynamorphic), such that the greater the effect of the environment on the soil, the more the qualities of the soil diverges from its parent material. Inspired by Glinka's work on how the external conditions can affect the type of soil formed, Hans Jenny (1983) went on to formulate a function that encapsulated the factors of soil formation, which remains relevant to this day. In essence, Jenny's model states that soil formation is a function of the parent material, topography, climate, the organisms that live within the soil as well as time.

In this study, it was found that the five parameters proposed in Jenny's model are able to complement the Total Geological History (TGH) approach in predicting the possible USCS soil class of an area. For this reason, a modular decision tree workflow is proposed, that captures both the geological history as well as the various soil-forming factors. The modular decision tree encompasses a single main tree, which can branch out into several modules that answer questions regarding a specific soil-forming path. At the end of the path, the user should be able to come to a prediction of a single or multiple possible USCS soil classes. Section 4.1 presents the main decision tree and introduces the modules and sub-modules which will be further elaborated upon in section 4.2.

4.1 Model workflow

The model proposed for predicting USCS soil classes in this thesis is in the form of a modular decision tree as shown below in Figure 4.1. The modular decision tree consists of a main tree which may require the user to diverge into one or more specific modules depending on the pathway chosen.

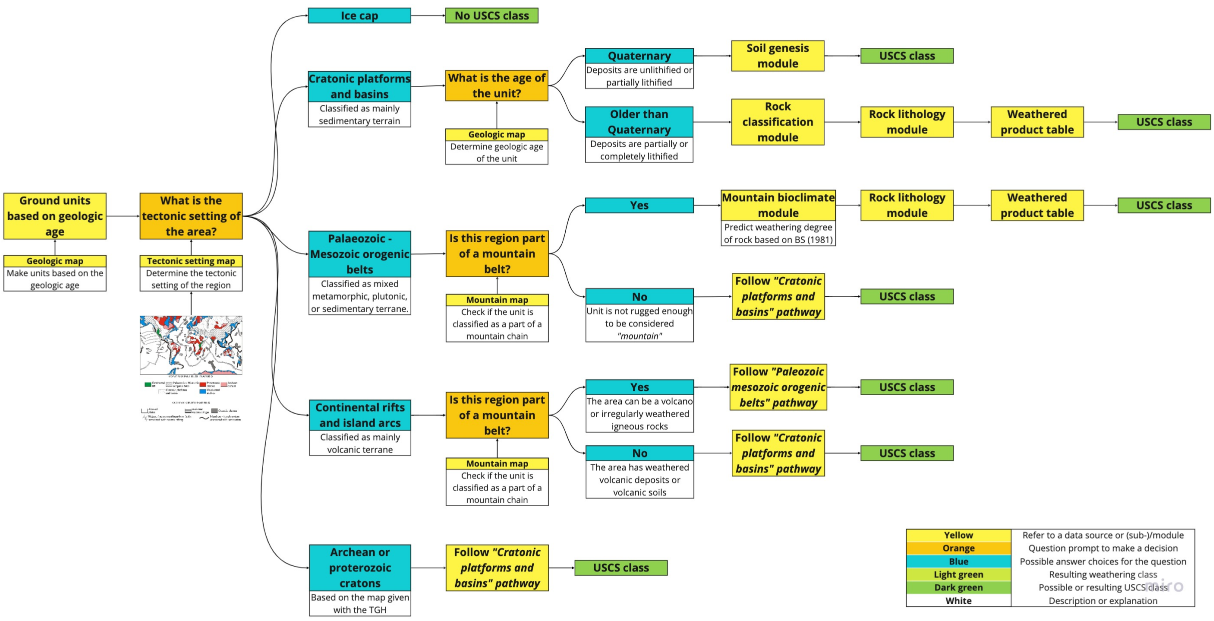


Figure 4.1: Main decision tree. A larger-sized image is attached in Appendix C.

The way the decision tree is set up requires the user to first collect and visualise all of the data sources in a geographic information system (GIS) tool such as QGIS or ArcGIS. The first step in preparing the data should be defining a study area. In this thesis, the study areas chosen are roughly 100 km x 100 km. Once the study area has been defined, the user can then add the relevant data sources as individual mapping layers into the GIS tool of choice. Further description of the data sources required is given in section 4.1.1.

Once the data has been prepared, the user can start using the decision tree from the left and make their way to the predicted USCS class on the right end of the decision pathway, shown in green. The decision tree is made in a colour-coordinated manner whereby each colour represents a different type of action that needs to be taken. For example, the first box that will be encountered is a yellow box. The yellow box gives a suggestion towards the data source or module that the user needs to use in order to be able to move forward in the decision process. In the case of the first yellow box, the user is asked to use the geologic map of the area to define units, such that each geologic unit will be treated as a unit of its own. For each unique unit within the area, the user will have to go through the entire decision tree, and the predicted USCS class is the general soil class expected throughout the unit. Therefore, the smaller the scale of the geologic map, the more detailed the classification of the area will be.

The next box encountered is orange. Orange boxes pose a question about the unit that will prompt a decision to be made. In order for a decision to be made at this point, the user must choose an answer to the question posed from one of the blue boxes. By choosing a blue box, the user determines the branch of the decision tree that is best applicable to the individual unit and subsequently moves on to the next decision.

At the end of the decision pathway, the user comes to a green box which states the possible USCS classes to be expected within the unit. At this point, the user can choose to do some further evaluation of the area using topography, terrain wetness index (TWI) and river channels to predict areas where water might percolate and as a result, have a thicker humus layer.

4.1.1 Data sources

In total, there are 7 types of data required for using the decision tree, which are:

- Geologic maps
- Tectonic setting maps
- Soil taxonomy maps
- Climate maps
- Mountain bioclimatic zone maps
- Land cover maps
- Digital elevation model (DEM) layer (can be used as an additional data source to highlight localised features.)

The purpose and type of each of these data sources are elaborated upon below, whereas a full list with links to the exact maps used in this study is given in Appendix D.

Geologic map

The geologic map is the most important data source for the decision tree to create the soil units. Although most countries will have their own geological department that provides the geological map, geologic maps with sufficient accuracy and reliability are difficult to find. As a rule of thumb, recent maps are more reliable as they represent the current state of the land as well as they have a technological advantage, such as aerial photography and the use of drones, over old maps for which the field geologist would have travelled to a couple of locations for a field survey and interpolated the findings over the whole area.

Within this thesis, finding a geologic map with a scale of at least 1:500,000 is aimed for, although if more detailed maps are available, they are preferred. In the case that the location does not have a map with at least 1:500,000, then it should be noted that there might be a lot of variation to be expected within each unit.

Tectonic setting map

The idea of using a tectonic setting map comes from the TGH approach by Peter Fookes. In his paper on the total geological history, Fookes presents a map of the tectonic elements (as shown in Figure 4.2) of the world based on the book Moores, Twiss, Twiss, et al. (1995).

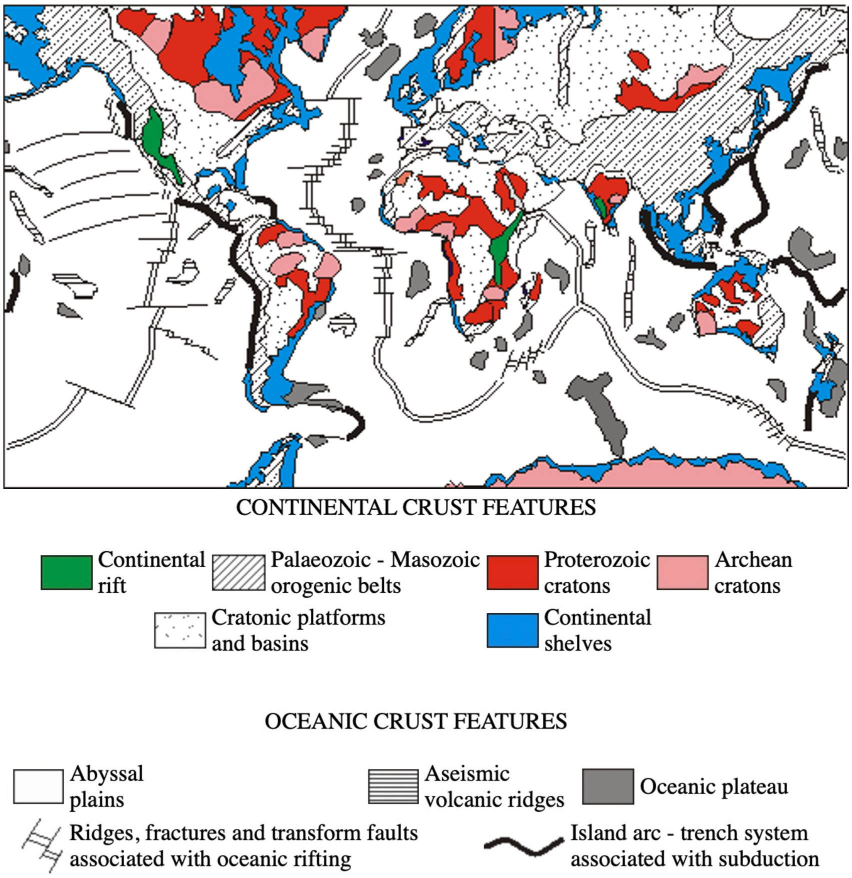


Figure 4.2: Tectonic elements of the world based on Moores et al. (1995), taken from the TGH website.

In order to visualise the tectonic setting in QGIS, a vector world tectonic setting map made by the Geological Survey of Canada to a scale of 1:35,000,000 is used in the pilot studies. A figure of this map is shown in Appendix D.2.

Taxonomical soil map

Soil taxonomy is a field of soil science that deals with the classification of soil in a way that accounts for its genesis or most notable characteristics such as the mineralogy of the soil or amount of organic content. Soil taxonomical classes have been extensively studied as they are used for understanding the agricultural potential of a soil. In this thesis, it was found that the information contained within soil taxonomical classes are also useful for determining USCS soil classes.

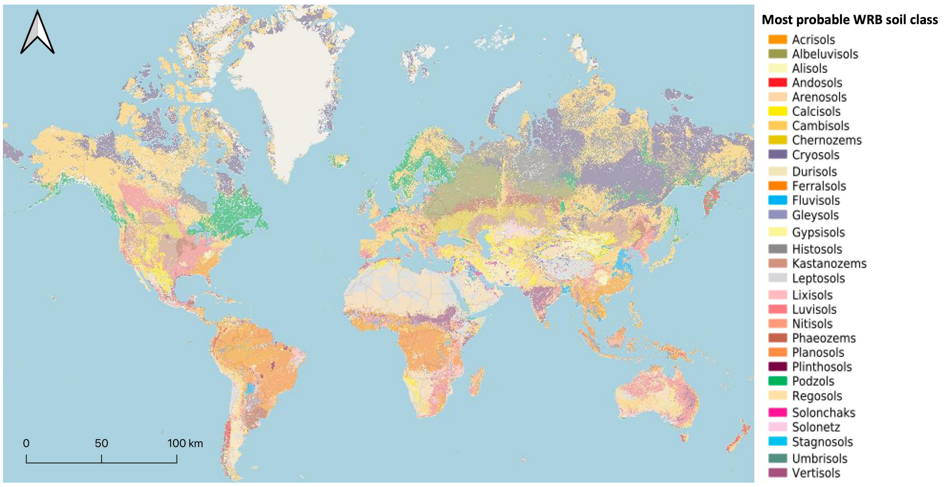


Figure 4.3: Soil map showing the most probable taxonomical soil classes at a scale of 1:500,000 (250m resolution), taken from SoilGrids.org. A larger image of the map is attached in Appendix D.

Within this study, the soil taxonomical system used is the World Reference Base (WRB) system which was first released by the Food and Agriculture Organization (FAO) of the United Nations in 1998. In 2006, the International Soil Reference and Information Centre (ISRIC) released a 1:500,000 scale WRB soil map (shown in Figure 4.3) for the world on a website called SoilGrids.org.

The WRB system consists of 32 Reference Soil Groups (RSGs) which can be further described by a set of principal and supplementary qualifiers. The RSGs are allocated to groups based on its dominant identifiers such as soil forming factors or processes that most clearly identify the soil (IUSS Working Group WRB, 2015). The WRB system is comprised of eight different types of dominant identifiers which are shown in Table 4.1.

Based on the dominant identifiers, some of the RSGs can be translated into USCS classes. Table 4.1 shows the possible USCS classes for the RSGs for which it was possible to make the translation. The translation is shown is an educated guess made based on the

		RSG	Possible USCS
1.	**Soils with thick organic layers**	Histosols	Pt, OL, OH
2.	**Soils with strong human influence**		
	With long and intensive agricultural use	Anthrosols	-
	Containing significant amounts of artefacts	Technosols	-
3.	**Soils with limitations to root growth**		
	Permafrost-affected	Cryosols	-
	Thin or with many coarse fragments	Leptosols	GW, SW
	With a high content of exchangeable Na	Solonetz	-
	Alternating wet-dry conditions, shrink-swell clays	Vertisols	CL, CH
	High concentration of soluble salts	Solonchaks	-
4.	**Soils distinguished by Fe/Al chemistry**		
	Groundwater-affected, underwater and in tidal areas	Gleysols	OL, OH
	Allophanes or Al-humus complexes (volcanic ash)	Andosols	OL, OH
	Subsoil accumulation of humus and/or oxides	Podzols	OL, OH, Pt
	Accumulation and redistribution of Fe	Plinthosols	(hardened layer)
	Low-activity clay, P fixation, many Fe oxides, strongly structured	Nitisols	ML, CL, MH
	Dominance of kaolinite and oxides	Ferralsols	ML, CL, MH
	Stagnating water, abrupt textural difference	Planosols	-
	Stagnating water, structural difference and/or moderate textural difference	Stagnosols	-
5.	**Pronounced accumulation of organic matter in the mineral topsoil**		
	Very dary topsoil, secondary carbonates	Chernozems	OL, OH
	Dark topsoil, secondary carbonates	Kastanozems	OL, OH
	Dark topsoil, no secondary carbonates (unless very deep), high base status	Phaeozems	OL, OH
	Dark topsoil, low base status	Umbrisols	OL, OH
6.	**Accumulation of moderately soluble salts or non-saline substances**		
	Accumulation of, and cementation by, secondary silica	Durisols	(hardened layer)
	Accumulation of secondary gypsum	Gypsisols	(hardened layer)
	Accumulation of secondary carbonates	Calcisols	(hardened layer)
7.	**Soils with clay-enriched subsoil**		
	Intercalations of coarser-textured, lighter coloured material into a finer-textured, stronger coloured layer	Retisols	-
	Low-activity clays, low base status	Acrisols	ML, CL, MH
	Low-activity clays, high base status	Lixisols	ML, CL, MH
	High activity clays, low base status	Alisols	CL, MH, CH
	High activity clays, high base status	Luvisols	CL, MH, CH
8.	**Soils with little or no profile differentiation**		
	Moderately developed	Cambisols	-
	Sandy	Arenosols	SW, SP
	Stratified fluviatile, marine and lacustrine sediments	Fluvisols	ML, CL, OL, MH, CH, OH
	No significant profile development	Regosols	-

Table 4.1: The first two columns are taken from "*Table 2: Simplified guide guide to the WRB Reference Soil Groups (RSGs)*" in the IUSS Working Group WRB (2015) report. The final column with 'Possible USCS' classes was made for this thesis.

description of the RSG. For example, if the description of the soil mentions the grain size, mineralogy or soil plasticity then it is possible to narrow down the expected USCS class. In contrast, when the soil description does not say much about the textural and plasticity quality of the soil, then it is not clear how to make the conversion to USCS classes. For example, when the description is 'rich in carbonates' or relating to the development of soil profile. In these cases, the 'Possible USCS' column is left empty.

Climate map

Climate is an important element in predicting soil conditions, such that it is included in both the TGH approach and Hans Jenny's soil forming factors. The book by P. Fookes, Waltham, and Pettifer (2015) states that climate affects the production of weathered residual soils and geomorphological features which affect the type of soils expected. When it comes to climate, the two parameters we are interested in are temperature and rainfall patterns. Therefore, the type of climate map chosen should be able to portray these two parameters.

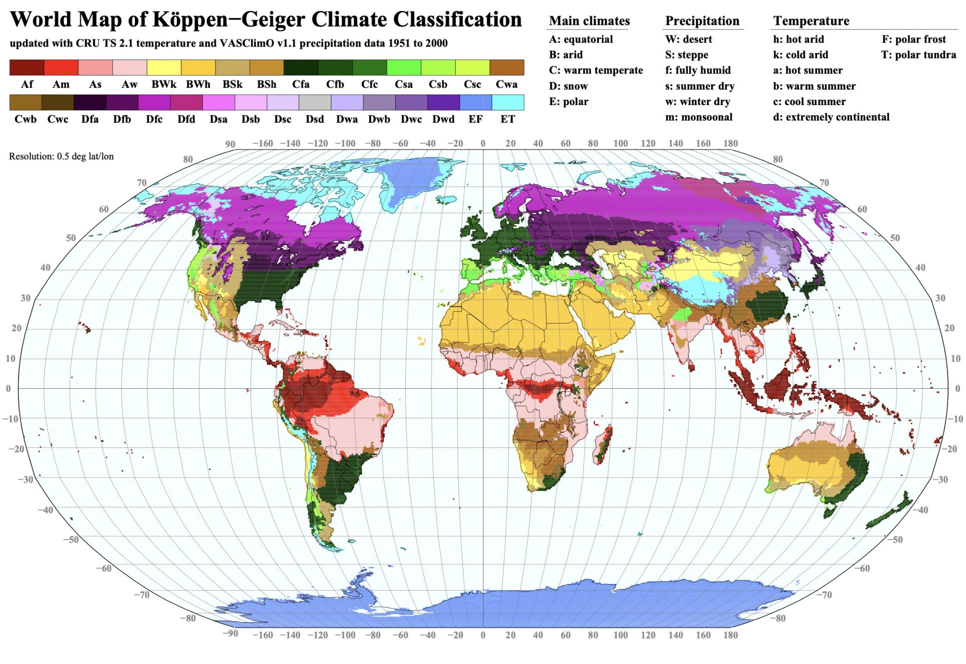


Figure 4.4: Climate zones of the world based on Köppen-Geiger climate classification scheme made using mean monthly temperature and precipitation data for the period of 1951 to 2000 at a scale of roughly 1:55,000,000 (0.5° x 0.5° grid), taken from the paper by Kottek et al. (2006). A larger image of the map is attached in Appendix D.

In this thesis, the Köppen-Geiger climate classification map is chosen as it is one of the most widely used climate classification schemes and is well documented. Therefore, it is possible to find a vector climate map that can be visualised in QGIS. An example of a Köppen-Geiger climate map is shown in Figure 4.4.

The Köppen-Geiger scheme denotes the climate zone of an area with 2 or 3 letter names. The first letter of the climate zone describes the main climate group into which the area falls into, the second letter represents the precipitation pattern whereas the third letter is sometimes used to give additional description about the temperature setting. The criteria for each climate class is described in more detail in Appendix D (Kottek et al., 2006).

Due to time constraints of this thesis, the decision tree presented in this thesis focuses primarily on the five main Köppen-Geiger climate groups, which are: tropical (A), arid (B), temperate (C), continental (D) and polar (E). Although some suggestions are given for specific 'Precipitation' and 'Temperature' classes, there is still a lot of scope for future work to expand on the climate classes used within the decision tree.

Mountain bioclimatic zone map

In addition to knowing the land cover, it is useful to know whether an area belongs to a mountainous zone or flat lands. This is because in terms of trafficability the greatest adversity in a mountainous zone is the presence of boulders and extreme ruggedness, whereas in low-lying areas, the greatest problem is often muddy and highly plastic soils.

Within this thesis, the definition of mountains by Global Mountain Biodiversity Assessment (GMBA) is adopted, such that a mountain is defined as an area of land which has a ruggedness value $\geq$ 200 m (Körner et al., 2017). Ruggedness is defined as the maximal elevation difference among points within 3 x 3 grid points. The grid used in the making of the GMBA Mountain Inventory has a spacing of 30" and uses mainly Shuttle Radar Topography Mission (SRTM) elevation data. A pixel is considered to be 'rugged' if the elevation difference between the highest and lowest of the nine points is greater than 200m.

Figure 4.5 shows the vector map made by GMBA which includes all of the mountain ranges of the world, overlain with a raster map indicating the different mountain bioclimatic zones within the mountain ranges. The different mountain bioclimatic zones are shown in Figure 4.6, whereby each zone represents a different vegetation, wildlife and cultivation pattern. By understanding the vegetation patterns, a prediction can be made for the depth of soil profile expected and the accumulation of humus. A logical assumption is that the more vegetated the slope, the greater the degree of weathering due to biological action can be expected.

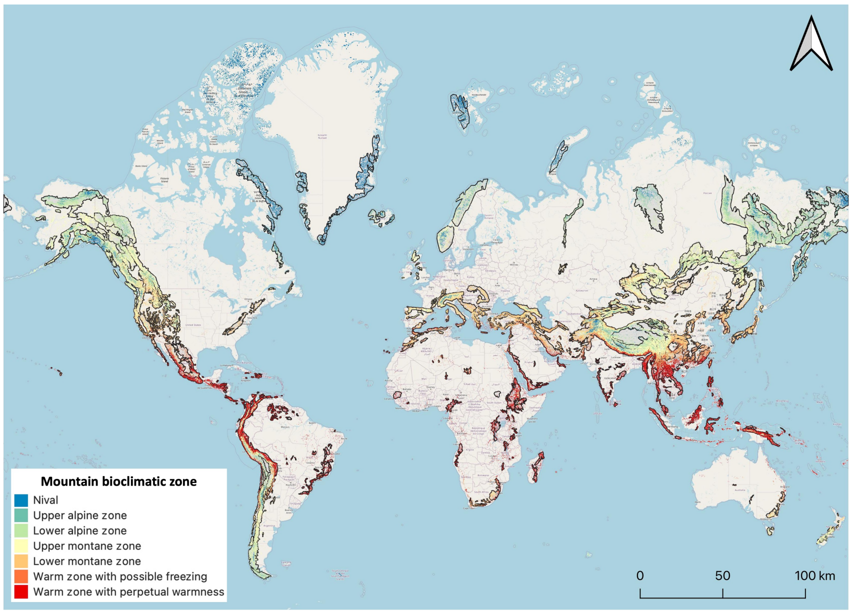


Figure 4.5: World mountain bioclimatic zone map made at a scale of about 1:100,000 (30 arc-seconds), taken from GMBA website. A larger image of the map and definitions of the bioclimatic zones are attached in appendix D.

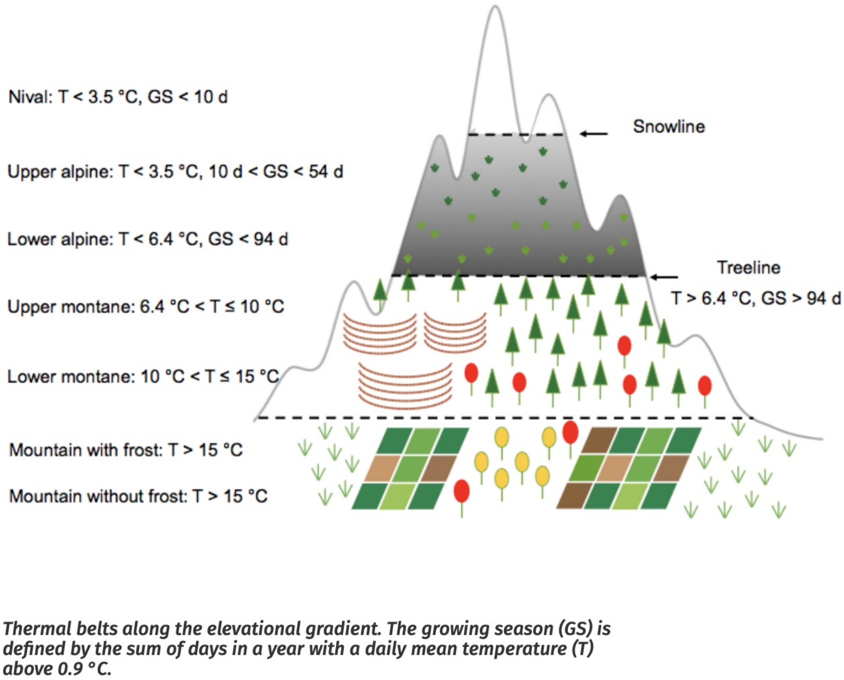


Figure 4.6: Different mountain bioclimatic belts, taken from the GMBA website. These bioclimatic zones are made based on Körner and Paulsen (2004); Körner et al. (2011); Paulsen and Körner (2014).

Land cover map

Next, the use of existing land cover maps were found out to be useful in understanding the type of terrain expected. Although satellite imagery such as Google Earth allows one to visually see the topography and terrain cover, it is useful to use a land cover map that has already been classified. Using a classified land cover map reduces the human judgement involved in the decision tree method as well as makes it easier to automate the process of determining land cover.

Within this thesis, a world land cover map made by the European Space Agency (ESA) called WorldCover is used. This land cover map was made in 2020 and 2021, using Sentinel-1 and Sentinel-2 satellite imagery that had been processed with a machine learning workflow. Figure 4.7 shows the WorldCover map.

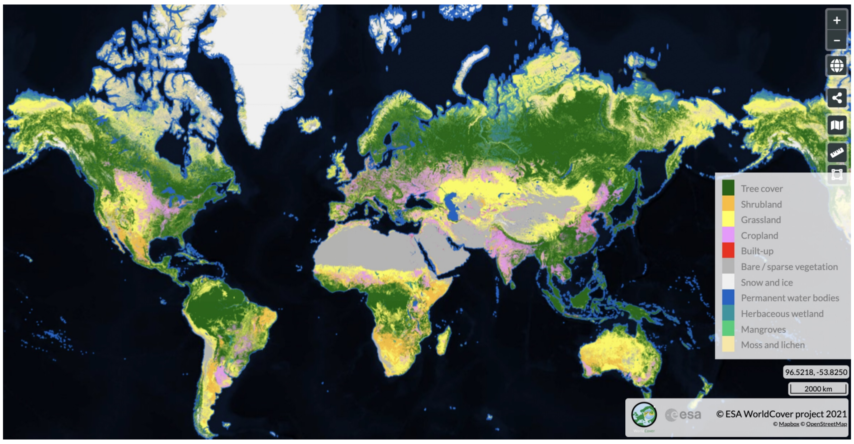


Figure 4.7: World land cover map made by ESA at a scale of 1:10,000, taken from WorldCover. A larger image of the map is attached in appendix D.

Land cover data is used within the decision tree model to close in on the type of environment we are dealing with. For example, when the land cover is bare ground, we can expect environments such as sand dunes, rocky surfaces, salt flats, desert pavements and tidal flats, to name a few. On the other hand, the presence of vegetation can be an indicator of soil profile depth and characteristics. For example, in areas where a lot of tree cover is expected, the topsoil usually has a significant layer of humus present. Another example is when the land cover shows mangrove forest or herbaceous wetland. Here, muddy soils (a mixture of silt and clay rich in organic matter) with high ground water levels are expected (Hossain, Nuruddin, et al., 2016).

Digital elevation model

Finally, a digital elevation model (DEM) raster is a very useful layer to have as it not only can be used to recognise local variations in geomorphology, but can also be used to generate other maps such as slope degrees, ruggedness, terrain wetness index (TWI) and groundwater flow maps, which can be useful in determining the trafficability of a terrain. For example, a forestry report on trafficability predictions made for Northern and Central European forests (Hoffmann et al., 2022), suggests to aid vehicle selection and execution for forestry operations by combining depth-to-water (DTW) maps made from high resolution digital terrain models (DTM). Another study by Salmivaara et al. (2020), proposes to use topographic wetness index (TWI) fused with DTW and topographical information to generate wet-area maps. Understanding the wetness of a soil is vital for predicting trafficability, as wet ground, especially when peat and clay are present is harder to traverse, not to mention more fuel consuming (Ala-Ilomäki et al., 2020). Therefore, for military mobility predictions, it is important to be able to understand the ground water the catchment and runoff within an area through maps such as TWI and Strahler stream order which will be described further in Section 4.3.

Apart from using DEMs to calculate the water flow patterns, DEM's are also vital in determining the ruggedness or slope angles present in an area. The maximum allowable slope that a military vehicle can climb on depends on the type of vehicle and can range anywhere from 25° to 60°. Therefore, generating slope angle maps from DEMs is an easy way to check if an area is trafficable.

In summary, this thesis proposes to use DEMs, in addition to USCS maps, for understanding the topography, and combining this understanding with steepness and soil moisture distribution maps in order to create a more complete image of the trafficability of a terrain. As a result, DEMs are extensively used in the supporting modules. The supporting modules proposed in this thesis are: 3D elevation module, Strahler stream order module, topographic wetness index (TWI) module, slope angle module and the land cover module, whereby 4 out of 5 of these modules require a DEM layer. It is therefore important to find a reliable DEM source. This thesis uses digital elevation data tiles from the Shuttle Radar Topography Mission (SRTM) with a spatial resolution of 30. These tiles are provided by the National Aeronautics and Space Administration (NASA) at the Earthexplorer.usgs.gov website. For an easier workflow, a QGIS plugin called the *SRTM Downloader* is used. More explanation on how the DEMs are used within the supporting modules is given in Section 4.3.

4.1.2 Tectonic setting

Inspired by the TGH approach (P. G. Fookes et al., 2000), the decision tree starts by determining the tectonic setting of an area to set the tone for the upcoming decisions. In the original TGH approach 10 tectonic settings are proposed, however in this model only five representative tectonic settings are chosen to be used. The five settings chosen here were found to be sufficient to guide the user towards the most logical decision path without over-complicating the model. The settings chosen here are inspired by the *"Tectonic elements of the world"* map (shown in Figure 4.2) by Moores et al. (1995), which is also used on the TGH website.

The five tectonic settings used in this thesis are:

- Ice caps
- Cratonic platforms and basins
- Paleozoic-Mesozoic orogenic belts
- Continental rifts and island arcs
- Archean or Proterozoic cratons

The first setting is *'Ice caps'*. Ice caps, ice sheets or glaciers refer to the parts of continental crust that is covered by a mass of ice such that there is no soil outcropping; soil is below the mass of ice. Ice caps and ice sheets usually occur close to the poles in places such as Greenland and Antarctica, meanwhile glaciers can also be found in other parts of the world, usually at high elevations, where the annual temperature is low enough for the glacier to be frozen all year long. If an the tectonic setting of an area is determined to be *'Ice caps'* then no USCS classification will be given for this area.

The second tectonic setting is called *'Cratonic platforms and basins'*. This setting refers to the part of continental crust that is tectonically stable and lies away from plate boundaries. These areas tend to have a lot of sedimentary formations that are either undergoing erosion or basinal structures that act as sinks for sediments to collect in. This tectonic setting is important as it covers most of the world's continental crust.

The third setting, called *'Paleozoic-Mesozoic orogenic belts'*, refers to mountain ranges that are formed at convergent plate boundaries formed during Paleozoic and Mesozoic mountain forming orogenies. Due to the high compressive stresses experienced during an orogeny, the rocks in this area may have been metamorphosed. Igneous rocks and intrusions are also common as this setting may be tectonically active. Since this setting is responsible for mountain building, the logical next step in the decision tree is to check if the area is part of a mountain range.

The fourth setting is *'Continental rifts and island arcs'*. This setting refers to tectonically active areas which are present on plate boundaries whereby the continental crust is either rifting or is being subducted under the oceanic crust. Both of these actions result in volcanic activity. Therefore, this setting is rich in igneous rocks.

The final setting is *'Archean or Proterozoic cratons'*. This setting refers to very old Earth crust which has been around for billions of years and has been exposed to prolonged weathering. Although these areas are currently tectonically stable, igneous and metamorphic rocks may still be present from past conditions. In fact, metamorphic rocks are commonly expected on cratons as the rocks have had a long time to be metamorphed.

Among all of the tectonic settings, the two most useful settings for the decision tree are the *'Cratonic platforms and basins'* and *'Paleozoic-Mesozoic orogenic belts'*, as they together make up most of the continental crust in the worlds. In general, within the *'Cratonic platforms and basins'* area, a lot of Quaternary sediments and soil profiles are expected, whereas within the *'Paleozoic-Mesozoic orogenic belts'* mountainous terrain which act as a source for sediments can be expected.

By determining the tectonic setting early in the decision pathway, the decision tree tried to predict if the unit should use the soil genesis, rock or mountainous module in the next step.

4.2 Modules

The main decision tree branches out into several modules before coming at the final USCS class prediction. As mentioned in the previous section, the user first determines the tectonic setting of the area. Based on the tectonic setting, the user chooses either a soil or a rock module. The soil genesis module accounts for Quaternary or young soils which have been recently deposited, whereas the rock modules account for soils that are formed in-situ due to years of physical, chemical and biological weathering. The various soil and rock modules used within this model are described in this section.

It should be noted that residual soils in the decision tree model are dealt with in the rock modules and not the soil genesis module.

4.2.1 Soil genesis module

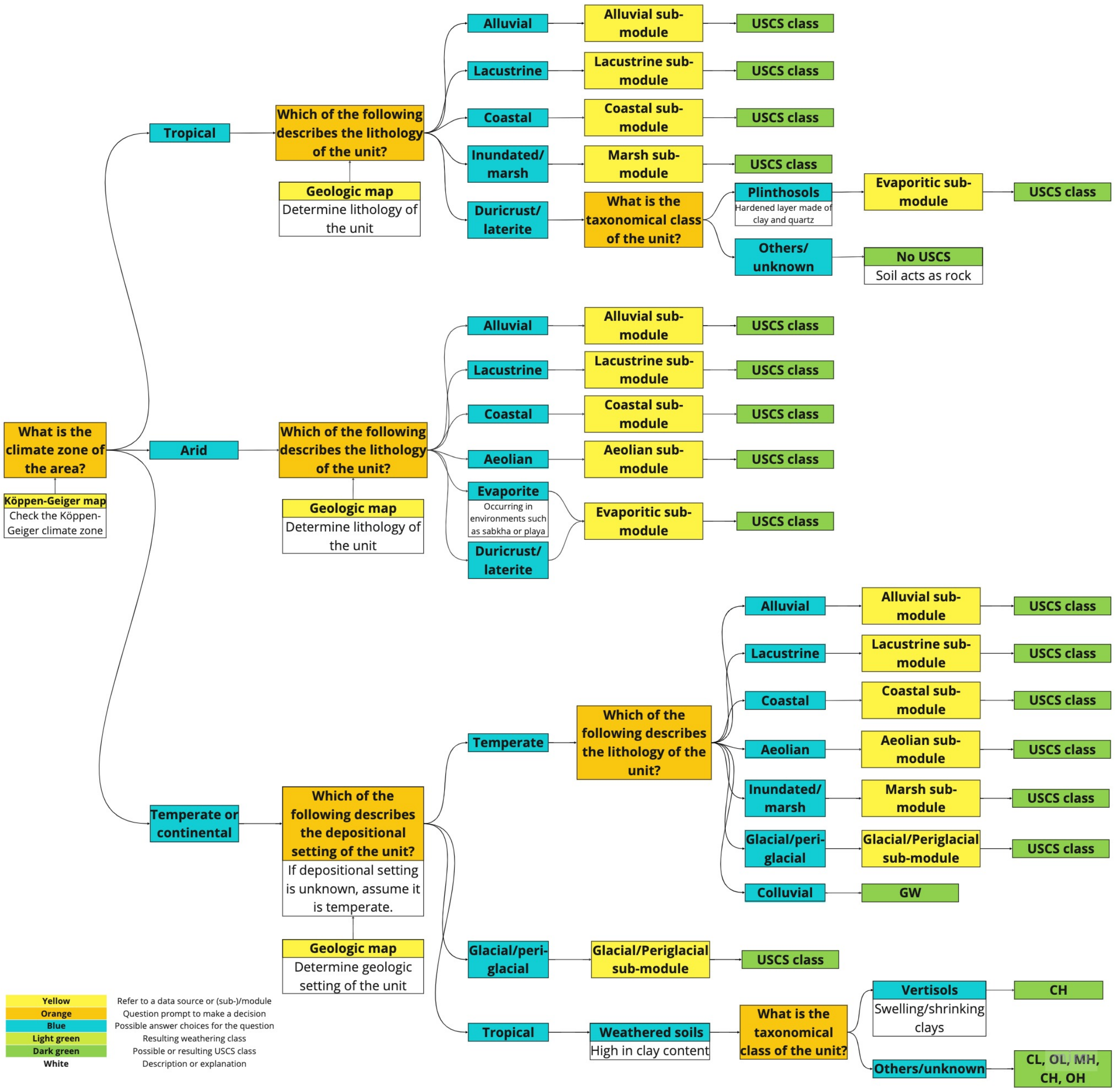


Figure 4.8: Soil genesis module which branches out to several sub-modules depending on the climate and depositional process of the material. An enlarged version of the image is attached in Appendix C.3.

In this thesis, soils in the soil genesis module are defined as unlithified sediments that have been transported to an area via water, wind, gravity or ice, and may have been worked upon by chemical or biological processes. Therefore, the soil genesis module (shown in Figure 4.8) classifies soils, first, based on their climatic zone and then based on their depositional setting. The climate zones used in the decision tree are the tropical, arid and temperate climates. By determining the climate zone early on in the decision tree, the model is able to converge to predicted USCS class quicker as each climate has some soils specific to its conditions. For example, desert playa or sabkha tend to occur in arid climates or in climates that have experienced past aridity. Meanwhile, tropical climates tend to have more clay and humus development compared to other climate zones. Temperate climates are considered to be a special case as a lot of the large-scale features in this climate zone are inherited from past climates (P. Fookes et al., 2015). Therefore, a second question is asked in the decision tree regarding the paleo-climate experienced.

Once the climate zone has been determined, the next step is to determine the depositional method experienced by the soil. The reason for using the depositional method as and major indicator of USCS soil type is that, within the soil genesis module, the type of sediments we are looking at are Quaternary deposits. In geologic terms, Quaternary deposits are young, and therefore, in general have not had the time to undergo lithification into rocks. As a result, their characteristics a largely influenced by how they were deposited (Culshaw, Cripps, Bell, & Moon, 1991).

Often, geologic maps will name units based on their genesis, for example: alluvial soils, aeolian sands, ancient lake deposits and so on. These depositional settings are encompassed by sub-modules within the soil genesis module. The depositional setting sub-modules used are the alluvial, lacustrine, coastal, marsh, aeolian, evaporitic and the glacial/periglacial soil modules which will be described next.

Alluvial soil sub-module

Rivers play an important role in forming the features of an environment and are also an important source of sediments. The various soils created by river processes include river channel, floodplain, delta, alluvial fan, mountain erosion and river terrace soils which are incorporated into the decision branch shown in Figure 4.9.

A further distinction can be made in river channel deposits depending on the type of river system present: braided, anastomosing, or meandering. This distinction is useful because each river regime has certain unique elements which can be used to gain a better insight on the type of soil present. As alluvial soils tend to be intrinsically heterogeneous, understanding the different elements present in a river system helps to deal with the degree of uncertainty present when dealing with such soils. However, the difficulty faced with using river systems in the decision tree is that geologic maps do not usually denote the type of river system. Therefore, additional information either from literature or a judgement call can be made by inspecting the river pattern on a satellite image in order determine the river type.

Once the river system has been determined, the concept of using block models is adopted from the TGH approach, whereby each block model visualises the type of landforms that

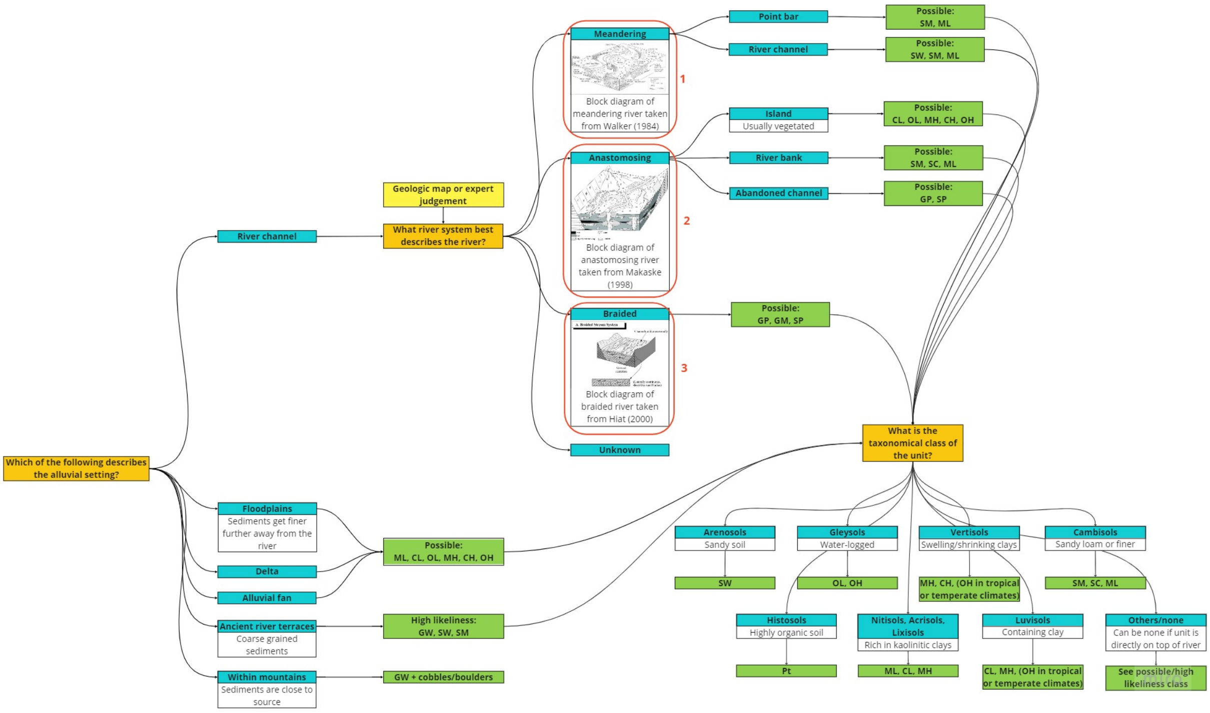


Figure 4.9: Alluvial soil sub-module.

can be expected with its respective river system. The block models are shown in Appendix C.2.1 and are described below to give the user an idea of what to expect in the area surrounding the river.

The first river regime, is the meandering river. The meandering river system is made up of a main river channel that bends and curves through a valley or plain. The main components of a meandering river are the sandy to silty levees, clay-rich floodplains, peaty marshes in ancient oxbow lakes away from the main river channel, sandy crevasse splays that get finer grained further away from the main channel, migrating river channels as well as clay-rich residual channels (Zhao, Jin, Zhou, Wang, & Pu, 2018).

Next, is the braided river system. Braided river systems are recognisable by their shallow, but wide multi-threaded channels, which are usually smaller channels that surround braid bars (also known as islands). Compared to meandering rivers, braided rivers tend to occur at a steeper channel gradient, which is proportional to the discharge of the river (Ferguson, 1984). When the discharge of the river is higher, it is able to carry within it heavier particles, and therefore the grain size of particles being deposited within the channel tends to be coarser. Just to give an idea of the sediments in a braided river, Ning, Xia, Zhongmin, Jiangqin, and Guangya (2018) made a study on the Yabus River in South Sudan, whereby the sediments within the channel ranged from fine sands to gravel, whereas on the braid bars the sediments were fine to coarse sands. Furthermore, this river system is also subject to rapid changes in structure, especially during floods. The dynamic changes experienced by this river system makes it difficult for vegetation to grow and stabilise on the braid bars.

The final river system considered is the anastomosing river system. Anastomosing river systems appear similar to braided river systems, in the sense that it consists of multiple river channels. The key difference is that anastomosing systems consist of channels that are more permanent than the channels of a braided river system. As a result, the islands within an anastomosing system tend to be stable and vegetated, with the exception of anastomosing rivers in an arid environment that is not conducive to plant growth. In fact, the islands in an anastomosing system are usually clay-rich floodplains, which is also what makes them very fertile. Lastly, the channels of this system can be meandering or braided and have silty to sandy levees (Makaske, 2001).

Lacustrine soil sub-module

Lacustrine soils occur in low-energy depositional environments, for example, in lakes or in the surrounding area of lakes. Due to the lower energy of the water, lacustrine sediments tend to be fine-grained. In this branch, soil taxonomical classes can be used to determine if the soil has a high clay or organic content.

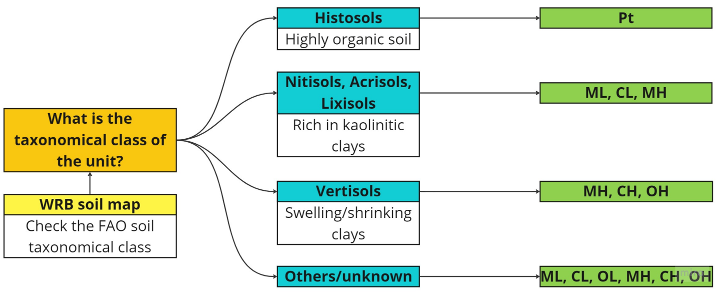


Figure 4.10: Lacustrine soil sub-module.

Coastal soil sub-module

Coastal soils occur in the environments near and at beaches. The elements that can be expected in a coastal environment include sandy beaches, sand dunes, salt marshes or sabkha in hot climates and tidal or marine clays. Characteristics and size of beach sand depends on the quality of parent material and distance of the beach from the source. Sand grains that have been undergone little transportation will be more angular than grains that have been transported a long way. Next, coastal dunes are formed when the beach has an ample supply of sand such that the breeze coming from the sea can cause sand dunes to form inland (Martínez & Psuty, 2004). Coastal environments can also have marine and tidal clays which are formed during previous sea level regression and transgression phases. These facies are often made up of intercalations of peat and clay to silty clay, for example as expressed by the Calais and Dunkerque series along the North Sea (Baeteman, Waller, & Kiden, 2011). Al-Bared and Marto (2017) associates this soil with high settlement and instability due to high moisture content and the presence of a high percentage of swelling minerals. The remaining two coastal elements are salt marshes and sabkhat which will be looked at in more detail in the marsh and evaporite sub-modules respectively.

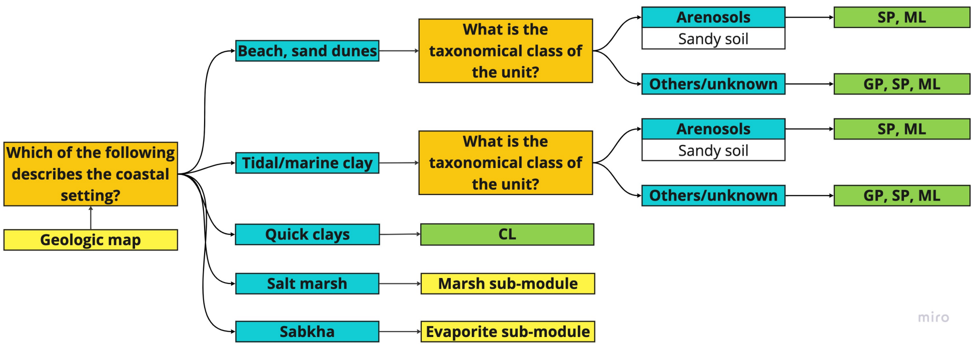


Figure 4.11: Coastal soil sub-module.

Marsh soil sub-module

In this thesis, a marsh is considered to be a water locked region that is poorly drained, such as salt marshes, swamps, mires or areas close to lakes and streams. Marsh soils typically contain a lot of organic matter from reeds, bushes or trees that are present. They can also contain a large amount of clay. Depending on the dominant material in the marsh, a prediction can be made of the USCS class.

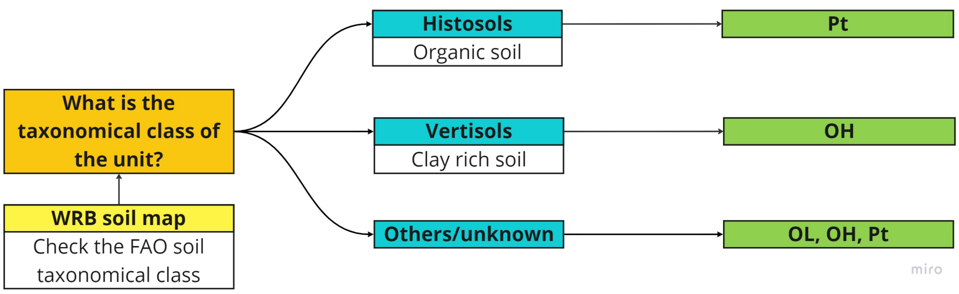


Figure 4.12: Marsh soil sub-module.

Aeolian soil sub-module

Aeolian soils are soils deposited by wind action and are predominant in arid environments, but can also occur in other climate zones. Aeolian sediments tend to be silts and fine to medium sands with uniform grading (P. Fookes et al., 2015). Two common aeolian deposits are dealt with in this sub-module, these are sand dunes and loess deposits a shown in Figure C.13. Sand dunes can occur in deserts or in the vicinity of beaches, whereas loess deposits can occur anywhere but are usually related to a past glacial period. In general, loess deposits tend to be silt-dominated whereas sand dunes tend to be sand-dominated (Karimi, Khormali, & Wang, 2017).

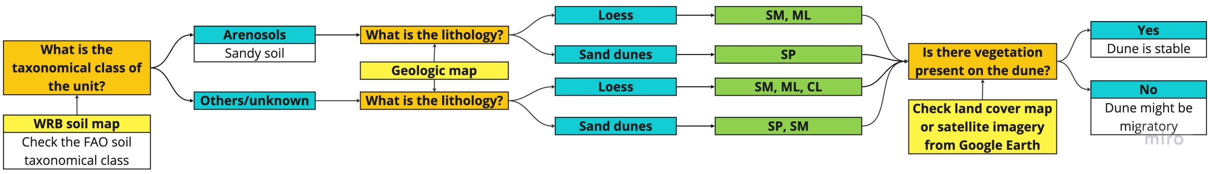


Figure 4.13: Aeolian soil sub-module.

For the military, sand and silt are in general easily trafficable however, small and bumpy dunes can create problems and slow down a bigger military vehicle but may benefit from the choice of using smaller and lighter vehicles such as armored ATVs. In addition, migratory sand dunes can also be a hazard to existing infrastructure and roads/paths. Therefore, understanding the size and behaviour of a dune can be a useful addition to the decision tree. By looking at satellite images of the sand dune, we can make a guess on whether the dune is stable or migratory. In general, stable dunes will have some vegetation growing on it. In addition, the satellite image, Digital Elevation Model (DEM) or aerial photographs in combination with the wind direction (if known) can give an idea about the size, height and shape of the dune. Migratory dunes can either be crescent in shape or elongated in lines perpendicular to the wind direction (Tsoar, Blumberg, & Stoler, 2004).

Loess formed during past periglacial environments, on the other hand, can also form high dune shaped terrain. However, the problem with loess is that it is very light and may be sensitive to water. Thus, it is prone to collapsing which was one of the problems experienced during the building of high speed railways in Northern France (Delage, Cui, & Antoine, 2008).

Evaporitic soil sub-module

Evaporitic soils are soils formed by the evaporation and precipitation of salts or minerals within a soil. the evaporitic environments covered in this sub-module are sabkhat, playas and duricrusts as seen in Figure 4.14.

In literature, there is a lot of confusion on the definition of sabkha, playas and other similar terms such as salinas, clay pans and playa lake to name a few. Therefore, this

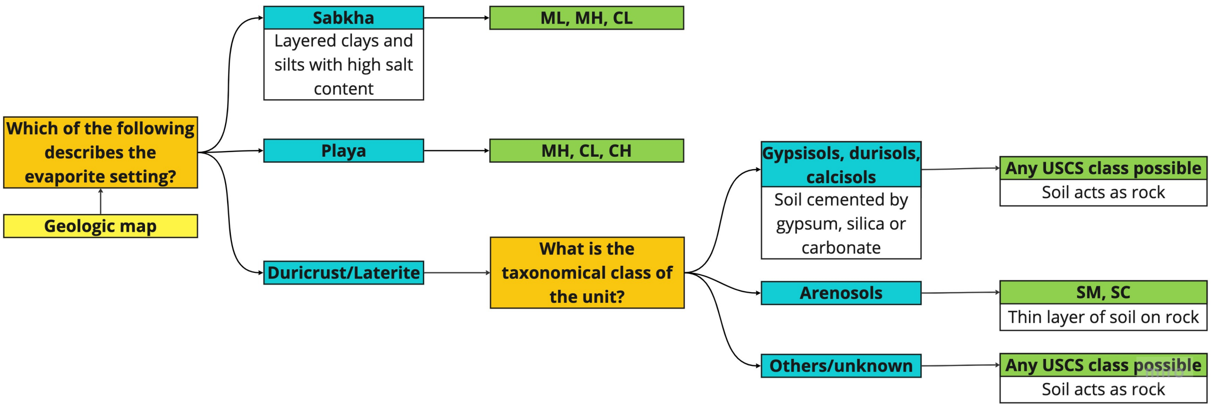


Figure 4.14: Evaporitic soil sub-module.

thesis uses the definitions for sabkha and playa by Briere (2000) to remain consistent. According to Briere (2000), sabkhat (plural for sabkha) are mudflats that occur in coastal plains due to the precipitation of evaporites whereas playas occur in an intracontinental setting where the water balance is negative for over half of each year and dry for over 75% of the time. In this thesis, continental sabkhat are called playas.

Sabkha soil is made up of clay and silts with high salt content, which may have layers of algal mats. Ali, Malik, and Ibrahim (2015) describes sabkha soil as soils with low strength, low bearing capacity and high compressibility. As a result, sabkha is a problematic soil prone to differential settlements. Next, playas are mud-flats that typically form within inorganic clays with a high plasticity index (Fairbridge, 2006). As playas are often present in hot an arid environments, they may show dessication structures. The risks associated with sabkhat and playas are corrosion and salt attack on military vehicles or structures, low soil strength and bearing capacity as well as the risk of flooding after rainfall (P. Fookes & Lee, 2018).

The next evaporitic soil accounted for in this sub-module is duricrust and laterite. These soils have a hardened crust that usually forms due to the accumulation and hardening of minerals such as silica, alumina, calcium carbonate and iron oxide (Finkl, 1984). In terms of mobility, duricrusts are usually strong and able to support the weight of heavy vehicles, however the environment in which the duricrust occurs in may have large boulders which can become an obstacle.

Glacial/Periglacial soil sub-module

According to Hughes and Woodward (2009), glacial soils are formed as a result of dynamic glacier ice whereas periglacial environments occur in non-glacial areas where the mean annual temperature is less than 3 °C. Some common soils formed in glacial and periglacial environments are shown in Figure 4.15.

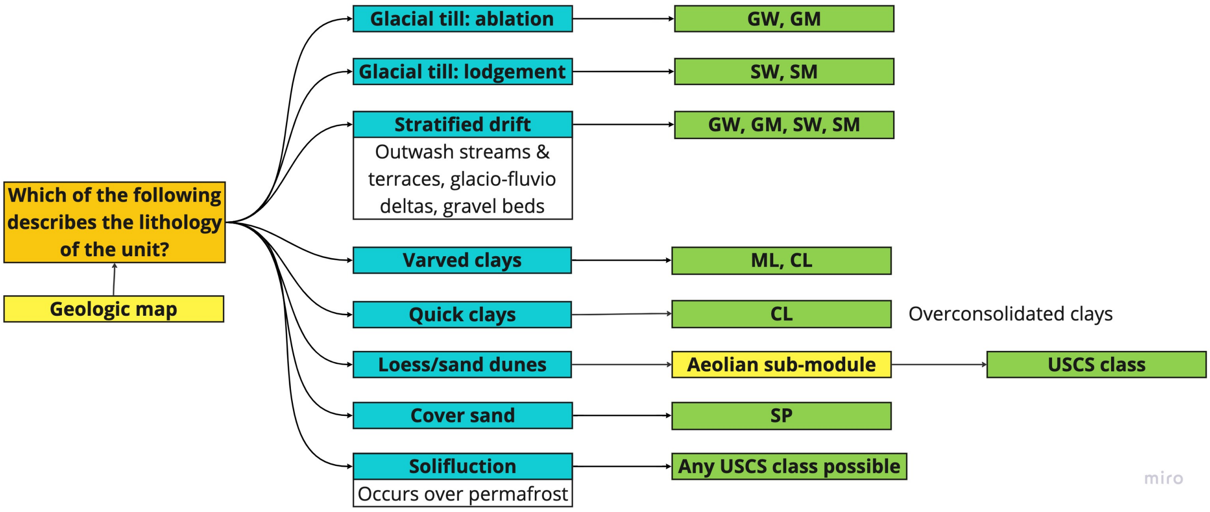


Figure 4.15: Glacial/Periglacial soil sub-module.

As glaciers advance across a terrain, they bring with them two main types of sediments: till and stratified drift. Glacial till refers to the unsorted deposits carried by a glacier as it advances. The deposits at the front of the glacier is called ablation till whereas the deposits under the the glacier is called lodgement till. Once the glacier melts, the soils that were pushed by the glacier are left as bumps in the landscape which are known as moraines. Glacial tills tend to be well graded and have particles ranging from gravels to clay and also contain cobbles and boulders (Cao, Peaker, & Ahmad, 2015). However, lodgement till is known to have a higher proportion of silt and clay compared to ablation tills. This difference in grain size distributions come from the fact that the deposition of ablation till is accompanied by extensive melting of the ice which leads to a partial loss of its fines constituents (Fairbridge, 2006).

Stratified drift on the other hand, refers to predominantly sorted sediments laid down by glacial meltwater, into streams or lakes. These sediments are predominantly sandy and gravelly. In contrast, the sediments which are deposited by glacial meltwater on the floors of glacial lakes tend to be fine-grained consisting of silts and clays (Culshaw et al., 1991). These sediments are called varved clays.

Next, quick clays can also be formed in glacio-marine environments. Quick clays are sensitive clays, usually containing non-swelling clays such as kaolinite and illite, that can experience significant loss of strength when disturbed, for example in the landslide in Rissa, Norway (Gregersen et al., 1981). Therefore, it is important for the military to be aware of the risks that come with quick clays.

Other periglacial deposits come from wind action which result in loess, sand dunes and cover sands. Finally, an area which is still experiencing periglacial conditions, may be exposed to solifluction deposits. Solifluction deposits are deposits that slowly move down a slope due to sliding caused by cyclic freezing and thawing of the ground. Although solifluction deposits can be of any soil type, it was deemed important to bear in mind the possibility of encountering these soils, as they bring a risk of landslides.

One final note on glacial and periglacial soils, is that clays that have been loaded by glaciers in the past are currently considered to be over-consolidated. This makes them have higher bearing capacities than normal clays and less prone to settlements, which for the military is good news.

4.2.2 Rock classification & mountain bioclimate module

There are two possible cases in which the rock module can be used. Either the geologic unit within a basin is older than Quaternary or the unit is part of a mountain belt. In the first case, the unit is from a geologic period older than the Quaternary and the condition of the top soil depends on degree of weathering the rock has undergone. For this case, the rock classification module (shown in Figure C.14) has to be used.

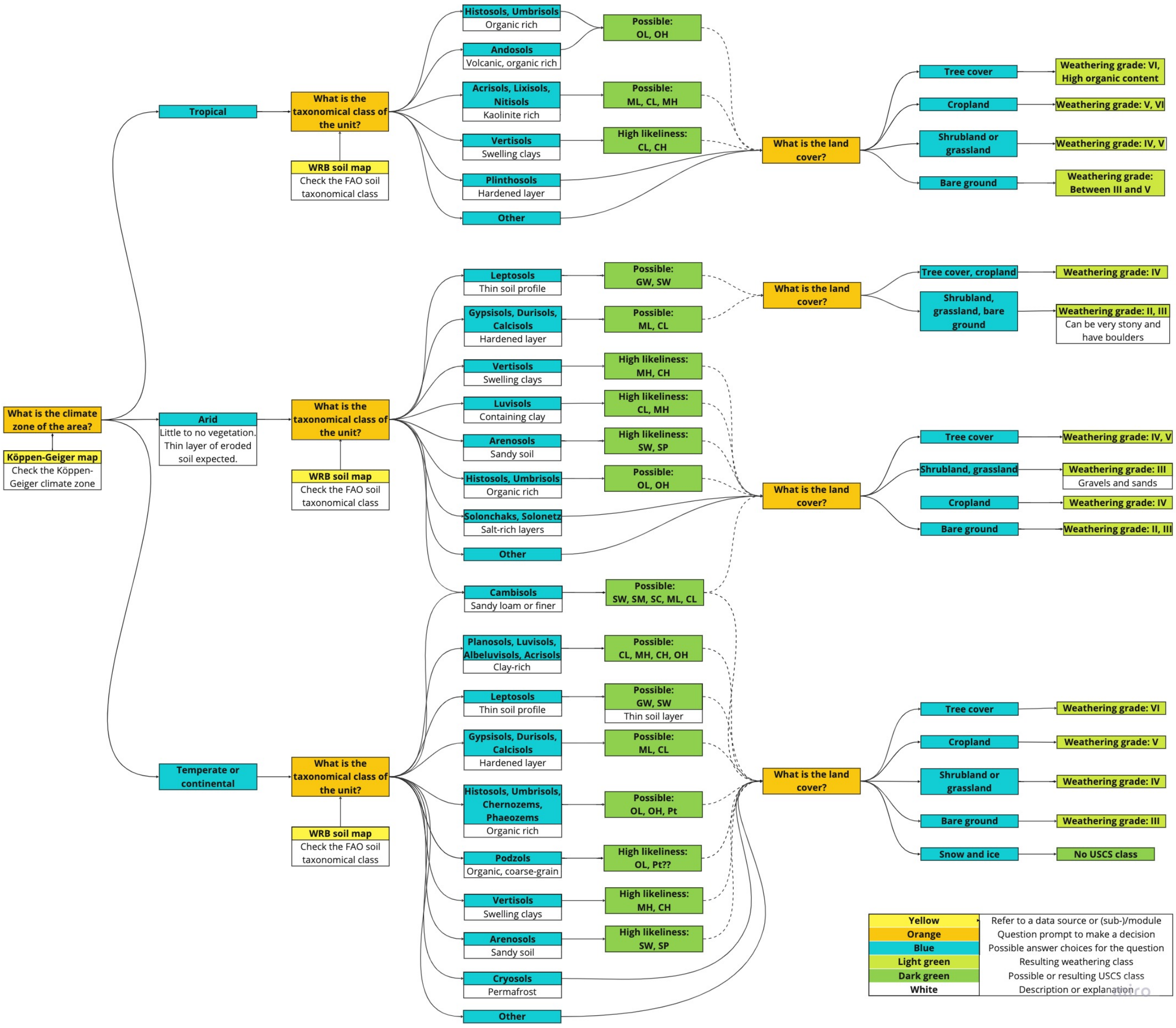


Figure 4.16: Rock classification module.

In the rock classification module, the first decision that has to be made is to determine the climate zone. The climate zone gives an idea of the amount of chemical and biological processes that are expected to work on the soil. This in turn will affect the depth of the soil profile as shown in Figure 4.17. Tropical soils, in general, undergo the most weathering and therefore have the deepest soil profiles, whereas arid and polar climates result in the thinnest soil profiles. The weathering depth in temperate soils are usually in between those of arid and tropical forest. The knowledge of weathering depths for each climate zone is used later to make the weathered rock table which will be described in Section 4.2.2.

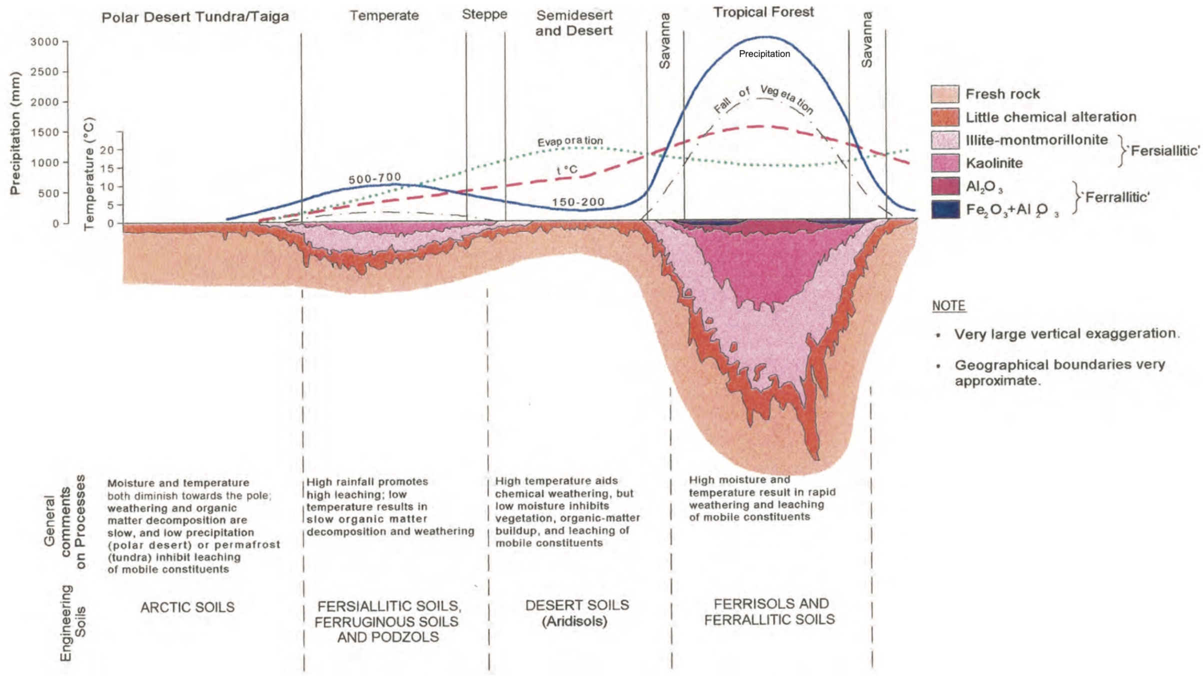


Figure 4.17: A simple cross-section showing the relationship between climate and rock weathering characteristics along different climate zones from the poles to equator taken from P. Fookes et al. (2015).

In the rock classification module, once the climate zone has been determined, the next step is to check the most prevalent taxonomical class of the soil present within the unit. Based on the most common soil taxonomical class, an initial prediction of the USCS class is made. This prediction is made using the same translation table (Table 4.1 from soil taxonomical class to USCS class which was used for the soil modules. It should be noted, that since this step depends strongly on the taxonomical soil map, therefore, the accuracy of the predicted soil map will be affected the resolution and accuracy of the taxonomical data used. Furthermore, as the most prevalent taxonomical class within the unit is used, some of the resolution of the taxonomical map may be lost if the geological units are too coarse. A solution to this is to further divide the chosen units based on the taxonomical classes. An example of how this can be done is shown in Section 5.4.3.

Once the initial prediction is made, the user goes on to determine the land cover type. Based on a combination of climate zone and land cover, a predicted weathering degree is given. The idea is for the user to use the rock lithology and predicted weathering degree in the weathered rock table from which the final USCS soil class can be predicted. In cases where the initial and final USCS prediction both point to the same soil class, then there is a greater confidence in the results.

Similarly, if the unit is part of a mountain zone, then the mountain bioclimate module (shown in Figure 4.18) is used to determine the predicted weathering degree which can then be used alongside the rock lithology module and weathering table to determine the predicted USCS class.

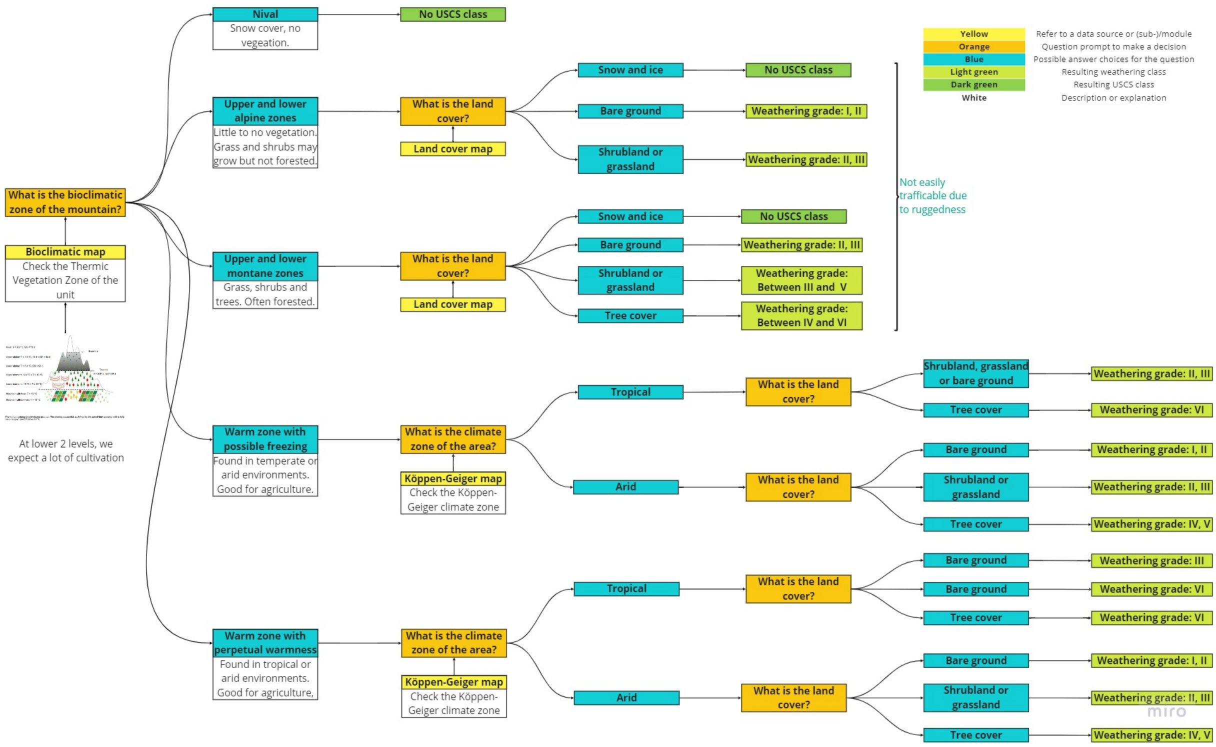


Figure 4.18: Mountain bioclimate module.

The mountain bioclimate zone is determined by the elevation and ruggedness (Körner et al., 2017) of an area whereby the highest part of a mountain falls under the nival zone. The nival zone is often covered with snow and glaciers and is not vegetated. Any soil eroded in the nival zone will have been transported downwards with gravity and therefor no soil profile is expected.

Next, in the alpine zones we can start seeing growth of shrubs and grass. The alpine zone generally experiences between 10 days to 3 months of growing season. In this zone, a thin soil profile could develop however, many boulders and gravel might still be present. Geologic maps might present this as scree or colluvium.

Going lower, the upper and lower montane zones are encountered. The montane zones experience more than 3 months worth of growing season, and are usually well forested. Here, a well developed soil profile can be expected.

The lower two mountain zones are the warm zones. These zones are usually found on the foot of mountains, may have abundant civilisation and be used for agriculture. In these zones, a soil profile is expected. The depth of the soil profile depends on the climate zone and presence of vegetation.

Based on the most prevalent mountain zone present within a unit, the mountain bioclimate module allows the user to come to a predicted weathering grade by using the rock lithology module and weathered rock table, which will be described in following sections.

Rock lithology module

The rock lithology module allows the user to determine the type of rock in a unit. The rock lithologies are divided into sedimentary, igneous and metamorphic, whereby in each group the most common rock types of that group are given as choices. In case the user is not able to find the exact rock lithology as described in the geologic map, then the user must choose the lithology that is closest to one of the options given.

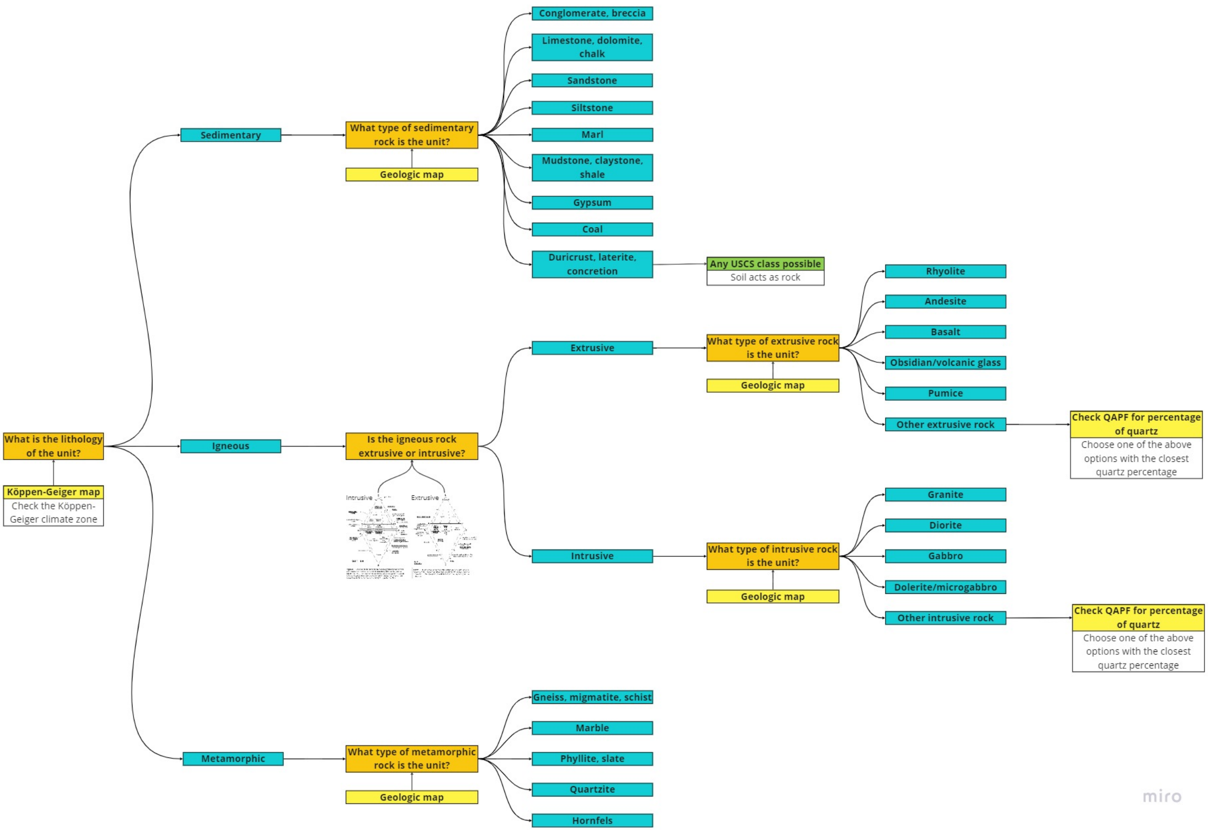


Figure 4.19: Rock lithology module.

Weathered rock table

Once the predicted weathering grade has been determined from either the rock classification or mountain bioclimate module, and the lithology of the rock has been chosen from one of the options within the rock lithology module, the user can finally use the weathered rock table to determine the weathered products of the rock unit. A full image of the weathered rock table is attached in Appendix C.3.3.

The weathering products for each rock lithology has been made based on a criterion which has been inspired by the table with the degrees of rock mass weathering published as BS5930 by British Standards (1981). The table published by British Standards (1981) was made with the intention of determining the strength of a rock mass due to weathering effects. In order to make the weathering effects more relevant to the prediction of soil types, some changes were made to better accommodate the degree of soil profile development. The resulting criterion for weathering grades used in this thesis are shown in Figure C.16.

Weathering grade Rock type	I	II	III (Thin soil layer)	IV (Thin soil layer)	V (Soil profile present)	VI (Developed soil profile)
Weathering state	Rock		Soil matrix between corestones		Residual soil	
	Fresh rock	Slightly weathererd rock	Moderately weathered, partly disintegrated rock	Highly weathered, disintegrated rock	Completely weathered to immature soil	Residual soil
Description	Bare rock exposed on the surface. The properties of the rock are same as the parent material.	Rock may be slightly weathered and is weaker than fresh rock. A thin layer of topsoil exists.	Less that 50% of the rock has disintegrated. Irregular weathering patterns and corestones may be present. Mostly mechanical weathering. Duricrusts may be present.	More than 50% of the rock has disintegrated to soil. Irregular weathering patterns and corestones may be present. Mostly mechanical weathering.	Rock has underwent complete mechanical weathering and some degree of chemical weathering. Soil may still have mineralogical features of parent rock.	Rock has underwent complete mechanical, chemical and biogical weathering such that soil is no longer like parent material. Humus layer or duricrusts may be present.
Conditions for weathering	Rock is geologically young and is part of a mountain bioclimate range.	Arid climates or mountain bioclimates that does not experience as much chemical weathering.	Rocks in arid climates that have experienced weathering in previous climates.	Meditteranean climate. Arid to temperate.	Temperate or continental.	Hot and humid environment.
Uniformity of weathering	No weathering	Slight weathering, depends on fracture patterns	Irregular weathering	Irregular weathering	Soil like, with occasional rocks	Complete weathering
Vegetation expected	Little to none	Bare ground but may have sparse grass or shrubs	Grass, shrubs or agriculture	Grass or shrubs	Can be completely vegetated or used for argiculture	Can be completely vegetated or used for agriculture
Consequences for trafficability	Depends on the ruggedness or steepness of the terrain	Depends the steepness of the terrain	Depends on the presence of large boulders and the plasticity of the soil matrix.	Depends on the presence of large boulders and the plasticity of the soil matrix.	Depends on the presence of organic matter or clay	Depends on the presence of organic matter or clay

Figure 4.20: Description of weathering grades made in this thesis for military mobility soil predictions, inspired by the adaptation of the BS 5930(1981) weathering grades made by P. Fookes et al. (2015). The classes description shown in this table are unique to this thesis. Larger sized table is attached in Appendix C.3.2.

4.3 Supporting modules

The supporting modules are not part of the decision tree but are additional calculations and visualisations that can be made in QGIS, to provide a more complete picture of a location. The main focus when designing the supporting modules were predicting areas where water is expected to accumulate. Knowing this is useful because in areas that tend to be water-logged, we can often expect a higher clay and organic content (Derr, Matelski, & Petersen, 1969). A second focus point of the supporting modules, is to determine the ruggedness of the terrain, as military vehicles can not traverse over areas that are very steep or rugged.

There are five possible supporting modules that can be used. These are the 3D elevation module, Strahler order module, topographic wetness index (TWI) module, land cover module and the slope angle module.

The 3D elevation module can be used to visualise potentially wet or water-logged areas. This method works by visualising the terrain in 3D, and choosing suitable colours for the DEM such that low-lying areas and peaks can be easily distinguished. A vertical exaggeration can be used to make the difference between low and high points more visually obvious. By determining locally low elevation areas, we can expect that these areas will be the first to fill up after heavy rain. Despite not being a quantitative map, this visualisation is useful for understanding the terrain.

Next, using processing tools in QGIS or ArcGIS, one can determine the catchment area that will be effective for a point in the middle of the chosen location. Once the water catchment area has been determined, further calculations can be run to visualise how the water will flow within the area of interest. Useful calculations include the topographic wetness index (TWI) calculations and river channel Strahler order calculations. TWI is an index which combines local upslope contributing area (a) and slope (β) to quantify the topographic control on hydrological processes, based on a simple equation as shown in 4.1 (Sörensen, Zinko, & Seibert, 2006).

$$TWI = ln(\frac{a}{tan(\beta)}) \tag{4.1}$$

The usual values for TWI range between -3 and 30 (Ballerine, 2017), whereby a low number means that the area will not accumulate water whereas higher index numbers have a higher chance of accumulating water.

The Strahler order calculation is another GIS processing tool that calculates the stream order which is based on the concept that when two rivers of order N join, they will form a river of order N+1 (Scheidegger, 1965). This calculation, when run in a GIS program, makes a geohydrological analysis to predict all the streams in an area, whereby each stream is given a Strahler order number. The higher the Strahler order, the greater the discharge of the river. Streams with low Strahler order are often only seasonally wet and may not be shown on geologic maps or satellite images. Regardless, it is still useful to know the location of low Strahler order streams, as after heavy rainfalls might become active streams again. The Spain pilot study will give an example of how the TWI and the Strahler order supporting modules can be used to gain additional information about an area of interest.

The land cover module works by checking the land cover of a given area at the end of the decision tree process. Areas with localised tree cover can be expected to have higher organic content than the surrounding soils. The Netherlands validation study will show an example of when this supporting module can be useful. This module is especially useful for units that have been determined using the soil genesis pathway.

Finally, the slope angle module is a simple module that calculates the slope angles in an area in degrees based on a DEM. Although a slope angle map is simple, it is very useful for the military to determine difficult terrain when going off-road. Most vehicles are able to handle a terrain with a slope of up to 20°. Although some military vehicles are able to traverse on slopes as steep as 60°, steep areas tend to be riskier and are better avoided if possible.

5 | Pilot study: Mali

The development phase of this research starts with an initial pilot study carried out at the location of a town called Konna in Mali. The goal of this pilot study is to use the decision tree workflow created to determine the expected soil cover at the chosen location. The exact location of the pilot study is a 100km^2 square located at quadrant 30PVB of the Military Grid Reference System (MGRS) mapping tiles as shown in Figure 5.1 below.

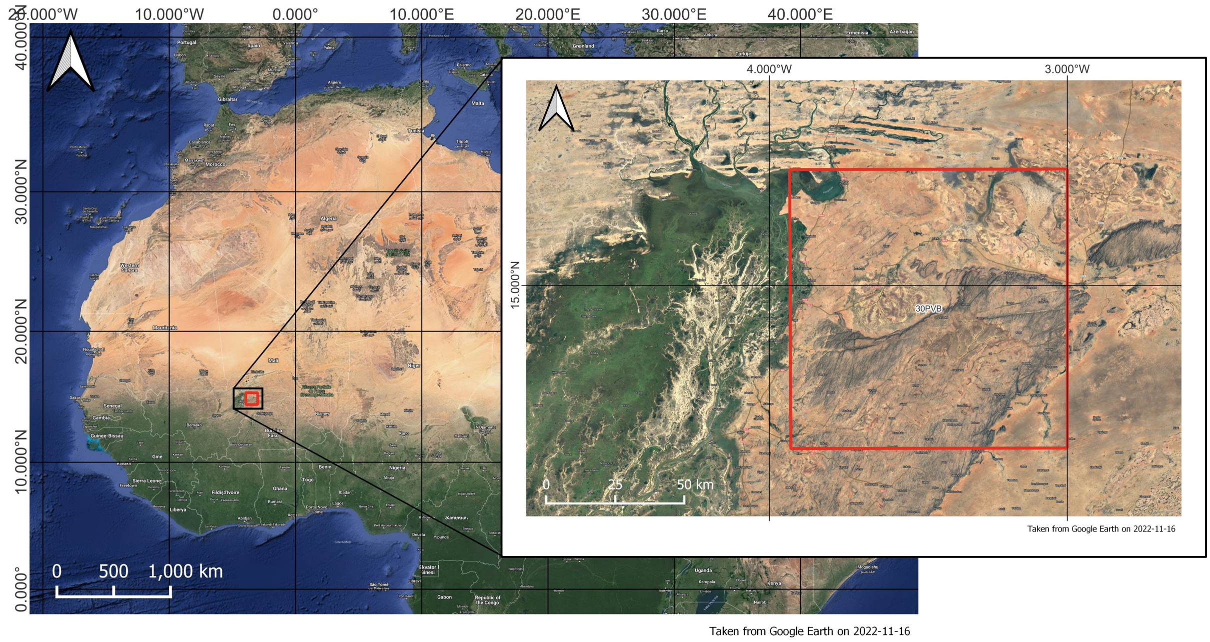


Figure 5.1: Location of pilot study in Konna, Mali. The red box shows the 30PVB MGRS tile.

5.1 Motivation for choosing this location

There are three main reasons motivating the choice of Konna, Mali as the location for the first pilot study. The first reason is that the Dutch Ministry of Defence has troops deployed there for humanitarian mission, thus making it a relevant case for illustrating the value of this tool in military decision-making. Second, this location is concurrently being used as a pilot study in the hyperspectral remote sensing project by NEO. Therefore, by choosing to make the study in the same location, we are able to cross-check the results and see the potential of using the two methods together. Finally, from a geologic standpoint, the town of Konna is an interesting location as it has river floodplains, sand dunes and mountains in close proximity, therefore, making a strong case for how the decision tree method can be used in complex areas.

5.2 Available data

The data used in this pilot study are mostly in the form of maps and literature. The types of maps used are tectonic, geologic, mountain bioclimate, land cover, soil taxonomical and Köppen-Geiger climate maps. A table showing showing the full list of maps used in the decision tree model for the area of Konna is attached in Appendix D.6.

Within the list, most of the maps used are generalised maps which provide information for the entire world. The only type of maps that must be area specific are the geologic maps. For this area, two scanned geologic maps were used. The first one is the Geological Map of the Bandiagara Plateau and Gondo Plain from 1934 (shown in Figure D.7). This map was made to a scale of 1:500,000 and comes with an explanatory document. The second map is the Geological Map of South Mali made in 1981 to a scale of 1:1,500,000 (shown in Figure D.8). Both of these maps were made by the French Geological Survey (BRGM), and therefore are annotated in French.

5.3 Background literature on the geological setting of Konna, Mali

Mali is a landlocked country in the west of Africa, which has been richly endowed with natural resources such as gold and kimberlite diamonds (Chirico, Malpeli, Anum, & Phillips, 2010; Montanistica, Ronk, & Kunr, 2001). The abundance of these resources motivated several studies into the geology of Mali. The area which we are interested in for this pilot study lies around the town of Konna which is visualised with a red dot in Figure 5.2.

As seen in Figure 5.2, the town of Konna lies in an interesting location. Not only is this town at the southern edge of the Taoudenni Basin, but it is also adjacent to the Inner Niger Delta to its west and the Dogon Plateau to its south. The Taoudenni Basin is a part of the West African Craton, an ancient craton, which is made up of crystalline sedimentary formations from the Archean period. During the Proterozoic, the West African Craton collided with the Tuareg shield to its northeast during an event known as the Eburnian orogeny. This collision resulted in the formation of various granite-gneiss complexes and granitic intrusions (Begg et al., 2009). Since then, the land has been tectonically stable, and any changes in the rocks are due to prolonged erosion and climate factors.

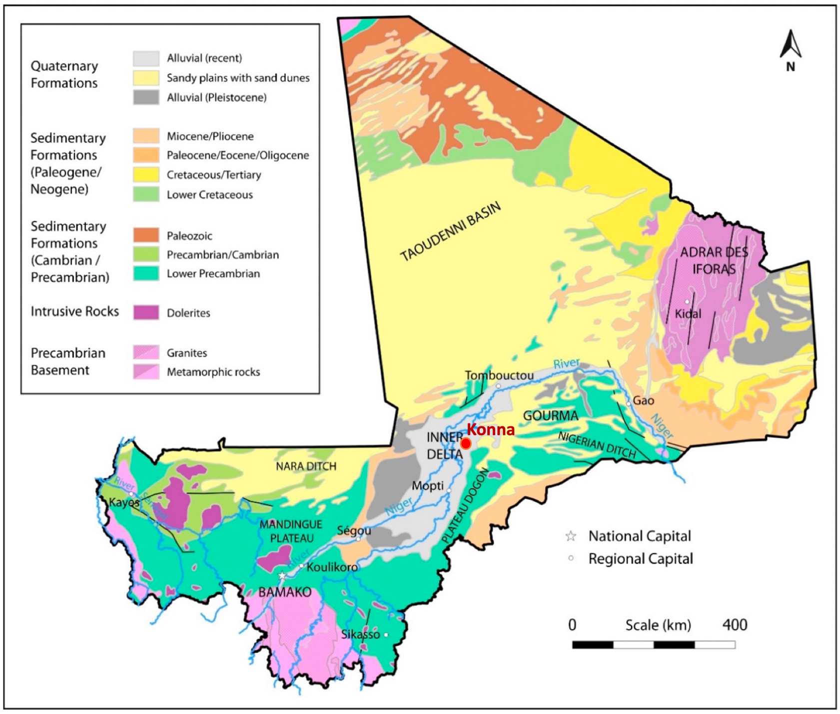


Figure 5.2: General geologic map of Mali, with a scale of 1:10,000,000, taken from Díaz-Alcaide et al. (2017). The red dot shows the location of the town of Konna.

Slightly south of Konna, in a town called Mopti, the Bani River merges into the Niger River, thus greatly increasing the discharge of the Niger River. As a result of the seasonal rainfall in summer which peaks in August (Abrate, Hubert, & Sighomnou, 2013), the Bani and Niger rivers flood the surroundings creating the lush floodplains known as the Inner Niger Delta. The Inner Niger Delta usually remains inundated throughout the months of September to December, during which silty clay alluvium is deposited to the land annually.

Although central Mali experiences a rainy season, the climate is primarily hot and arid. In fact, the area also experiences a seasonal dry season from October to May (McTainsh, Nickling, & Lynch, 1997). During the dry season, especially in December, the Harmattan wind blows over from the Sahara towards the Gulf of Guinea. This wind brings over aeolian silts which fills up the Taoudenni Basin and also settles over the floodplains in the Inner Niger Delta. As a result, the soils within the Inner Niger Delta are made up of cyclic deposits of river alluvium and aeolian silts superimposed. (Jacobberger, 1987).

5.4 Prediction of USCS soil classes using decision tree

5.4.1 Making soil units

The first step in using the decision tree model is to define units based on the geologic maps. As two geologic maps have been in this study, some decisions had to be made on which map to follow as there were slight variations between the two maps. As the main difference between the two maps was that the larger scaled map (Figure D.7) differentiated between sand dunes and a unit called *"clayey sand with pisolites"*, the decision was made to include clayey sand with pisolites as a unit of its own. The reason being, that when the satellite image and elevation map were considered, a difference was seen that suggested that there was indeed some type of hardening (pisolites) within the soil. The resulting map with units is shown in Figure 5.3.

Within the study area, five main units are identified: Bandiagara sandstone, sand dunes, clayey sand with pisolites, fluvial alluvium and laterite. The decision tree model will be used for each of these units to make a prediction of the expected soil cover.

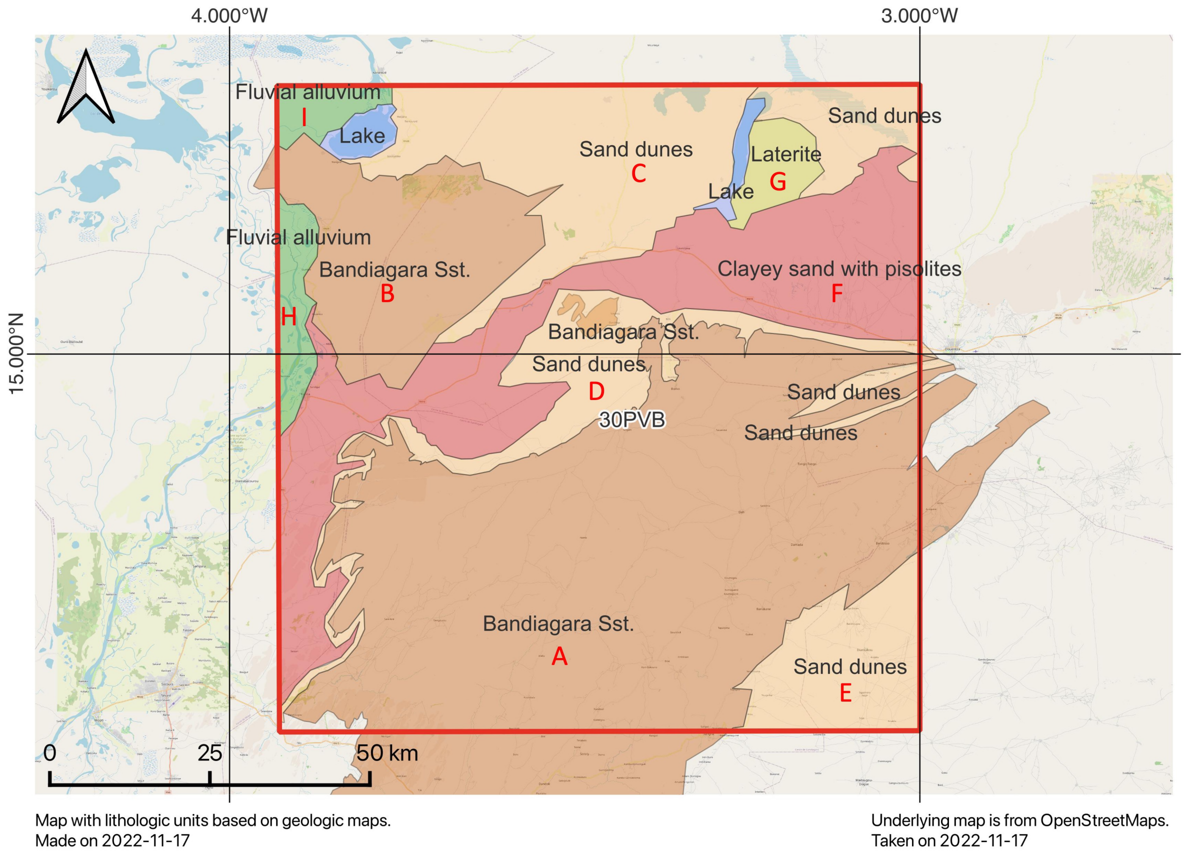


Figure 5.3: Units made for the area of Konna, Mali based on geologic maps.

5.4.2 Decision pathways

First, the tectonic setting of the area is checked using the global tectonic map (such as the one in Appendix D.2). Based on the map, the tectonic setting of the area falls under the *"Cratonic platforms and basins"* soil path. Based on this tectonic setting, the possible decision paths are shown in Figure 5.4:

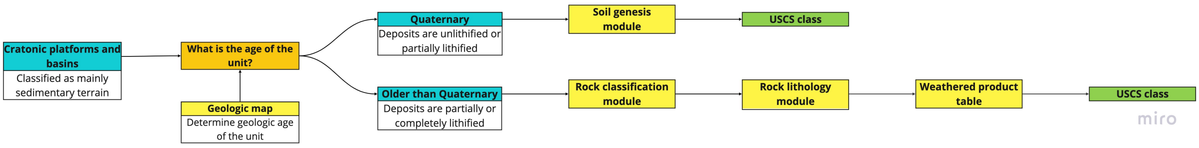


Figure 5.4: Possible decision paths for Mali pilot study.

The soil units made for the Mali map are then put through the decision paths shown above, whereby the unit either goes through the soil or rock modules to come to a final USCS class prediction. Figure 5.5 shows the full pathways followed in order to predict the USCS class for each of the units.

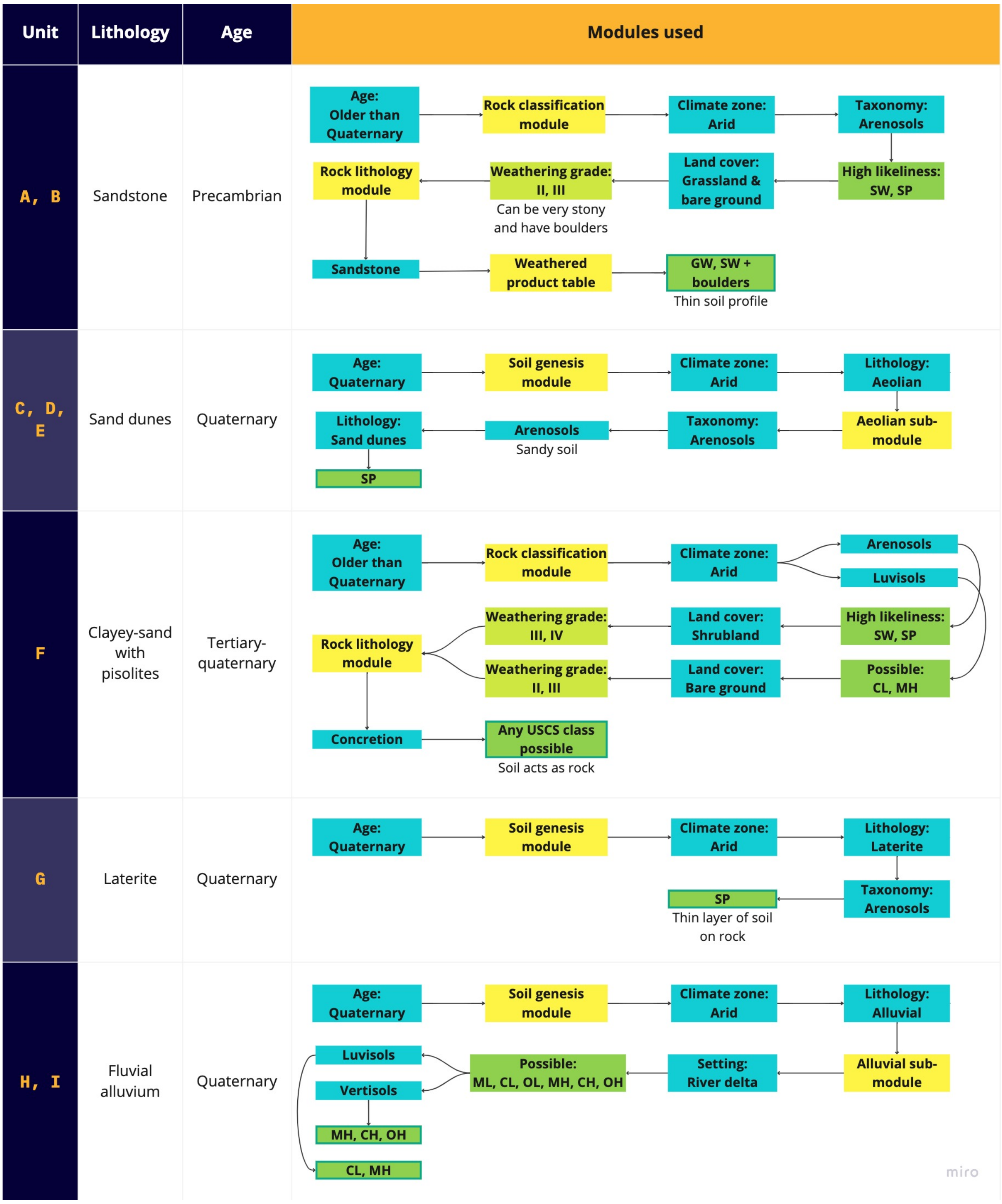


Figure 5.5: Decision pathways used in the Mali pilot study.

At the end of every decision pathway is one or more expected USCS class. The expected USCS classes are then filled in to the units made at the start of the model to produce a predicted USCS classes map, as is shown in Figure 5.6.

5.4.3 Resulting USCS soil map

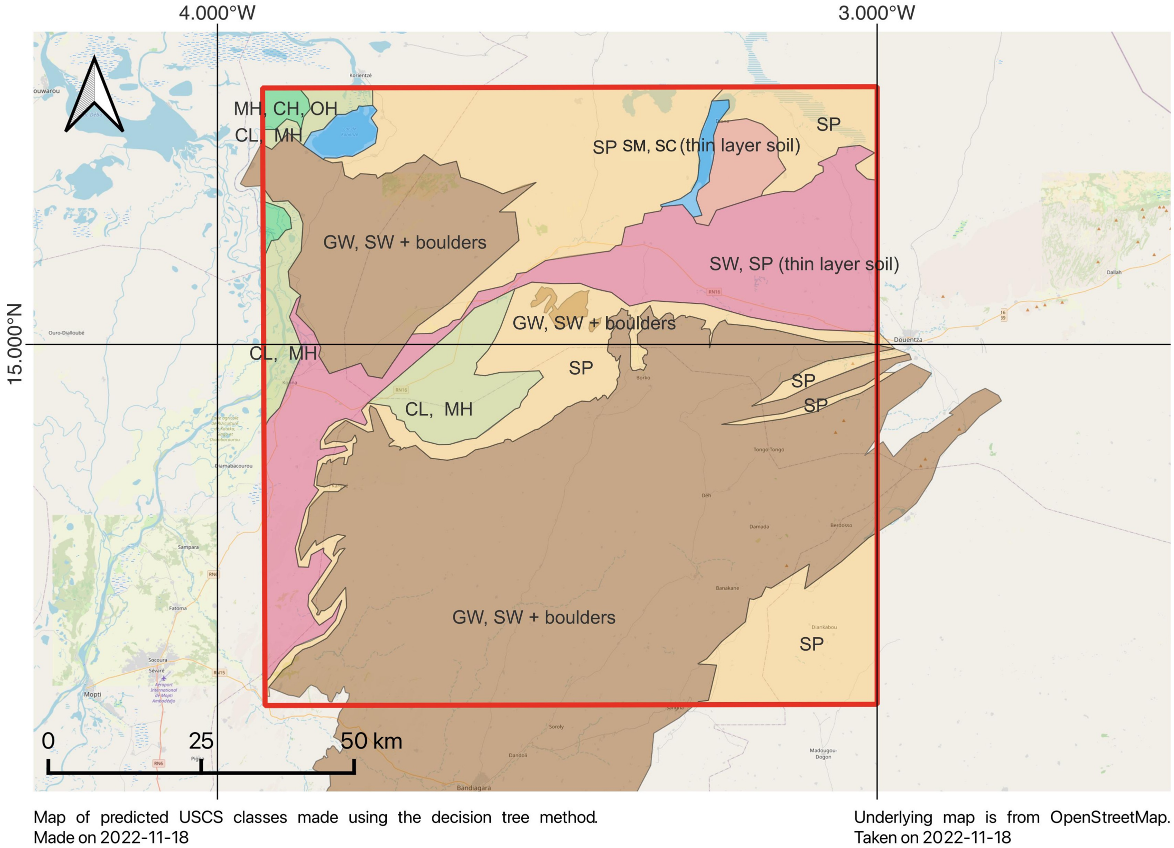


Figure 5.6: Predicted USCS soil map of Konna, Mali.

While going through the decision tree, units such as the *"clayey sand with pisolites"* and the *"fluvial alluvium"* units, had some internal variations based on the land cover and soil taxonomy maps. This can be seen in Figure 5.5, where the decision tree ends with two branches of USCS predictions. In order to incorporate these variations, the *"clayey sand with pisolites"* unit was subdivided into two units, shown in pink and light green in Figure 5.6. The pink unit is made up of arenosols with shrublands whereas the light green unit is made up of luvisol bare ground. As a result, the pink unit is classified as sandy SW or SP, whereas the light green unit belongs to the finer CL or MH classes.

Another tricky situation is when a decision branch has a *"High likeliness"* USCS prediction in the middle of the decision pathway. This situation occurs because the *"High likeliness"* USCS prediction is made using only part of the information, however by the end of the decision tree, the information might point towards a different conclusion. In this situation, it is important to fairly weigh the initial and final predictions, and based on that make a judgement call on the most likely USCS soil class. In this MSc research, the general belief followed is: when a repetition of the same class is seen in the *"High likeliness"* and end USCS prediction, then there is a higher probability of this class being present in the area, as more data supports this conclusion. Thus, often the repeated classes are kept in the final USCS prediction map.

A special case relating this conundrum is seen when dealing with the *"clayey sand with pisolites"* unit, whereby the end prediction of *"Any USCS class possible"* is not able to narrow down the possible USCS class. However, the middle of this decision branch does predict which classes have a high likeliness of occurring based on the soil taxonomical map and climate zone. Therefore, the *"High likeliness"* predictions are used in making the final map.

5.5 Validation of predicted USCS soil map

As there are no proper USCS maps available for this area, an estimation of the expected USCS class is made based on the Harmonized World Soil Database (HWSD) soil map by converting the USDA soil classes to USCS soil classes. The conversion of classes is made according to a paper by the US Army Corps of Engineers (Zakikhani et al., 2017). The relevant paper from this study is attached in Appendix B.4. Figure 5.7 shown the expected USCS classes based on the HWSD map.

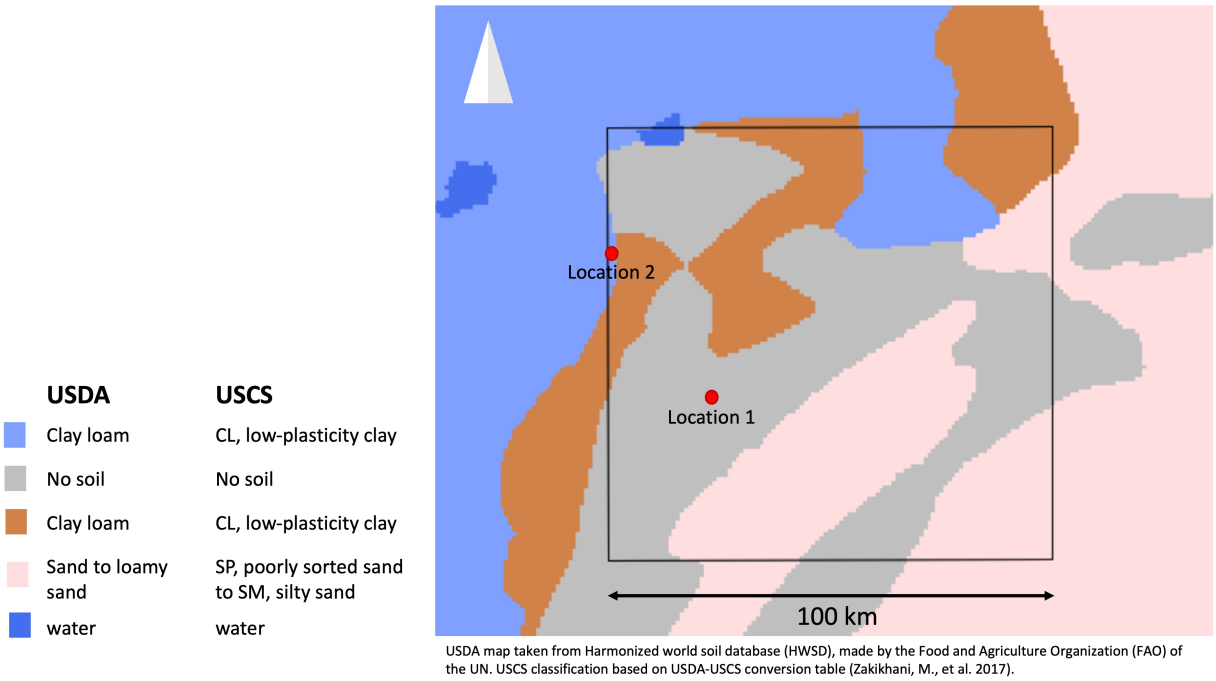


Figure 5.7: Mali soil map made by the Harmonised World Soil Database (HWSD) project by the FAO at a scale of 1:5,000,000 published in 2012.

The HWSD soil map shows four main soil units in the Mali pilot study area. In general, the soil classes shown in the HWSD map are similar to the ones predicted by the decision tree method, thus proving that the decision tree method is able to differentiate various different units in close proximity.

For example, in the HWSD map, the Bandiagara Sandstone unit is mostly not given a soil class (seen in grey) except for on top of the southern sandstone cliff (seen in pink) where some sand to loamy sand is expected (SP and SM). The decision tree map represents all the sandstone cliffs as an area with a thin soil profile consisting of gravel or sands (GW and SW). This description is similar to the validation map as both maps suggest very little soil formation, whereby if any soil is present the texture of the soil is expected to be sandy. A photo of this unit (at Location 1) is shown in Figure 5.8a. This photo shows the steep sandstone cliffs which are covered with sparse vegetation. As is seen in this photo, there is only a thin soil cover and most of the soil is in the form of weathered sandstone, which includes large blocks. Although the picture is a bit blurry, the opposing cliff shows a large scree slope.

Next, looking at the unit in between the two sandstone cliffs (shown in brown in the HWSD map), both the HWSD and decision tree map suggests that the soil is a low plasticity clay, CL. The decision tree goes on to predict that the areas right next to the sandstone cliffs are more sandy. This distinction is not seen in the validation map which has been made to a smaller scale.

Lastly, the soil prediction for the Niger delta and the surrounding sand dunes are the same in both the HWSD and decision tree map; as CL and SP respectively. For the Niger delta unit, the decision tree also predicts MH and, in specific areas, CH and OH as possible soil classes. This distinction is once again not captured by the HWSD map which is made on a coarser scale.

A photo of the soils next to the Niger River (at Location 2) is shown in Figure 5.8b. This photo shows red soils in the flat plains next to the Niger River. This is not a surprise as red soils are very common in Africa due to iron accumulation in the soil. The prediction for this soil to be CH is possible as red soils tend to have high clay contents. According to Eswaran (1988), the clay minerals act as a template for the concentration of iron, which leads to the reddish colour.

(a) Location 1 (Damagari, Mali)

(b) Location 2 (along the Niger River)

Figure 5.8: Photos of Location 1 and Location 2 taken from Google Earth. Shown in larger size in Appendix D.6.

5.6 Comparison of results using TGH and hyperspectral methods

As mentioned at the start of this chapter, one of the reasons for choosing Mali as the pilot study location was to be able to compare the results with the hyperspectral method. The hyperspectral method uses training data to classify similar spectral reflectivity bands into a single class. These classes can then be compared to the classification made by the total geological history (TGH) method to see if there are any visible similarities in the classification or if they can be used to improve the other. The hyperspectral classification made by a student, Tom Flipsen (2022), from the University of Utrecht is shown in Figure 5.9. It is useful to note that the classification by Flipsen (2022) is made using two different PRISMA satellite (by the Italian Space Agency) images. Therefore, the classification is divided into Soil Type map A and B. As a result, the quality of the classification in map A and B are slightly different.

Figure 5.10 shows the predicted USCS map superimposed on the hyperspectral classification map for comparison purposes. Based on this figure, it can be seen that the hyperspectral method's identification of the Bandiagara Sandstone formation is similar to that of the TGH method. Moreover, the hyperspectral classification is also able to recognise the vegetation growing in the fracture lines on the southern sandstone cliff. Next, the area which the hyperspectral classifies as dunes also correlated to the areas the decision tree classifies as SP. One difference however, is the TGH also shows part of the dunes as SW, SP (thin soil cover), whereby 'thin soil cover' could hint to a hardened layer being present below the sand, which could possibly hint towards the presence of a lateritic layer.

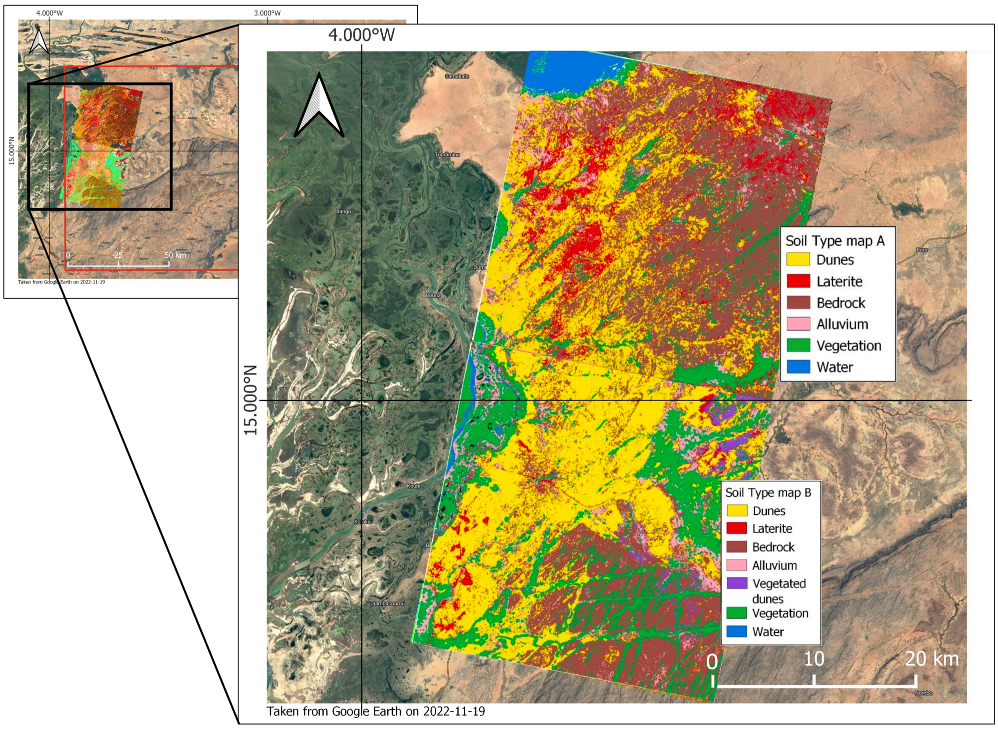


Figure 5.9: Hyperspectral classification made by Flipsen (2022).

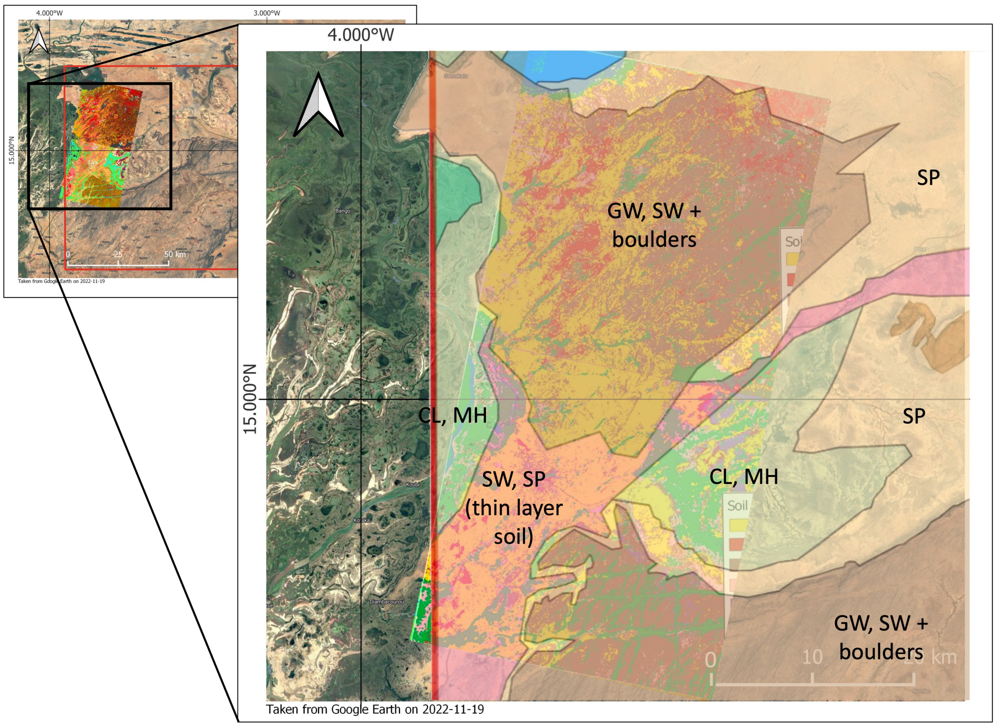


Figure 5.10: Predicted USCS map superimposed on hyperspectral classification made by Flipsen (2022).

The hyperspectral method is able to recognise several patches of red laterite soil within this unit. In fact, the classification between laterite and sand dunes is much finer in the image of the hyperspectral classification.

Finally, the hyperspectral recognises the vegetation present on the Niger River floodplains and in between the two sandstone formations. These soils, are classified as CL, MH using the TGH, however, if the units of the decision tree is looked at, the unit next to the floodplains is made up of fluvial alluvium whereas the unit in between the sandstone cliffs is a clayey-sand with pisolites. This distinction can give us information that although the two units are classified into the same USCS classes, they are in fact different soils.

When comparing the strengths and weaknesses of both methods, it can be seen clearly that the hyperspectral is able to make a more detailed classification than the TGH method. As the hyperspectral method uses classification algorithms, it is able to detect features faster and with more detail than would be possible with the manual inspection of maps. However, by the same token, since the hyperspectral method is very sensitive to variations in the soil reflectance profiles, it may therefore may distinguish separate soil classes where none exist. For example, Flipsen (2022) mentions that the laterite soil in Soil Type map A is likely over-represented, due to the quality of the training data. This is where the hyperspectral method can benefit from some knowledge-based judgement which can be provided by the TGH method.

On the other hand, the hyperspectral method is less capable of determining the properties of the distinguished features, which the TGH method is able to allude to by understanding the local geology. The hyperspectral method is good at grouping together similar soils as one soil class, however it is not yet able to make a solid prediction of what the soil properties are, and therefore it is dependent on having good training data. This is where the TGH method can shine, as it is able to classify soils based on their genetic properties. For example, the area that the hyperspectral method classified as vegetation, is classified as CL, MH by the TGH method, whereby a further division can be made to distinguish the fluvial alluvial soil from the clayey sand with pisolite soil.

All in all, the results of the TGH and hyperspectral method are able to complement each other nicely, and this leaves scope for future integration of these two methods into a combined method that is able to take advantage of the the strengths of each method.

5.7 Impact on mobility

Mobility of military vehicles depend on much more than just USCS soil classes, yet an attempt can be made in making a reasonable prediction for mobility by combining USCS soil data with terrain ruggedness (in the form of a slope angle map), topographic wetness index (TWI map) as well as the knowledge inherent to the TGH approach.

Based on the predicted USCS map of Konna, Mali in Figure 5.6, five different types of soil units were recognised. Each soil unit has its own unique characteristic which should be taken into account when traversing. These characteristics are described in Table 5.1 below.

Unit	USCS class	Consequences for trafficability
Bandiagara Sst.	GW, SW + boulders	Presence of boulders may make the road bumpy. Large boulders can occur near slopes, and may obstruct mobility.
Sand dunes	SP	As there is little to no vegetation, dunes might be migratory. Height of dunes should be checked, as high dunes can reduce visibility may be steep.
Clayey sand with pisolites (arenosols)	SW, SP	Soil has concretions, this is good for mobilty.
Clayey sand with pisolites (luvisols)	CL, MH	Medium plasticity soils; strong when dry, can be sticky when wet.
Fluvial alluvium (vertisols)	MH, CH, OH	High-plasticity soils with organics; low bearing capacity and can cause tyres to get stuck if muddy.
Fluvial alluvium (luvisols)	CL, MH	Medium plasticity soils; strong when dry, can be sticky when wet.
Laterite	SM, SC	Hardened top layer, good for mobility.

Table 5.1: Mobility predictions based on characteristics of units and USCS classes.

Next, a slope angle map is made for the study area. As there is no specific type of vehicle for this study, the maximum climb angle of the vehicle is chosen to be 25°; a conservative value for a military vehicle. As con be seen in Figure 5.11, areas with slope angle greater than 25° are visualised with dark purple such that they are obvious in contrast to the light yellow surroundings. The majority of the mapped is mapped as light yellow meaning the area has a slope angle of less that 5°. As can be seen in the figure, there are steep cliffs surrounding the Bandiagara Sandstone formation. These cliffs will pose a challenge to trafficability as the military might have to take longer routes to go past the steep cliffs.

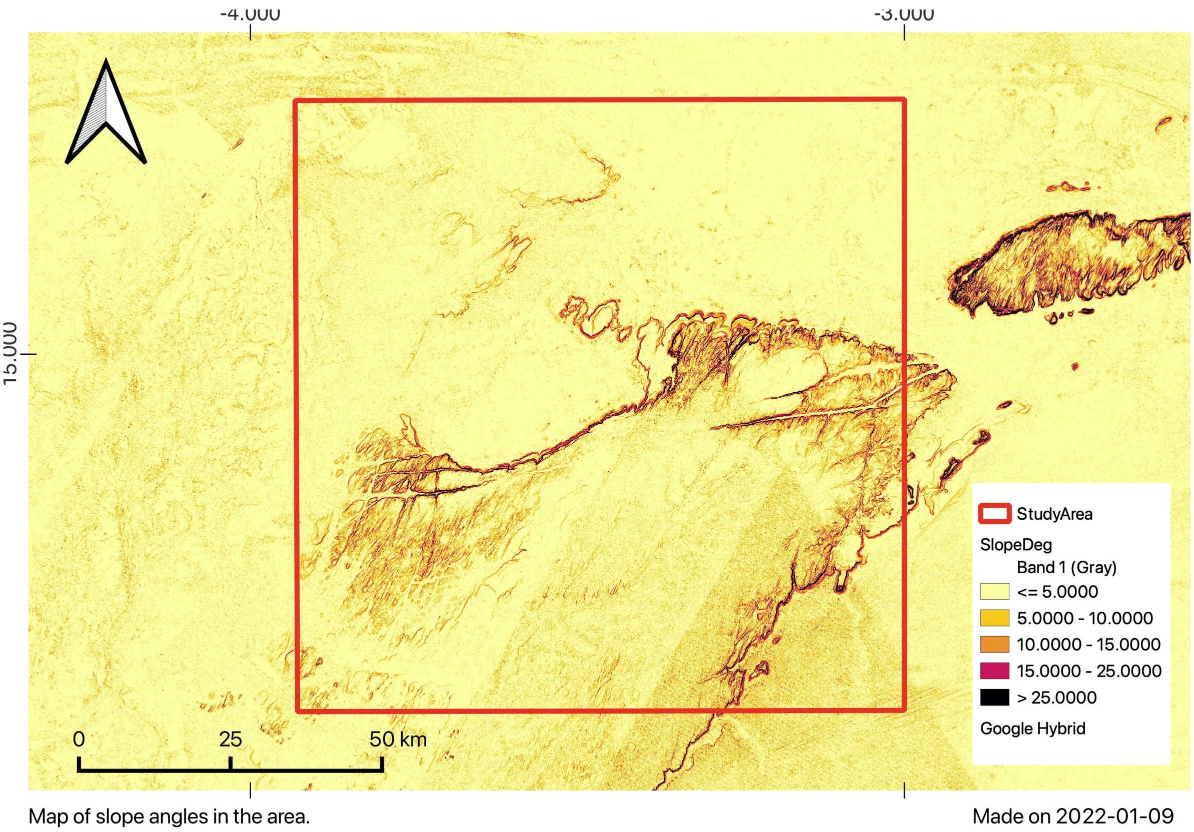


Figure 5.11: Slope angle map made for Konna, Mali.

Finally, a TWI map is generated to visualise areas that can accumulate water after a rainfall. The TWI map for Konna, Mali is shown in Figure 5.12. Small stream patterns can be seen throughout the study area. It is interesting to note that most of the obvious streams are flowing towards the southwest of the map. There are streams flowing down from the southern Bandiagara Sandstone formation and also streams flowing into the low area between the two Bandiagara formations. Between the two Bandiagara formations, the unit is 'clayey sand with pisolites (luvisols)' and is predicted to be CL or MH. These medium plasticity soils can prove to be tricky when wet due to their inherent stickiness and plasticity. Therefore, attention should be paid to this area after rainfall.

Furthermore, as Mali is in an arid climate zone, the risk of flooding after rainfall is high, especially on soil which has concretions or laterite. The hard crust of such soils prevent water from being absorbed immediately.

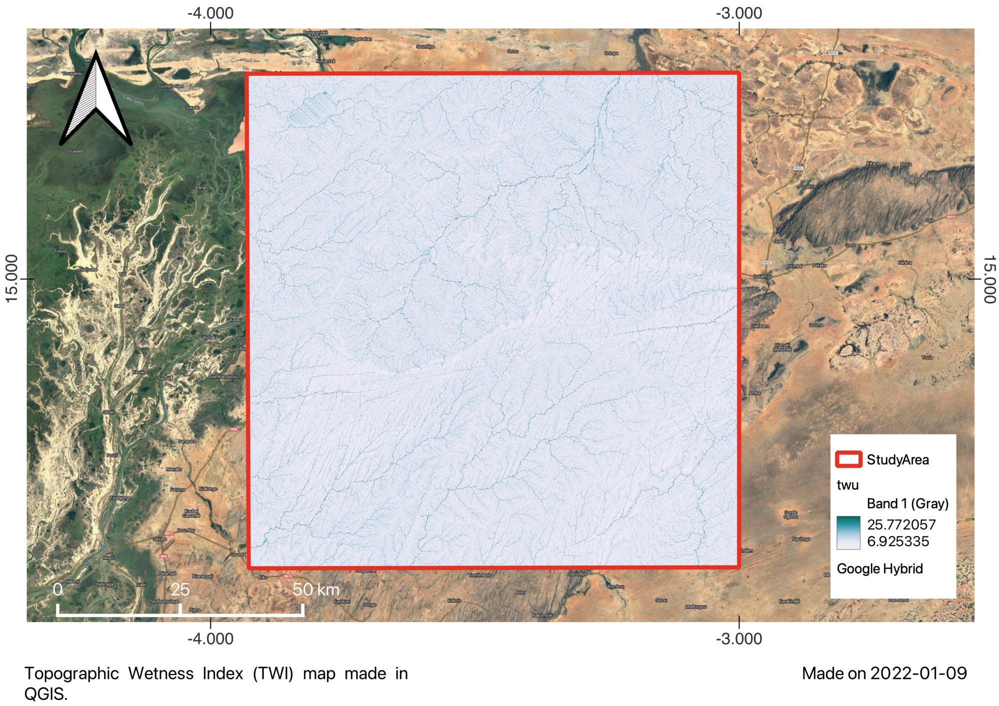


Figure 5.12: Topographic wetness index (TWI) map made for Konna, Mali.

In conclusion, the mobility for the area of Konna during the dry season is relatively good, with the exception of the scree slopes and steep cliffs along the Bandiagara Sandstone formations. During the wet season however, the Niger River floodplains as well as the low area in between the Bandiagara Sandstone formations might flood. The floodplain soils during this time can be risky to traverse upon as they are sticky and have low bearing capacity. Finally, being in an arid zone with sand dunes, sandstorms may also affect mobility.

6 | Pilot study: Spain

As the Mali pilot study showed promising results for the decision tree method, a secondary pilot study was decided to be done in order to test the reliability of the method using another location. The location for the second pilot study was chosen to be in northwestern Spain, in the vicinity of a town called Zamora. The exact location of the pilot study is a 50km x 100km rectangle which covers the upper quadrants of the 30TTL and 30TUL of the Military Grid Reference System (MGRS) mapping tiles as shown in Figure 6.1 below.

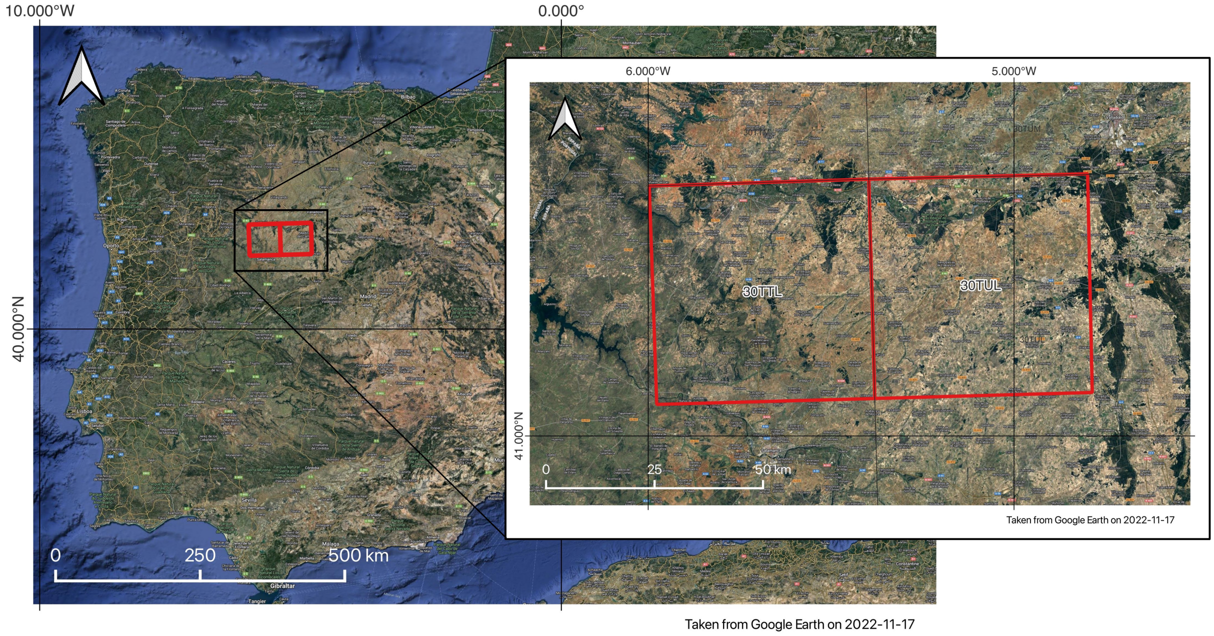


Figure 6.1: Location of pilot study in Zamora, Spain. The red boxes show the 30TTL and 30TUL MGRS tiles.

6.1 Motivation for choosing this location

The choice for using the area near Zamora, Spain as the second pilot study location is motivated by two main reasons. Firstly, this area is also being used in a concurrent study by NEO to generate soil temperature and moisture content maps using remote sensing methods. The town of Zamora is chosen because it is part of the REMEDHUS soil moisture network (Martínez-Fernández & Ceballos, 2003) and is therefore well documented. This will allow us to make a study on how soil USCS data can be used alongside soil temperature and moisture data to determine the trafficability of an area. Secondly, this location lies within a basin that is surrounded by three mountain ranges: Cantabrian, Central and Iberian mountain ranges, therefore giving the area an abundance of natural topography that has been shaped by rivers. This makes it is a useful area to visualise how the supporting modules (using elevation and stream order calculations) can be used to further determine local wet-spots or areas with higher organic content.

6.2 Available data

In addition to the general maps required by the decision tree model, this pilot study makes use of geologic maps that indicate both the age and lithology of units in the area. The first geologic map used is part of the National Geological Map (MAGNA) series made by the Geological and Mining Institute of Spain (IGME) between 1972 and 2003. These maps are made to a scale of 1:50,000 and are highly detailed, such that each map sheet comes with its own explanatory document in Spanish. Although, detailed maps are appreciated for the decision tree model, the MAGNA map sheets were hard to use because a total of 9 map sheets would be needed to cover the study area, and the legends used from one map sheet to the next were not consistent.

In order to overcome this problem, the decision was made to use a smaller scale map that could cover the study area within one sheet and would be easier to make units out of. Therefore, the Geological Map of Spain at scale 1:1,000,000 (1994) was chosen to be used. This map was also made by the IGME and denotes the geologic age of the units. In addition to this map sheet, a similar map made by the Portuguese National Laboratory of Energy and Petroleum (LNEG) which included the lithology of the units in the legend was chosen to be used together. A full list of the maps used in the decision tree model for the area around Zamora is attached in Appendix D.7.

6.3 Background literature on the geological setting of Zamora, Spain

Zamora is a city in northwest Spain, famous for its Romanesque architecture art. Apart from being a popular tourist destination with cruises along the Duero River running from March to October, a big part of Zamora's economy lies in agriculture. For this reason, a large portion of the studied area is cultivated farmland.

From a tectonic standpoint, the town of Zamora has undergone a complex history with multiple orogenies leading to the formation of the Duero Basin in which it sits today. The location of the Duero Basin is visualised in Figure 6.2 below.

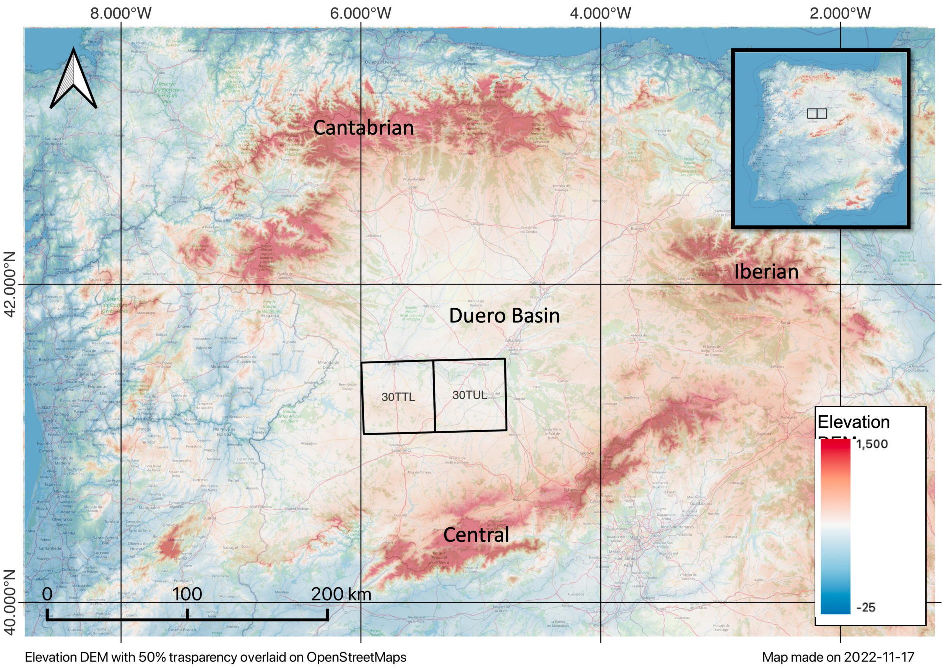


Figure 6.2: Location of the Duero Basin.

Spain lies on the Iberian Plate which came into existence on the margin of the Gondwana continent during the Precambrian. During the Late-Devonian to Carboniferous, the Variscan orogeny begins where Gondwana collides into Laurussia. This results in metamorphism and uplift of rocks from the Late-Cambrian to Carboniferous which can be seen to outcrop in the western part of the Iberian Peninsula. The Variscan orogeny also resulted in intrusion by different types of granitoids which can be seen outcropping in the Central Mountain Chain.

During the Early Permian, the Iberian Plate starts to experience rifting which resulted in the formation of the Iberian Basin, which is today known as the Duero basin. The rifting continues until Pangaea breaks up in Late Jurassic. During this time, the Duero Basin was in a marine environment which allowed carbonate sediments to be collected in the centre of the basin.

Finally, during the Cretaceous, the Alpine orogeny begins, whereby the Iberian Plate collided with the European Plate and formed the Alps, Pyrenees, and Iberian and Central chains. This caused uplift of the borders of the Duero Basin and retreat of the marine environments. This phase also induced progradation of alluvium systems towards the centre of the Duero Basin, whereby the Duero River acted as a drain, evacuating enormous volume of sediments into the Atlantic Ocean. There used to be many lacustrine environments within the Duero Basin, but eventually the uplift and drainage of sediments through the Duero river caused the lacustrine environments to disappear (Arche & López Gómez, 2013; Martínez-Catalán, Aller, Alonso, & Bastida, 2009).

Today, Zamora experiences Mediterranean climate, with hot and dry summers and moderately cold and wetter winters (Climate-Data.org, n.d.). The Köppen-Geiger climate zone of Zamora is mostly arid (Bsk) with a bit of temperate (Csb) climate in the hills on the west.

6.4 Prediction of USCS soil classes using decision tree

6.4.1 Making soil units

The first step of using the decision tree is to make soil units based on the geologic map. In this pilot study, the process of making units was relatively straight forward as the units were made based on the Geological Map of Spain at scale 1:1,000,000 (1994). However, at some places it was noticed that the units representing the alluvial sediments from the river distributaries of the Duero River were not aligned with the current location of the streams based on the Google Earth map. Therefore, the LNEG soil lithology map was used as reference to make the units for these river streams. The resulting map with units is shown in Figure 6.3 below.

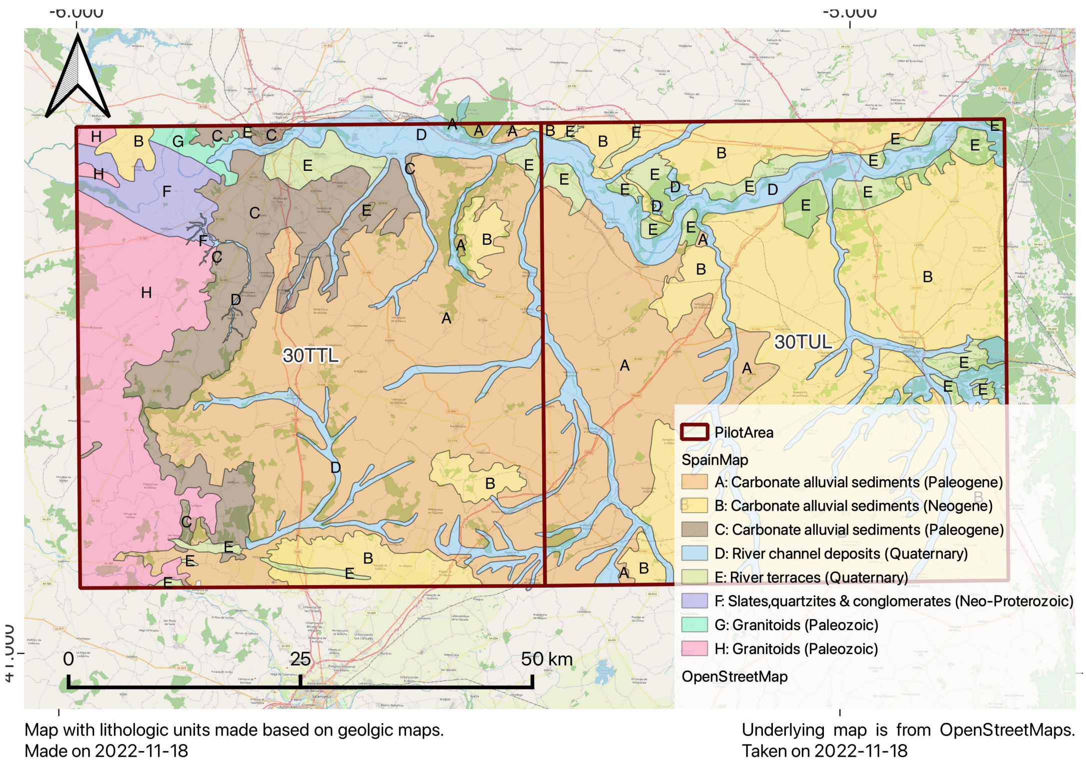


Figure 6.3: Units made for the area of Zamora, Spain based on geologic maps.

6.4.2 Decision pathways & river block model

Once the units have been made, each unit is then put through the decision tree. As seen in Figure 6.4, units with similar lithologies and age are put through the decision tree together to reduce repetition in the workflow.

To expand on this point, units A, B, and C are all calcareous alluvial sediments from the Paleogene to Neogene period. The lithology of these units are described as conglomerates, sandstone, slate, limestone and evaporites. Based on what is known from the literature study, the wide variety of lithologies are likely from the time that the Duero basin was undergoing uplift due to the Alpine orogeny. During this time, the conditions within the basin were changing from marine and alluvial to terrestrial. As a result, the area has highly heterogeneous deposits which are reflected by the diversity soil taxonomical classes. Units A, B and C are then further divided into smaller units based on the soil taxonomical class, as can be seen in the resulting USCS map in Figure 6.6. All other units are classified as per the normal procedure.

For unit D, which are river deposits from a meandering river system, more information can be derived by using the meandering river block model. This block model is shown in Figure 6.5.

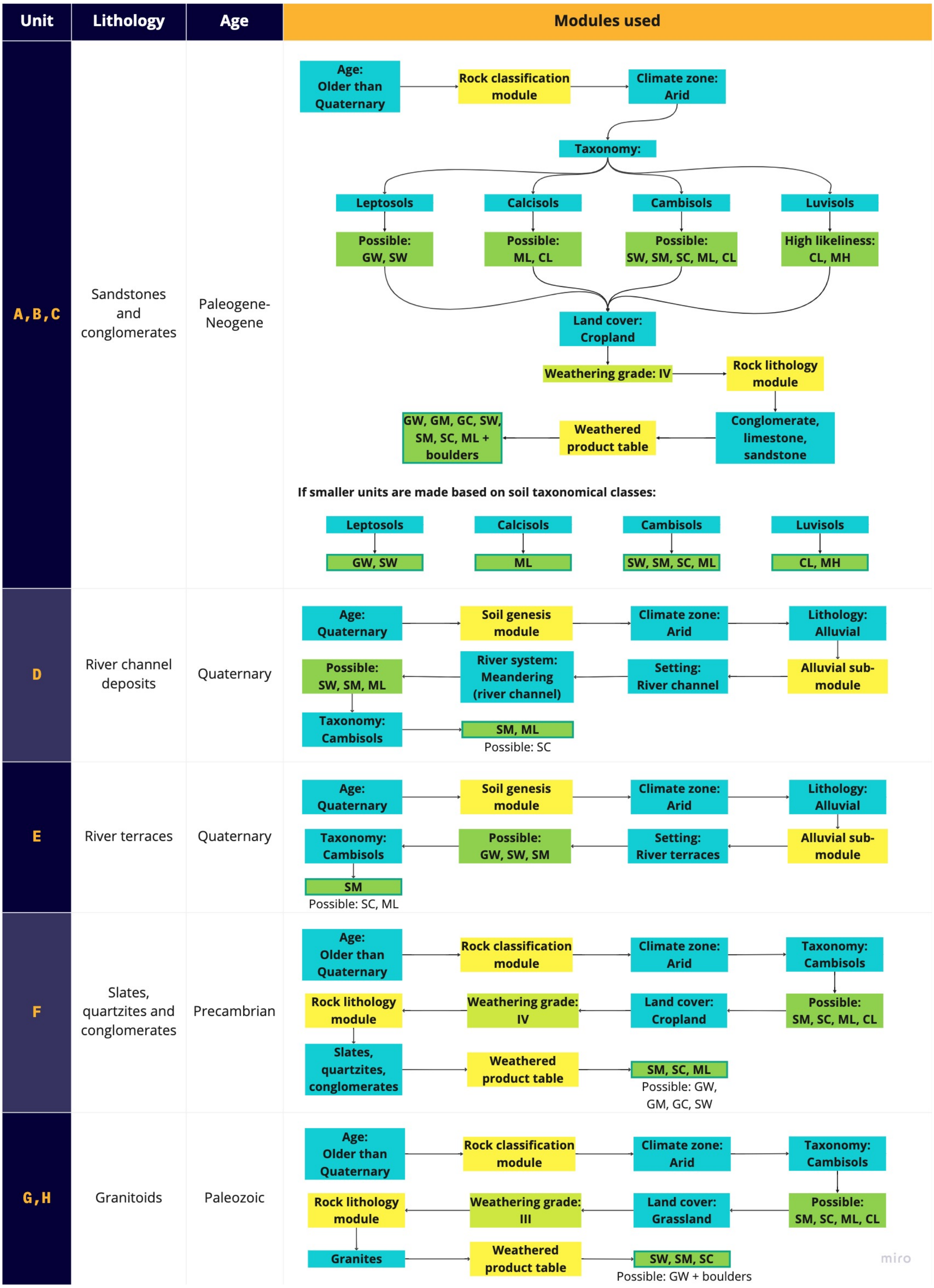


Figure 6.4: Decision tree pathways used in Spain pilot study.

Based on the block model for meandering rivers, there are several features we can expect in the area surrounding the Duero River. For example, by the river banks we can expect sandy levees. However, in some places the river might have broken through the levee to form a crevasses splay. The soil within a crevasses splay tends to be sand and gravel near the river, but it slowly gets finer the further away we go from the Duero. These fine silts and clays can create fertile soils on the river floodplains. As vegetation starts to grow, the soils may also accumulate a layer of humus. However, as Zamora is within an arid climate zone, the accumulation of organic matter will be slow, unless the area is forested.

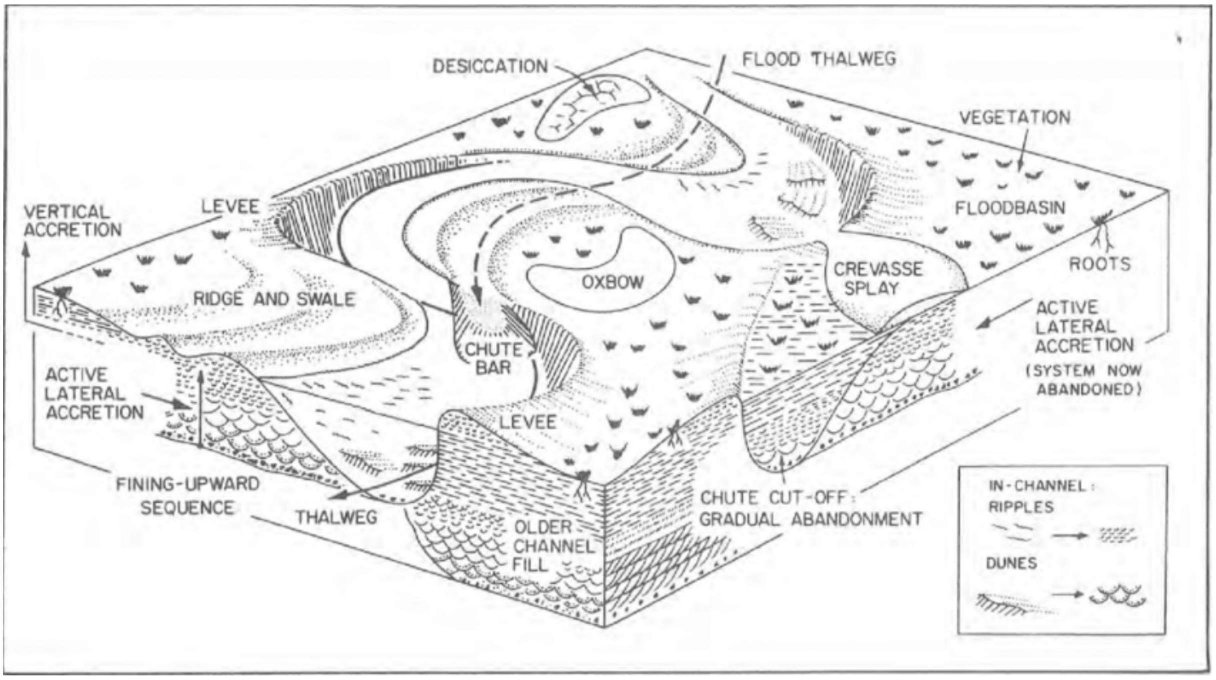


Figure 6.5: Block model of meandering river taken from Walker (1984).

The decision tree classified unit D as either SM or ML, with a chance of encountering SC. However, with the extra information gained from the block model, we can expect that in general the soils close to the Duero to be coarser, such as SM or even SW, whereas further away from the river the soils may transition to SC or ML, unless acted on by other factors.

6.4.3 Resulting USCS soil map

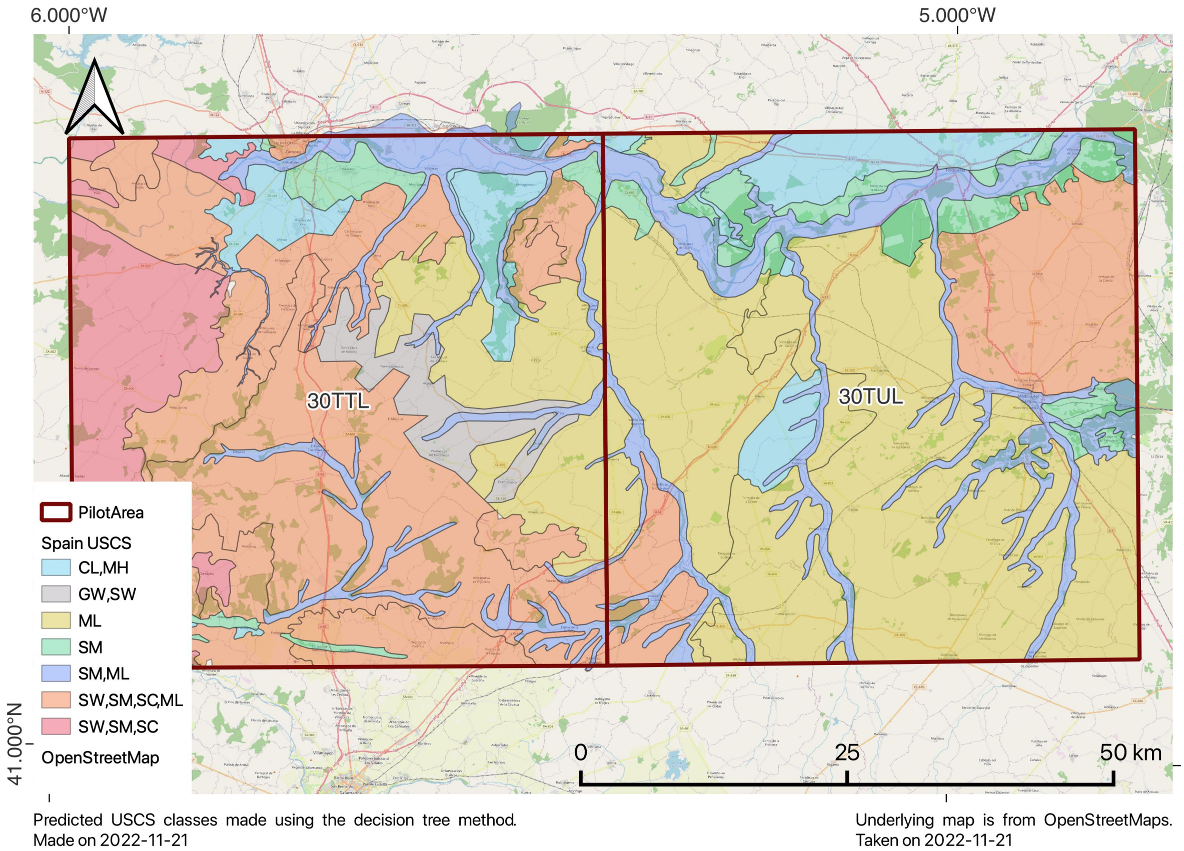


Figure 6.6: Prediction of USCS classes made for the area of Zamora, Spain using the decision tree.

Looking at the resulting USCS map, the first thing to notice is that many units have more than one possible USCS soil group. In fact, the same USCS soil class can appear within multiple units in combination with other USCS soil classes.

The large yellow area in the centre of the map belongs to the part of the Neogene marine or alluvial unit. Based on the soil taxonomical map, this area contains lime-rich soils, with possibly cemented layers, known as calcisols. These soils are classified as ML, therefore silty soils which are not very plastic.

Next, there are multiple soil units associated with the Duero river and its distributaries. Along the main river channel, the channel deposits (shown in purple) are classified as either SM or ML, whereas the river floodplains (shown in blue) are classified as fine grained CL or MH. As discussed in the previous section, it is likely for the soils close to the river bank to be sandy SM or SW, whereas the sediments further from the river bank could be finer, such as ML. This coincides with the fact that the floodplains are classified as CL and MH. Next to the river banks, there are also Quaternary river terraces, which tend to be coarser grained than the floodplains. These units are consequentially classified as SM.

The rest of the map has multiple possible classes, mostly with a medium-grained texture, from a Paleogene alluvial or marine origin, the weathering of Paleozoic granitoids or Precambrian metamorphic rocks. An interesting point to note is that the unit which is made for the Paleogene alluvial/marine sediments (shown in orange) is described using multiple lithologies in the geologic map. The heterogeneity expressed in the geologic map translates into having many possible USCS classes upon going through the decision tree model.

6.4.4 Validation of predicted USCS soil map

Although no USCS maps exist for the Zamora area, the area has been extensively studied for agricultural purposes. A 1:400,000 soil texture map was digitized and completed by The Agricultural Technology Institute of Castilla y León (ITAcyl) in 2011. This map, shown in Figure 6.7, classifies soils into four possible groups based on the FAO soil texture classes.

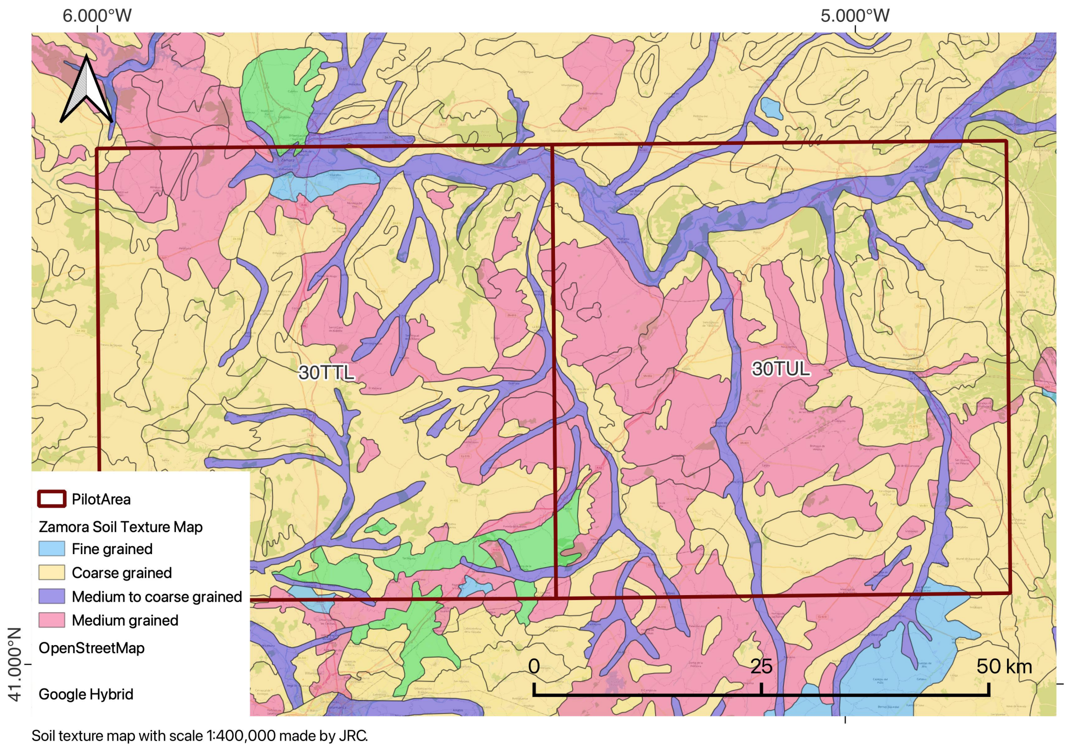


Figure 6.7: Soil texture map made by ITAcyl with a scale of 1:400,000. Light green is used where the soil texture class is undefined.

In order to validate the USCS map made using the decision tree method, the FAO soil texture classes have to be converted into USCS classes. This conversion is made based on *FAO Soil Textures* (n.d.) and Zakikhani et al. (2017). The conversion is shown in Table 6.1.

FAO soil texture class	**USCS class**
Coarse grained	SW, SP, (possibly SC)
Medium to coarse grained	SM
Medium grained	ML
Fine grained	SC, CL, MH, CH

Table 6.1: Conversion table from FAO soil texture classes to USCS.

Upon first glance at the FAO soil texture map, we can see some similar patterns with the USCS map. For example, the units surrounding the Duero River are classified as medium to coarse-grained soils. This classification is in accordance to the units determined using the decision tree method, as the decision tree suggests that the river channel banks and river terraces can be classified as sandy loam (SM) which is a medium to coarse grained soil. The decision tree also classifies a river floodplain unit which is classified as a clay loam (CL or MH), which in the FAO map is shown as a medium grained soil. Although the decision tree method predicts a soil that is finer grained than the one predicted by FAO, both maps agree that the floodplains are made up of a finer material than the river channel and banks.

Next, looking at the Paleogene-Neogene units which make up the majority of the map, both the USCS and FAO map predict the class of the lime-rich soils to be ML. As for the remaining Paleogene sediments, the USCS predicts the soil to be either SW, SM, SC or ML, which ranges from coarse to medium grained soils. Although, the FAO map classifies this unit as coarse grained sands, based on the geologic map and geologic history, we can expect local variations due to the conditions during the time of deposition. This heterogeneity is reflected in the USCS classification.

For the unit derived from weathered granite, the decision tree predicts the soil to be a sand rich: SW, SM or SC. The possibility of having a SW soil is in accordance with the coarse grained classification from the FAO map.

6.5 3D visualisation of the area using supporting modules

In this study, a couple calculations from the supporting modules are used to visualise local wetter spots to aid the soil classification and mobility predictions. Figure 6.8 shows the elevation DEM with a vertical exaggeration of 20 times. The high areas are shown with brown whereas the lowest areas are shown in blue. The Duero river is coloured blue in this visualisation. The areas right next to the rivers, which include the river banks and floodplains are shown in green.

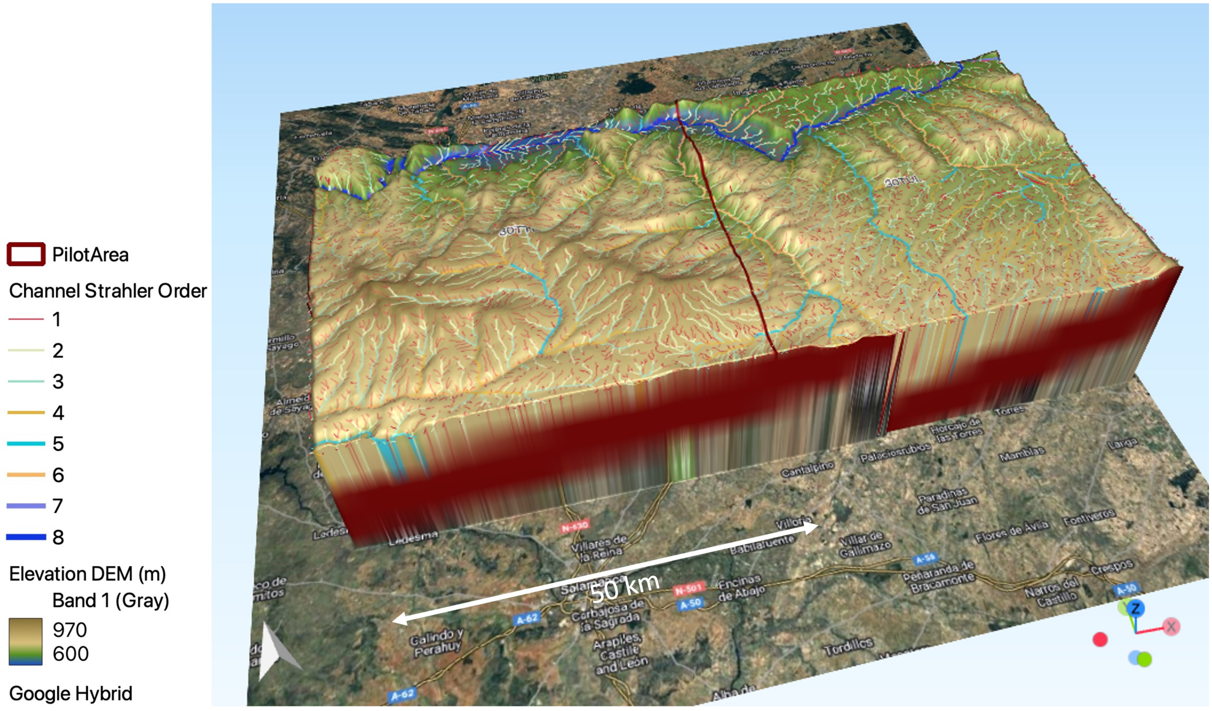


Figure 6.8: 3D visualisation of the digital elevation model (DEM) of Zamora, with channel Strahler Order. The vertical exaggeration is scaled by 20 for this visualisation.

The next supporting module used is the stream Strahler Order calculation. The way the Strahler order works is that, first, using the catchment area of a point (a point in the middle of the map sheet is chosen) all the streams expected within the area are calculated. Each initial stream is given a Strahler Order of 1. Then, whenever two streams merge, their Strahler order goes up by 1. This is done for the whole map, until the stream with the largest Strahler Order will be the main river in the area, which in this case is the Duero river. Using the Strahler Order calculations allows one to predict where local small streams may exist, which may not be visible on the geologic map. These small streams can cause local variations in the soil type and can help predict which areas will become water-logged after a rainfall event.

Alternatively, a calculation for the Topographic Wetness Index (TWI) can be run to determine areas which are expected to high soil moisture content. Similar to the Strahler Order calculation, the TWI is also available as one of the processing tools in the QGIS or ArcGIS toolbox. A map of the TWI calculated for Zamora, Spain is shown in Figure 6.9. It is important to note, that the TWI is a type of soil index, therefore the values calculated are relative and not absolute values that represent moisture content. Typically, TWI values range from -3 to 30 (Ballerine, 2017). As seen in Figure 6.9, the deep red areas follow the river and stream patterns similar to the Strahler Order map.

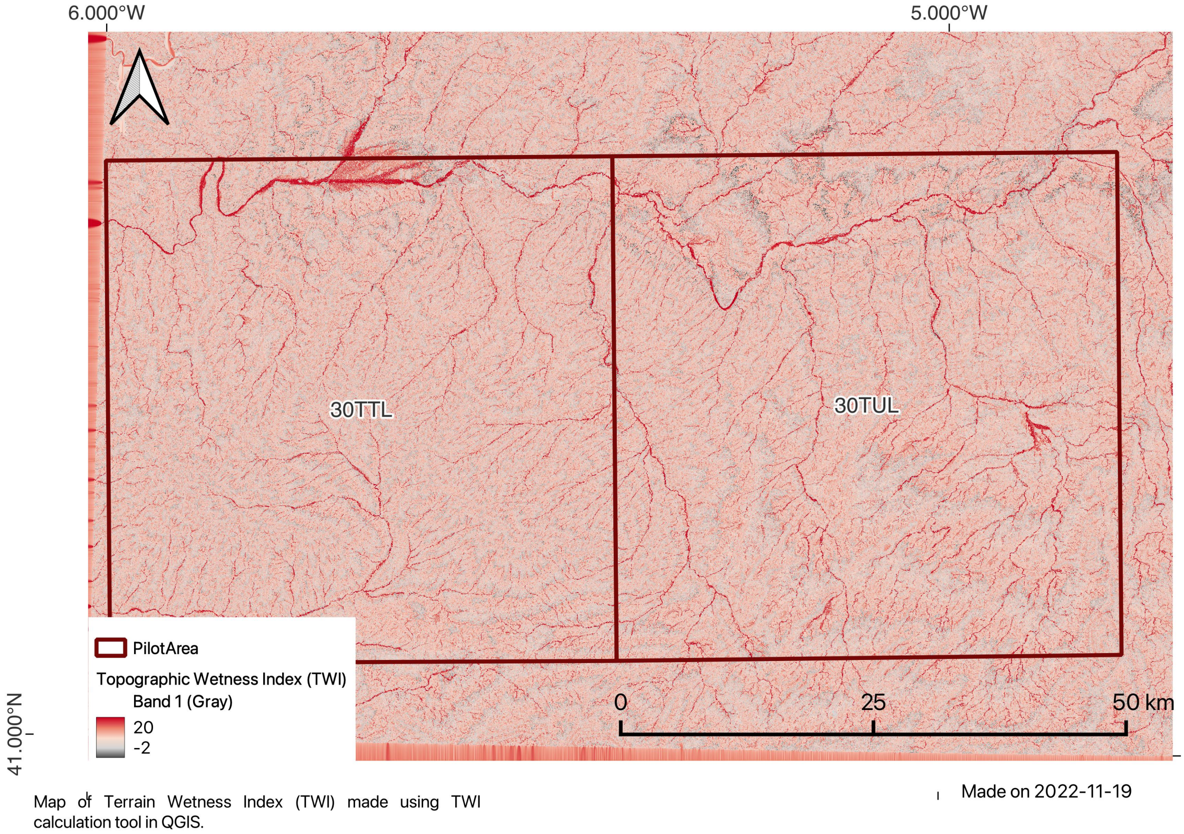


Figure 6.9: Topographic wetness index (TWI) map for Zamora, Spain made in QGIS.

6.6 Comparison of USCS soil map with soil moisture data

In order to determine the absolute values of soil moisture, maps such as in Figure 6.10, made by Flipsen (2022) can be used. These moisture maps can be used in combination with USCS soil maps to predict the trafficability of an area. It should be noted that several areas in the map are missing data, which are shown to be 0.

In Figure 6.10, several interesting patterns have been indicated that can be recognized in the data. For example, when looking at regions A and B, it can be seen that the soil moisture in region A consists of sharper transitions than region B, where smooth transitions are observed. Furthermore, it can also be seen that the average moisture is slightly greater in region A than in region B, which is recognized by the darker colour. The reason behind these differences is likely due to the fact that region A is hillier than B and the sharp transitions are a result of the topography, as can be seen in Figure 6.8.

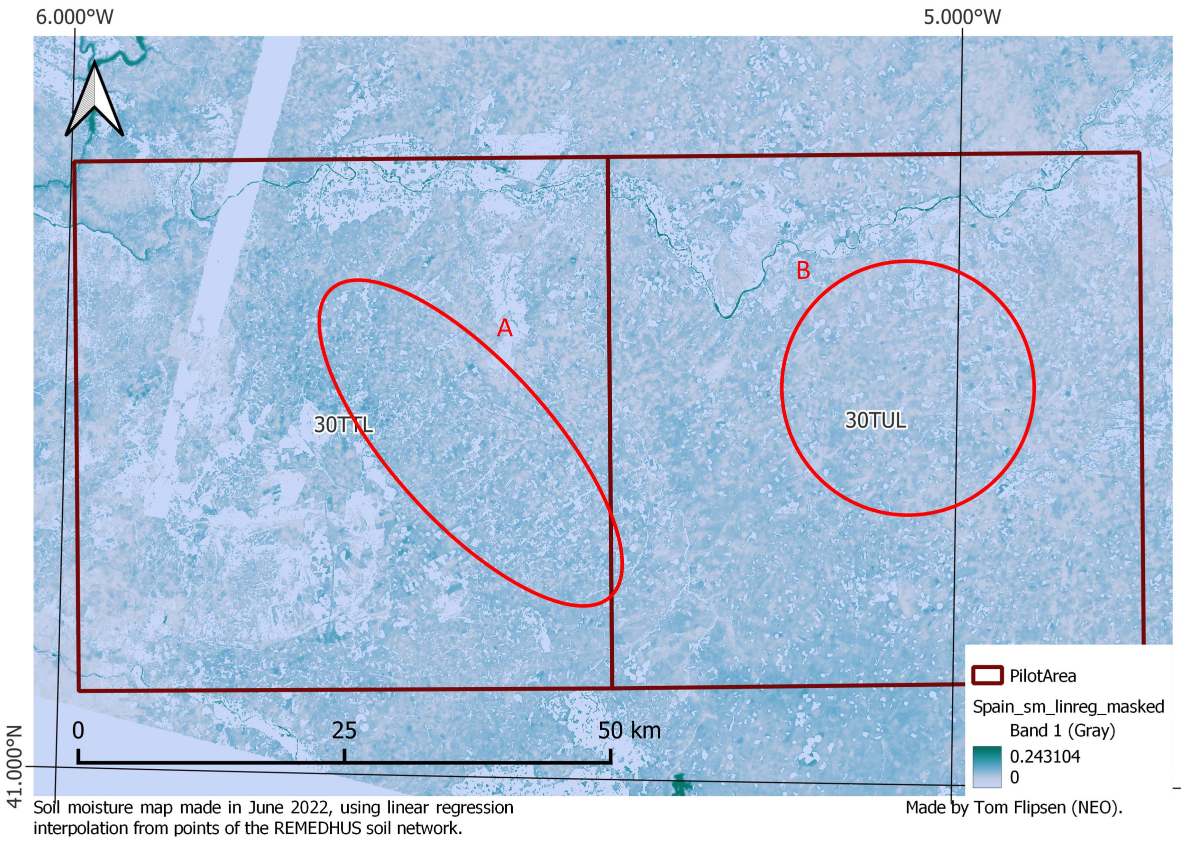


Figure 6.10: Soil moisture map for Zamora, Spain made in QGIS by Flipsen (2022). The soil moisture values are on a scale from 0-1, where 1 is fully saturated.

The main difference between the TWI and the soil moisture map, is that the TWI illustrates the flow of water and where water will collect, whereas the soil moisture map shows where water is at the time of measurement.

6.7 Impact on mobility

An evaluation on the trafficability of the area in the vicinity of Zamora can be made by combining the information in the predicted USCS map, 3D visualisation, TWI and moisture content, slope angle as well as land cover maps.

According to the predicted USCS map, a large portion of the study area consists of sandy and silty soils. These soils are usually unproblematic with regard to trafficability. The only exception is the river floodplain unit, which consists of medium plasticity CL and MH soils. These soils tend to have lower bearing capacities as well as become sticky when wet. Also, if forested, then the floodplain soils might accumulate humus which also has low bearing capacity. Therefore, it is useful to check the soil moisture and land cover of the floodplain of the Duero river.

Based on the 3D visualisation, the floodplains are shown in green meaning they can often have higher soil moisture contents compared to other soils in the area. This assumption is supported by the TWI map which shows multiple streams going through the Duero river floodplains.

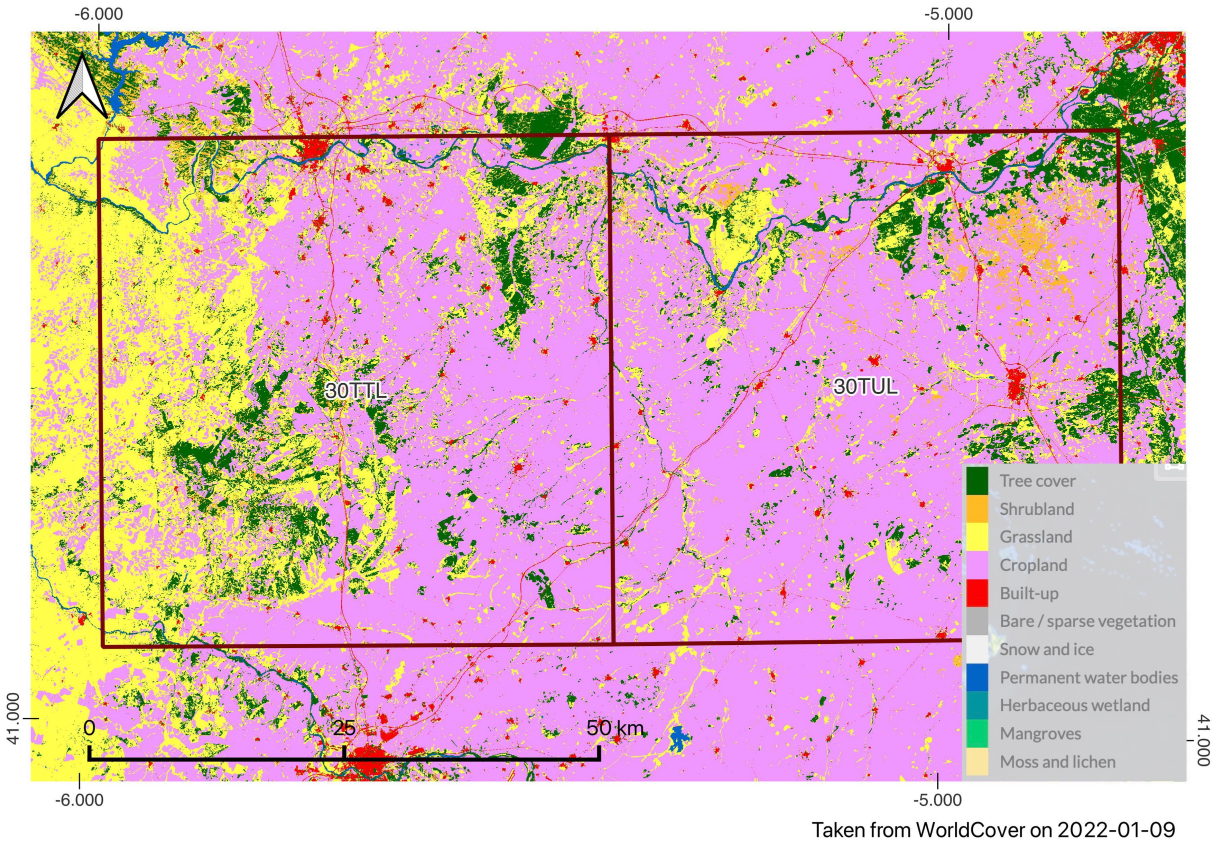


Figure 6.11: Land cover map for Zamora, Spain taken from WorldCover.

Figure 6.11 shows the land cover map for Zamora. From this map it can be seen that most of Zamora is cultivated as croplands, with and exception of some forested regions by the floodplains of the Duero river, and some grass land to the west of the map. The presence of forests on the floodplains of the Duero, indicates that those areas are fertile and have fine and organic rich soil which are usually undesirable for military mobility. Moreover, forests are also hard if the trees are too close to each other. Therefore, the green areas next to the Duero river in the land cover map are better avoided.

The grassland on the west of the study area coincides with the hillier area seen on the 3D model and is known to be Paleozoic granitoids. This area is classified as sandy soils, which do not pose a problem for mobility, however the slope angles of the area should be checked. A slope angle map of the study area is shown in Figure 6.12. As can be seen in the slope angle map, the area is relatively flat and steep slopes do not pose a problem in this area. The only steep slopes are seen on the western part of the Duero river, which is due to the river cutting through the Paleozoic rocks.

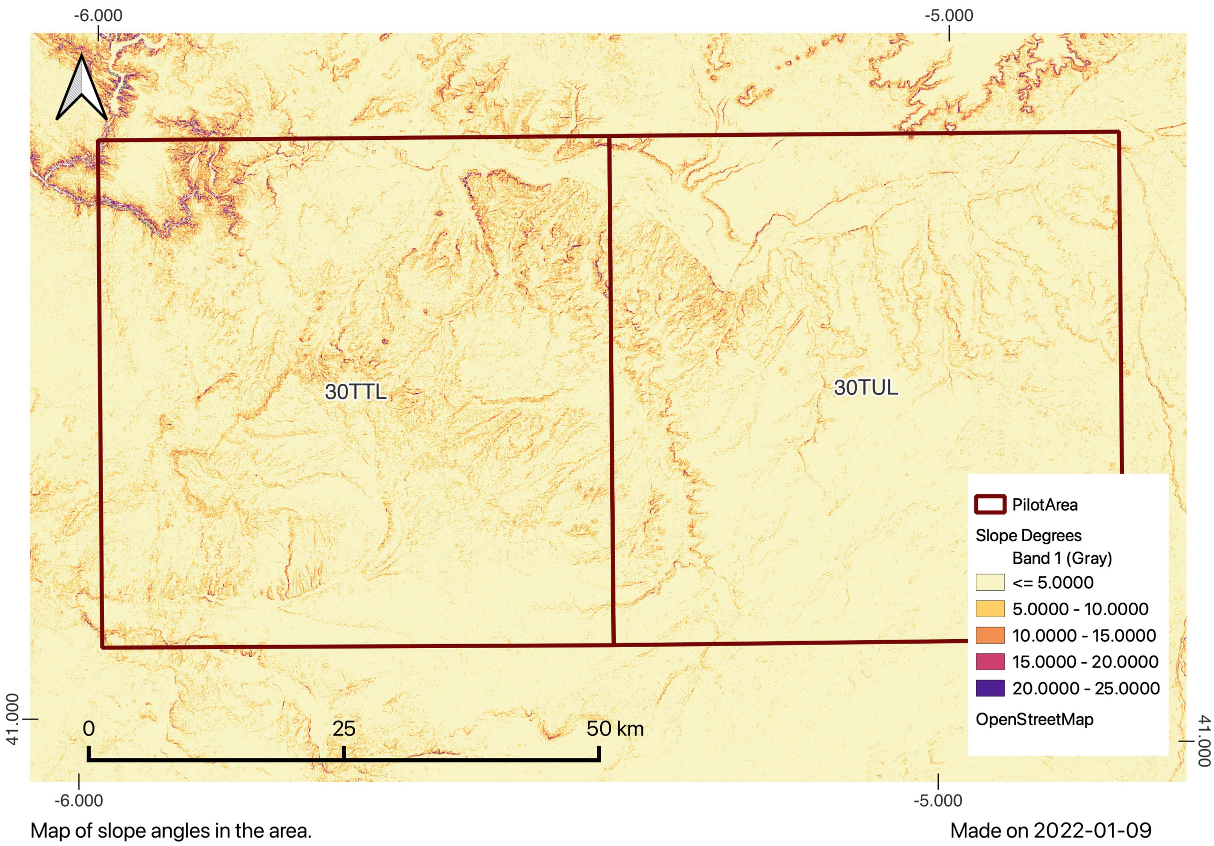


Figure 6.12: Slope angle map for Zamora, Spain made in QGIS.

In conclusion, Zamora does not pose a difficult terrain to traverse on. The only areas that might be nice to avoid are the forested floodplains of the Duero river.

7 | Validation study: Netherlands

Finally, once the different aspects of the decision tree model have been tested out using the two pilot studies, a validation study is carried out with the goal of determining the accuracy and usability of the decision tree model. The validation study is carried out in the Netherlands, in the vicinity of a city called 's Hertogenbosch. More precisely, the region of interest is a 30km^2 square located within 30UFT of the Military Grid Reference System (MGRS) mapping tiles and is shown in Figure 7.1 below.

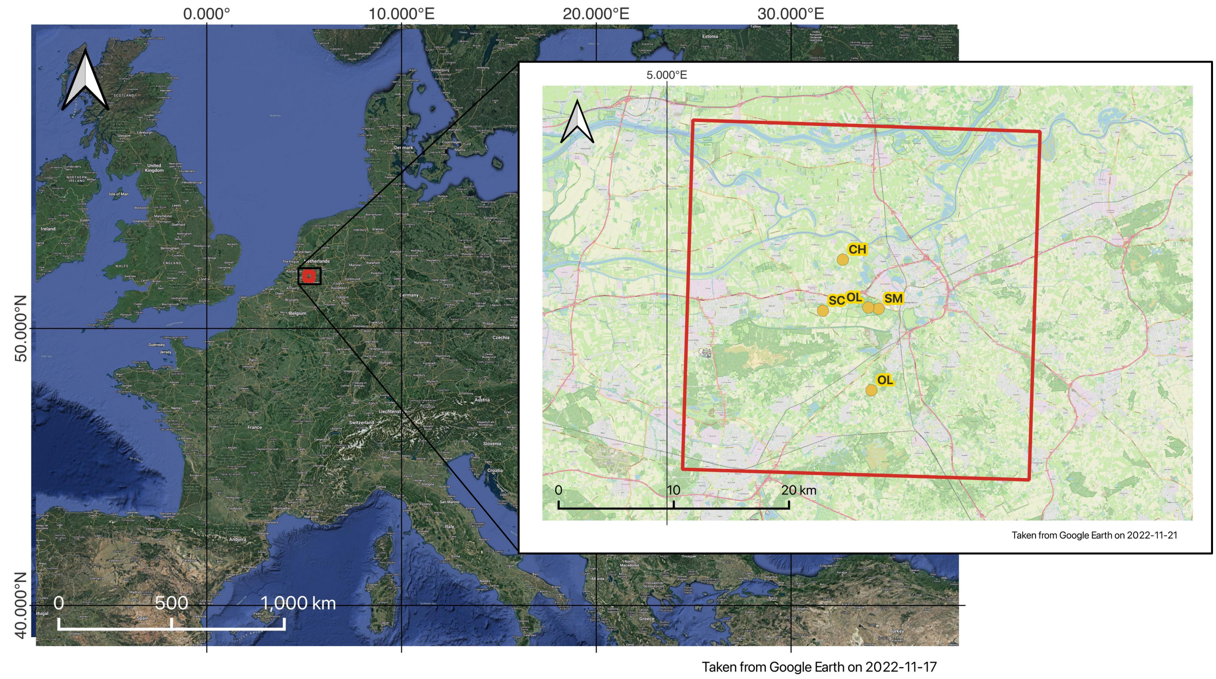


Figure 7.1: Location of pilot study in 's Hertogebosch, Netherlands. The red box is part of the 30UFT MGRS tile. The yellow dots show the ground truth datapoints received from the Dutch Ministry of Defence.

This study area is quite interesting as the landscape carries characteristics of its past periglacial environment, but is also worked upon by the current geomorphological processes and human action. To the north of the study area lies the Waal River; one of the main distributaries of the River Rhine, while the western part is covered by sand dunes and a dense pine forest which together make up the Loonse and Drunense National Park. As a result of its past and present conditions, the sediments in the area comprise of sandy areas, sand dunes with a complex topography, fluvial deposits of clay in the river floodplains and sandy fluvial ridges, which have been worked upon to become agricultural crops and grasslands in some places and densely occupied in others.

7.1 Motivation for choosing this location

The town of 's Hertogenbosch was chosen as the location for this validation study for two strong reasons. First, as part of the project proposed by the Dutch Ministry of Defence, the ministry was able to collect ground truth USCS data from five locations within this study area, as visualised in Figure 7.1 above. Second, as part of the bigger project by Cohere Consultants, NEO and Utrecht University, a predicted USCS soil map was made by Siefko Slob by converting the soil classes in the 1:50,000 Soil Map of the Netherlands into USCS soil classes. For this conversion, each Dutch soil unit within the study area was mapped to one or two USCS classes based on the soil description, experience and expert judgement. The conversion was later checked by Prof. Steven de Jong from Utrecht University. By comparing the results of the decision tree method to the ground truth points and the converted USCS map, a good evaluation can be made of the strengths and weaknesses of the decision tree method.

7.2 Available Data

The specific map used for this area is a geologic map of the Netherlands made to a scale of 1:600,000 in 2021 by DINOloket. The choice of using this map, instead of the more detailed 1:50,000 Soil Map of the Netherlands, was made because the decision tree model uses geologic data such as the age and genesis of a unit in the early branches of the decision tree. Furthermore, the branches of the decision tree model are not yet ready to appreciate all of the details and nuances that can be found in a 1:50,000 soil map, as it was trained on geologic maps with scales of 1:500,000 and 1:1,500,000. Therefore, the details encapsulated in the 1:50,000 soil map might be lost in the process. Lastly, classifying the units in the 1:50,000 soil map would have required a substantial amount of manual labour, as for the time being the decision tree model still has to be implemented by hand. This decision, however, brought up an important question of whether the decision tree is able to make good use of all of the resources available, which will be addressed in the discussion chapter (Chapter 8).

As with the previous studies, the other maps used are general world soil and climate maps, which are listed in Appendix D.8.

7.3 Prediction of USCS soil classes using decision tree

For the Netherlands pilot study, an in-depth background study is not carried out but rather only the necessary information is researched before using the decision tree model. Currently, the Netherlands experiences temperate climate without a significant dry season (Cfb) and is in a delta setting, therefore receives a lot of sediments from the Rhine River and its distributaries.

7.3.1 Making soil units

The making of soil units for the Netherlands pilot study was a straightforward process as the Dutch soil portal has well-made vector geological maps that are easily available for download. Therefore, the units are simply translated from Dutch to English and taken as they are on the map. Within the chosen study area, six different geological units were defined. Figure 7.2 shows the units made for the town of 's Hertogenbosch.

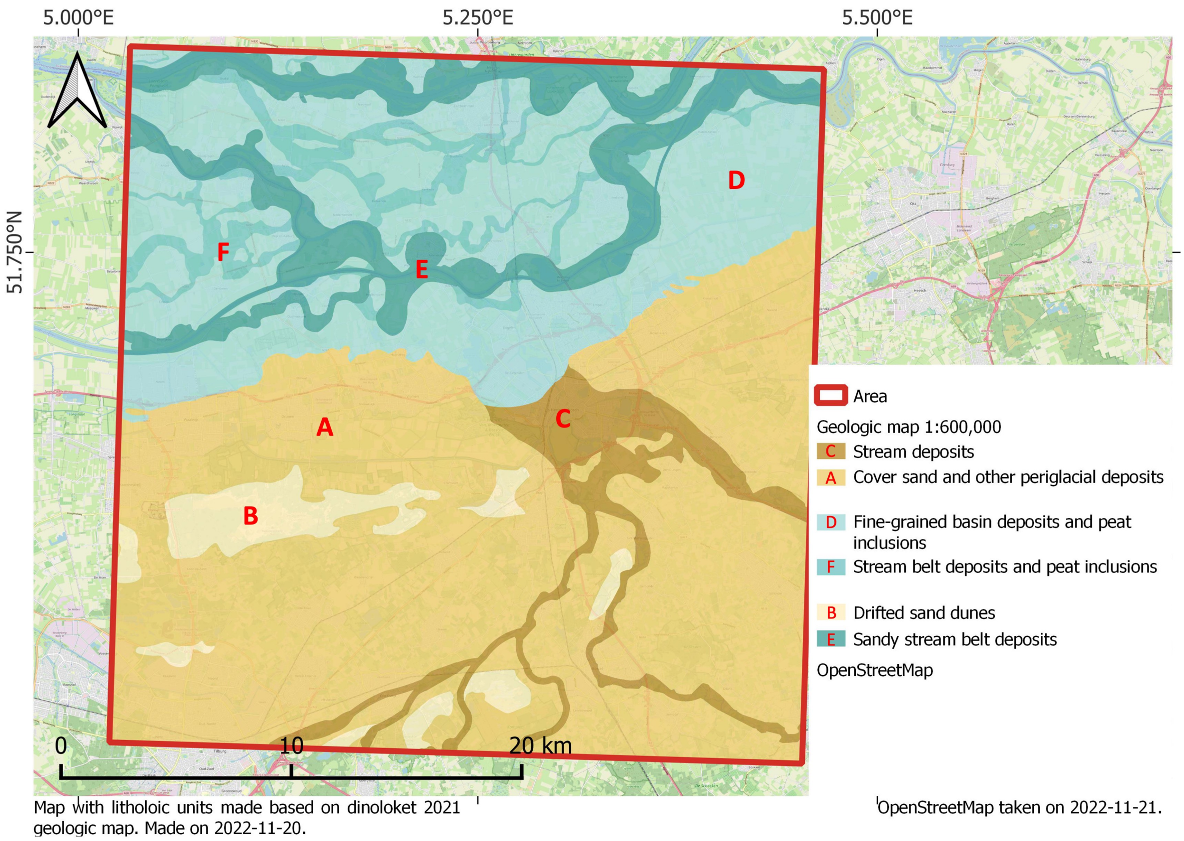


Figure 7.2: Units made for the area of 's Hertogenbosch, Netherlands, based on DINOloket geologic map.

7.3.2 Decision pathways

As all of the units are from the Quaternary and in the temperate climate zone, the decision pathway is shown from the depositional setting onwards. The decision pathways used for the units in 's Hertogenbosch are shown in Figure 7.3.

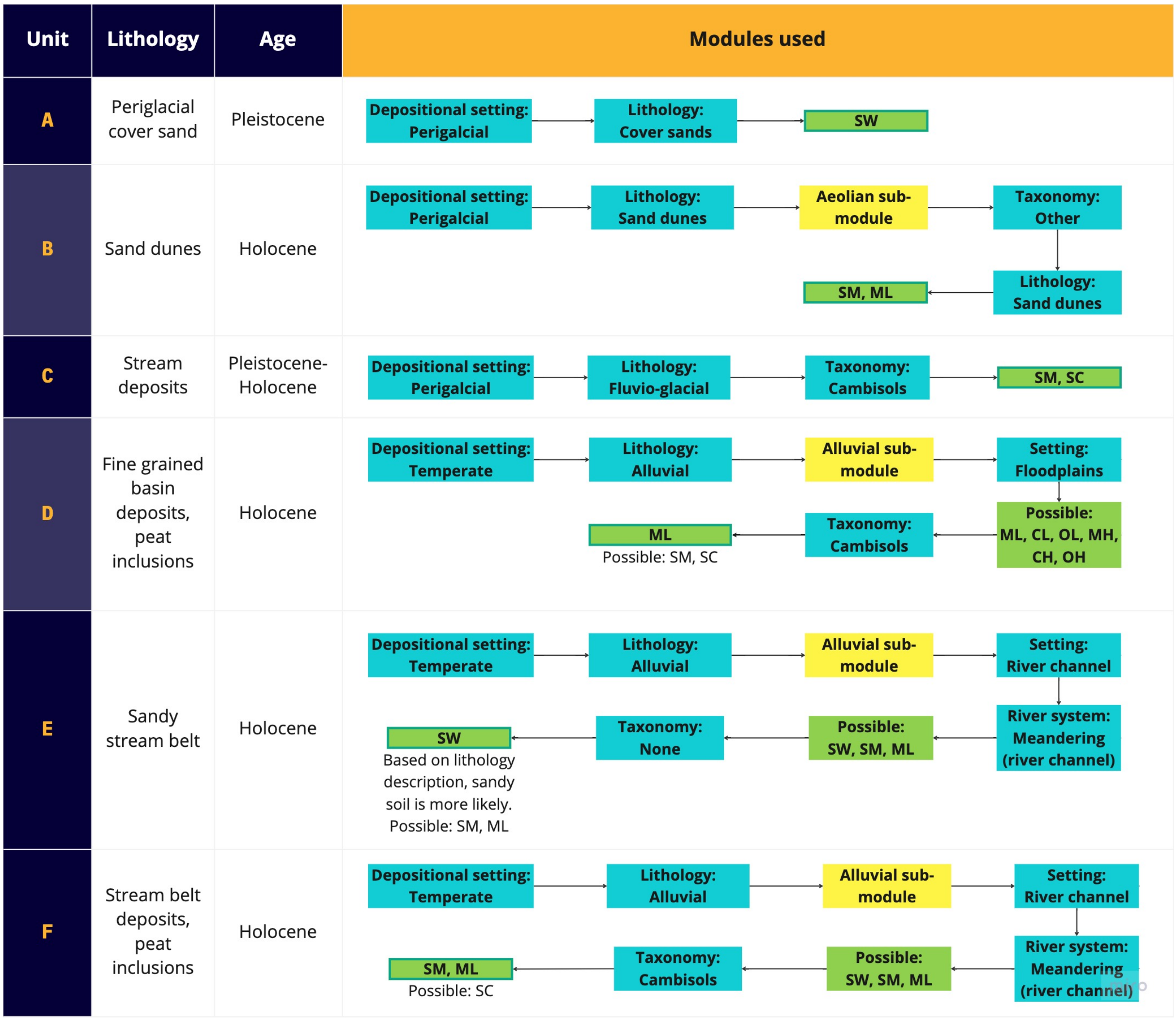


Figure 7.3: Decision tree pathways used in the Netherlands pilot study.

Unit A represents 'Cover sands and other periglacial deposits'. Based on the term 'cover sand', the unit is expected to be of uniform grain size and is therefore classified as SP. However, the term 'other periglacial deposits' make it possible that there are other soil types present as well. Thus, the possibility of SM or SC is not ruled out.

Next, an interesting case can be seen on the decision path for unit E. Based, on the decision tree itself, the resulting unit for Unit E should be SW, SM and ML. However, seeing that the name of the lithology itself includes the word *sandy*, a priority is given to the USCS class that represents a sandy soil: SW.

However, the same is not done for Units D and F although peat is included in their unit descriptions. The term 'peat inclusions' usually refers to peat layers found within the soil profile, meaning that it does not always appear on the soil at the surface. Furthermore, both units are classified under the taxonomical class of Cambisols, which is known for the absence of accumulated clay and humus. This however, is not enough to discredit the presence of peat in the unit. Since both units are a part of the River Waal's fluvial system, the 3D block model for meandering rivers can be referred to (see Appendix C.2.1). Unit D represents the floodplains of the River Waal whereas unit F are old channel belt deposits. According to the block model, river channel deposits tend to be sandy, whereas floodplains can have sediments that vary in size from sand to clay. In general, the further away from the river the sediments are, the finer they will be. Moreover, floodplains tend to be very fertile. In a temperate climate zone, the presence of trees and vegetation can lead to an accumulation of humus. Therefore, it is possible for Unit D to have organic soils at some locations but less likely for Unit F.

7.3.3 Resulting USCS soil map

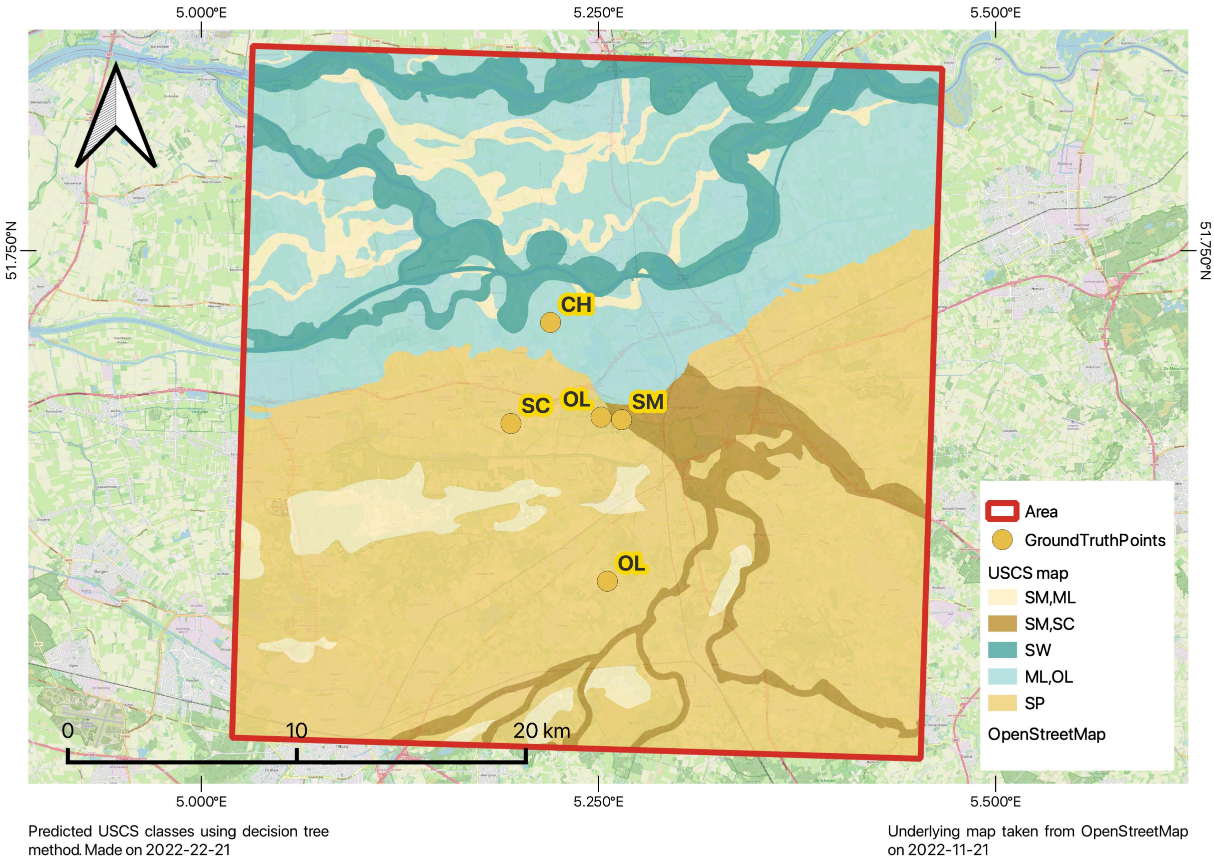


Figure 7.4: Predicted USCS soil map using decision tree method in the Netherlands pilot study. The yellow points show the ground truth data points collected by the Dutch Ministry of Defence.

Based on the results of the decision tree, the map shown in Figure 7.4 is made. A large part of the area is covered by the yellow unit which represents the Pleistocene cover sands. These sands are classified as poorly graded sands (SP). Next, in the western part of the map, on the sand dunes of the Loonse and Drunense National Park, the soil has been classified as a medium grained, non-plastic soil (SM and ML). For the deposits surrounding the River Waal, the river channel sands are classified as well graded sands (SW), whereas the smaller river channels are classified as silty sands (SM) or low plasticity silts (ML). The River Waal floodplains are classified as mainly loam (ML) with low plasticity organic soils (OL) in areas with a lot of vegetation.

According to the predicted USCS classes, a large portion of the map is mapped as sandy soils which are relatively unproblematic from a mobility standpoint. Sandy soils in general drain fast and have higher bearing capacities compared to fine-grained soils. However, there is a sand dune unit for which the mobility will also depend on the size and height of the dunes. The one soil unit that is potentially problematic for mobility is the River Waal floodplains unit which is classified as ML or OL. ML has the potential of being sticky when wet, whereas OL can be compressible. Thus, there is a chance of tyres getting stuck in this soil if the soil is wet.

7.3.4 Note on the use of supporting modules

Supporting modules such as the topographic wetness index (TWI) or Strahler Order do not work well for a country that is very flat and where the ground water level is being maintained artificially. Due to the water level in canals, rivers and streams not being a result of water collected from catchment areas, which is the assumption made in TWI and Strahler Order calculations, these supporting modules will show inaccuracies. Furthermore, as the land is relatively flat, the slope angle module is also not necessary as the slope will never be more than 25°.

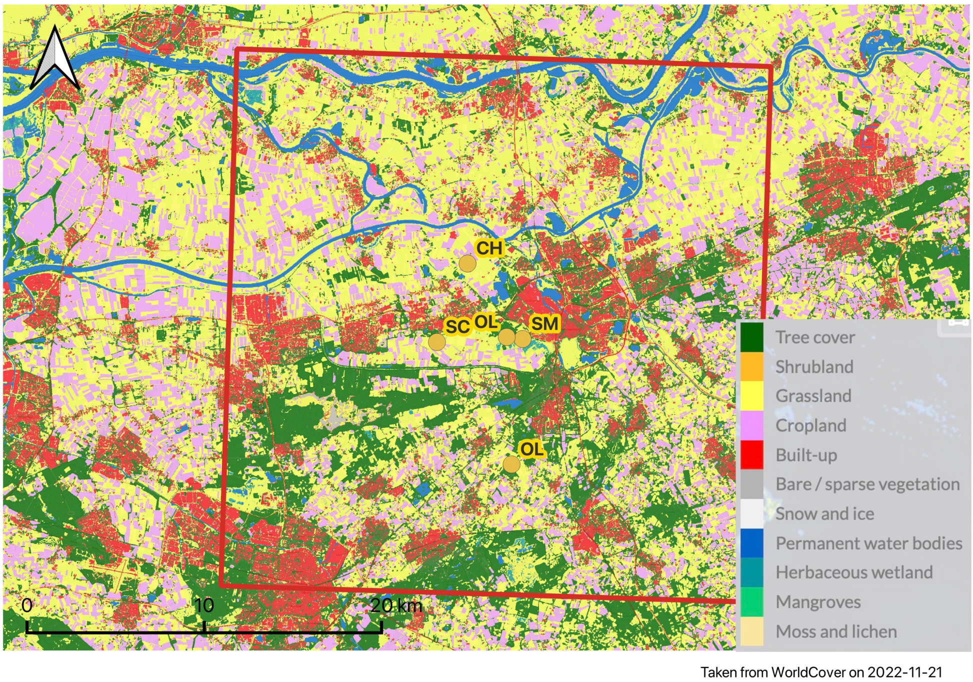


Figure 7.5: Land cover map of the Netherlands with 10m accuracy, taken from World-Cover.

The land cover module however, is very suitable to be used for this study area as the land cover can be a useful indicator of the soil type. The presence of forested areas will mean more organic content accumulation in the soil, whereas barren areas are probably the sand dunes. Figure 7.5 shows the land cover map of the Netherlands, based on which local areas with higher organic content can be expected where the land cover is called *tree cover*.

Figure 7.5 shows that the areas which the land cover map shows as *tree cover*, are classified as OL in the ground truth points, thus showing a positive correlation between tree cover and soil organic matter.

7.4 Validation of predicted USCS soil map

In this section, the results of the predicted USCS map will be compared to the soil map made by Siefko Slob as well as the ground truth data points. The similarities and differences with the two maps and ground truth points are discussed as well as a final comment on the quality of the results is given.

7.4.1 Against predicted USCS classes map based on DINOloket

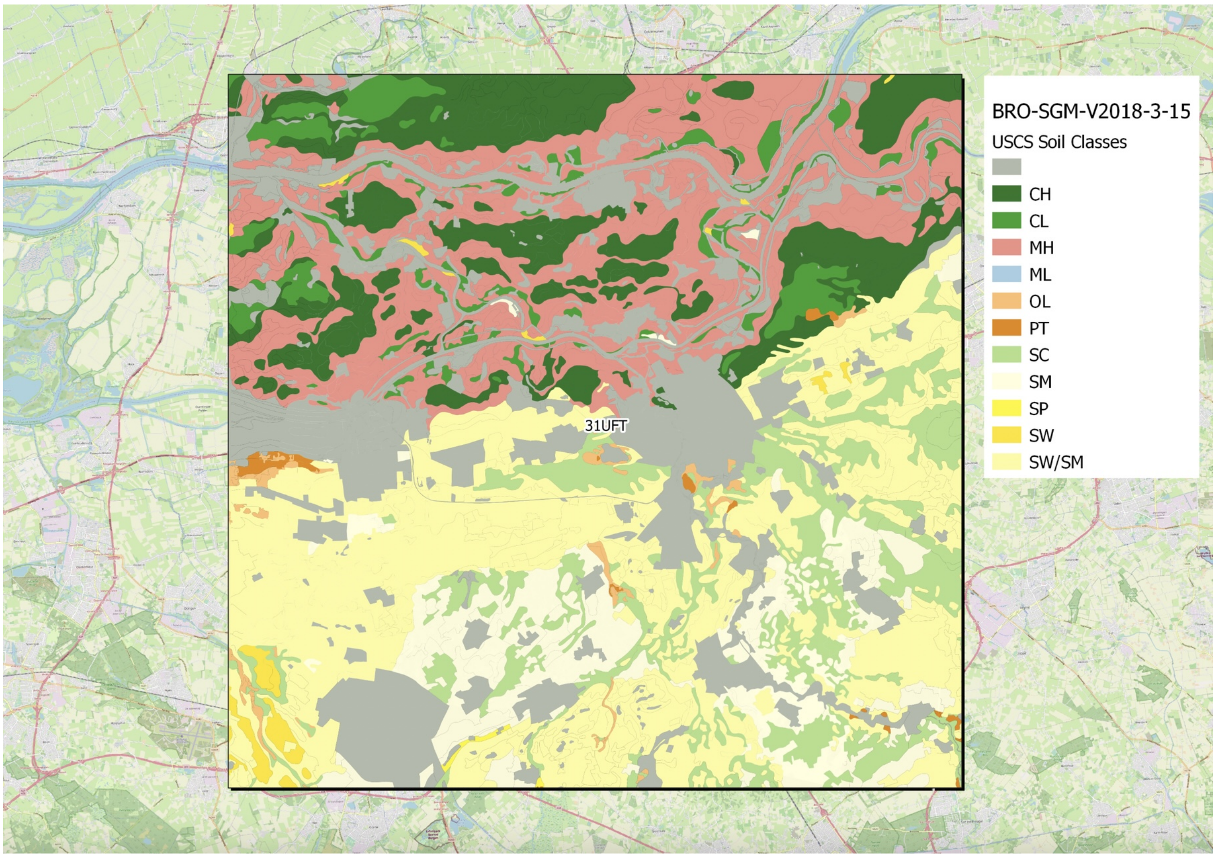


Figure 7.6: USCS map made by Siefko Slob from Cohere Consultants, by converting soil classes from DINOloket to USCS classes.

Figure 7.6 shows a map with expected USCS classes made using a different method. The method used in the above map includes a conversion table made for Dutch soil classes to USCS classes.

In Figure 7.6, the cover sands unit is classified as either well-graded sands (SW) or silty sands (SM). The decision tree classifies this unit as SP as cover sands are from an aeolian origin and hence, tend to have uniform grain sizes. However, since other periglacial deposits may also be possible in this unit, the decision tree also suggest the possibility of encountering SM or SC. Both methods predict the soils in this unit to be sandy, but with different grain size distribution.

Next, the sand dunes unit is classified as silty sands (SM) in both methods, however the decision tree also suggests that a low plasticity (ML) may be possible. The main difference with these two soil groups is the proportion of fine soils. SM has less than 50% fines whereas ML has more than 50% fines. In terms of mobility, this should not make a significant difference.

As for the periglacial stream deposits, both maps predict that a sandy clay (SC) soil may be possible. It can be noted that a big part of this stream unit is classified without a soil class in the map made based on DINOloket soil classes, which is caused by those areas being covered by civilisation, as can be seen in red the land cover map (Figure 7.5).

Lastly, the units relating to the Waal river are classified as plastic silts (MH) and plastic clays (CH) based on the map in Figure 7.6. The decision tree, however, predicts the floodplain soils to be predominantly low plasticity clay (ML) or low plasticity organic soil (OL). In the decision pathway for this unit, the possibility of the soil being a finer-grained soil such as: CL, MH, CH or OH, was suggested. The meandering river block model also supports the possibility of fine-grained soils on river floodplains, especially further away from the river. However, these classes were overruled by the soil taxonomy class of Cambisols, which are known to lack clay and humus. This situation brings up and interesting question of what weight should each suggestion hold on the final prediction. This is a potential area for improvement for the decision tree.

7.4.2 Against ground truth data

The Dutch Ministry of Defence carried out in-situ USCS soil tests to determine the USCS classes of five points within the study area. The five ground truth points are visualised against the resulting USCS soil class predictions in Figure 7.4.

Out of the five points, only one unit is classified exactly as is determined by the ground truth point. This is the stream deposits unit which is classified as SM or SC, whereby the ground truth determined the soil to be SM.

Next, the unit for cover sands is classified as SP with a possibility of SM or SC, which includes the ground truth result of SC. This can be considered to be a good classification, however there might still be room for improvement be able to better close in on a single USCS prediction. There are two other points within the cover sand unit, which the decision tree predicts to be SC however the ground truth reveals that they are actually OL. This is not a surprise, because as seen in the land cover map module, these areas are predicted to have higher organic matter content.

The final discrepancy between the ground truth points and decision tree results is in the classification of the river floodplains. The in-situ soil tests determined the river floodplains to be high plasticity clays (CH), which the decision tree has classified as low plasticity clays (ML). As discussed in the previous section, this point leads to a possible area for improvement with how the decision tree model weighs the suggested classes.

7.4.3 Final comments on validation study

In general, the decision tree is able to do a good job with distinguishing areas with coarse and fine grained soils, which is a good step as the soil texture makes a big difference when it comes to mobility predictions. Furthermore, the land cover supporting module is able to give a good indication on the presence of soil organic content, so the three large divisions of the USCS can be handled well by the decision tree.

The decision tree, however, does struggle with distinguishing between low and high plasticity soils such as ML, CL and MH, CH. This issue becomes more obvious when dealing with inherently heterogeneous environments such as river floodplains. All in all, the decision tree model has formed a solid base for a knowledge based soil prediction model, however there is still a long way to go to make a truly robust yet detailed model.

8 | Discussion

The goal of this MSc research is to study the potential and subsequently create a framework for classifying soils into Unified Soil Classification System (USCS) classes by using the total geological history (TGH) experienced by an area. This study achieves its goal by presenting a model that incorporates the main concepts of the TGH approach that was proposed by P. G. Fookes et al. (2000) into a decision tree. Therefore, the end product of this study is the proposed decision tree model for predicting USCS soil classes. In this chapter, the strengths and weaknesses of the proposed decision tree model will be discussed and supported by results of the pilot and validation studies.

8.1 Strengths of the method

The decision tree model incorporates the TGH approach by asking simple questions relating to the tectonic setting, geological age and lithology, past and present climates, genetic processes underwent, land cover class as well as soil taxonomy class. In order to incorporate these conditions into the model, this thesis provides the user with a list of data sources that can be used to derive the relevant information. In addition to that, the model also comes with its own weathering grade system and a table with the weathering products for 23 common rock types. All in all, the decision tree model provides the user with many tools and data sources that can be used to characterise the total geological history of an area in a simple and coherent manner.

A strength of the decision tree model is that it is a knowledge-based approach. This means that qualitative knowledge has to be used at each step of the decision tree in order to reach the final USCS class prediction. The benefit of such a method is that each decision made is supported by reasoning and logic, and the final USCS class can be justified. The decision tree workflow ensures that information about the total geologic history of an area is collected in a standardised and orderly manner, to reduce the impact of individual judgement on the final result. The aim is for the same map to be reproducible, irrespective of the person who made the map.

Furthermore, the decision tree model presented in this thesis makes use of a wide range of knowledge. The soil modules and sub-modules make use of 7 different data types, which are: geologic maps, tectonic setting maps, soil taxonomy maps, climate zone maps, mountain bioclimate zone maps, land cover maps and digital elevation models (DEM), whereas the supporting modules incorporate DEM derived products such as topographic wetness index (TWI) and slope angle maps, to better illustrate the terrain. By using a wide range of data sources, which include modern maps that have a high resolution and have been made using machine learning techniques, the decision tree model is also able to capture some of the advancements made in the field of soil sciences. By the same token, as the quality of maps improve over time, so will the predictions made by the decision tree model.

Finally, this thesis shows the potential for the TGH method to be used in combination with a remote sensing approach, as done in the collaboration with Flipsen (2022), to generate a high quality map. As shown in Chapter 5, the hyperspectral map is able to make a more detailed classification than the TGH method, whereas the TGH method is able to give a more detailed description of the qualities of the soil. Therefore, it is worth considering to use the the TGH and hyperspectral method together as the strengths of each method complements the other nicely.

8.2 Comparison to previous works

The use of the TGH in this study for predicting soil characteristics is comparable to the work of Dambrink (2011), who used the TGH approach for predicting the presence of boulders in glacial till along the Finnish coast. In her study, Dambrink presents an extensive literature study describing the geological history of the Finnish coast with the relevant 3D models from the TGH approach to make a list of anticipated features for her location of interest. Dambrink's methodology closely follows the original TGH approach as proposed by P. G. Fookes et al. (2000) which is different from what is proposed in this thesis. Although the workflow presented in this thesis maintains the key concepts of the original TGH approach, the decision tree model goes further to provide modules and tools that are specific to the prediction of USCS soil classes for military mobility. For example, within the description of each sub-module, some information is given on how the genesis of the soil affects its ability to be trafficable.

Next, as this thesis is also interested in making soil maps for military mobility predictions, the method used in this thesis is compared to the one used by the German Military during World War II. At that time, the German military was producing cross-country mobility (CCM) maps using soil and geological maps aided by aerial photographs (Malm, 2018). Despite being well-made, Malm mentions that these maps were made under extreme time pressures and were very subjective to the judgement of the respective geologist in-charge of making them. One of the aims of the decision tree model is to reduce the subjectivity of such a map map making method. Therefore, the decision tree model provides a workflow that can be carried out in a standardised and organised manner, whereby any extra judgement made by the user has to be supported by reasoning.

It should be mentioned that nowadays, most militaries have also found ways to reduce the subjectivity in soil map making by using GIS tools or other methods for classifying soils such as remote sensing or by making a conversion from an existing soil map to soil USCS classes. However, I was not able to find any method that formalised the thought process that is required to combine various data sources into a soil class prediction as is done in this thesis. Therefore, the decision tree model can hopefully provide some new ideas for classifying soils into USCS classes.

8.3 Shortcomings of the method

While making the validation study in the Netherlands, a possible weakness of the decision tree model was encountered when determining which soil determining factor to give priority to. For example, if a certain decision pathway gives some suggestions of 'Possible' or 'High likeliness' classes but the final USCS prediction does not contain any of the previously suggested classes, then the user will have to prioritise the classes in the final prediction. This can cause some important information to be left out in the predictions and if the decision tree is someday to be automated completely, this weakness may allow incorrect judgements to be passed if not accounted for.

Some difficulty was also faced in the process of finding suitable geologic maps and then creating geologic units from the map to be used by the decision tree. A lot of judgement may have to go into this step of the process, especially when the name or description of the unit on the geologic map does not provide a clear indication of the type of formation. For example, in the Spain pilot study, there were 3 units called 'Carbonate alluvial sediments' which were described in the geologic map as conglomerates, sandstones, limestone, marls and gypsum. This made it difficult to conclude the decision tree with just one pathway, and in the end the soil taxonomy classes were given more weight in the determination of the final USCS soil class. If this decision tree model is to be automated, a potential difficulty can be expected here, as a program might not be able to capture the full information contained within a unit name without human supervision.

Next, the decision tree presented in this thesis has been improved on and tested with three study locations. However, in order to build a truly robust model it should also be tested in various other conditions such as tropical climates or weathered mountains, which have not been done in detail in the making of the model presented within this thesis. More studies to validate the model will result in a better model. Furthermore, as the decision tree was made using soil maps of 1:500,000 and 1:1,500,000, it does not have enough detail to treat finer scales geologic maps. This was realised in the Netherlands validation study, whereby even if a more detailed geologic map was to be used to make the units, the extra details would be lost on the decision tree.

Finally, concern could be raised about the validity of climate as an indicator for predicting local soil classes, as climate can change or time. However, as we are only interested in the topsoil, climate changes, unless recent, will not heavily impact the predictions.

9 | Conclusion and recommendations

9.1 Conclusion

This MSc research was carried out with the aim of laying down a framework for classifying soils into their Unified Soil Classification System (USCS) soil class, by using the total geological history (TGH) approach that was proposed by P. G. Fookes et al. (2000). The premise of the TGH approach is based on the concept that the ground conditions at any site are a product of its total geological history, which includes the stratigraphy, structure, former and current geomorphological conditions, as well as the past and present climatic conditions. The hypothesis of this MSc study is that, with the total geological history of an area, we are able to predict soil USCS classes.

This thesis tackles the hypothesis by implementing the core concept of the TGH approach into a decision tree model that prompts the user to answer simple questions regarding the geological history of an area, that will eventually lead to a predicted USCS class. The decision tree makes use of many modules and sub-modules that consider the tectonic, geologic and geomorphological setting of a unit to determine its characteristics and subsequently USCS class. Supporting modules are also added to the decision tree model to create a more complete picture of an area as a whole. In order to help the user answer the questions in the decision tree model, this thesis also provides a list of maps that can be used to derive the relevant information. There are 7 data types used in the decision tree model, which are: geologic maps, tectonic setting maps, soil taxonomy maps, climate zone maps, mountain bioclimate zone maps, land cover maps and digital elevation models (DEM). In addition to that, a weathering grade system with grades that reflect the consequences of weathering for mobility is created. This grade system is used along with a table that was specifically made to predict the USCS classes of 23 common rock types for each weathering grade.

The performance of the decision tree model was tested using two pilot studies (in Mali and Spain) and one validation study (in the Netherlands). For each study, a predicted USCS soil map of the area was generated. By combining the predicted USCS map with additional information about the topographic wetness index (TWI) and slope angle, a qualitative mobility prediction is made for the pilot studies. Based on the pilot studies, it can be said that the TGH approach for predicting USCS classes shows some promise for being expanded into a tool for aiding military mobility predictions. The validation study in the Netherlands compares the predicted USCS map made to 5 ground truth points collected by the Dutch Ministry of Defence. This study concluded that the decision tree was able to distinguish coarse grained soils from fine grained soils, however struggled a with determining if a soil had high or low plasticity.

The pilot study in Mali also compared the USCS soil predictions made using the decision tree model to those made using hyperspectral remote sensing (made by Flipsen (2022)). Based on the comparison, the hyperspectral method was able to make a more detailed classification than the one made by the decision tree model. The decision tree however, was better at determining the qualitative properties of the soil units present. As a result, the two methods were able to nicely complement each other.

By the end of the research period, this thesis was able to produce a working model, that when used in combination with elementary geologic knowledge, provides the basis of an organised framework for soil classification across the world. The strengths of this model include making use of data easily available online as well as allowing each decision made towards the predicting the USCS soil class to be accountable by data sources and fair reasoning. All in all, this thesis provides a framework towards a knowledge based approach for predicting USCS soil classes and shows the potential for such a tool to be used in making military mobility maps.

9.2 Recommendations

Among the areas of improvements, the first recommendation is to fix issues that were noticed during the pilot and validation studies. With the decision tree, there is sometimes a difficulty is determining which soil forming factor should take precedence in an area. This can affect the final result as prioritising the wrong soil forming factor can alter the USCS prediction significantly. For example, in an area with an extreme climate such as arid climate, the soil taxonomical class is a good indicator of the soil type expected. On the other hand, in zones with temperate climate, often the soil taxonomical class does not hint to any specific characteristics that can be used to determine its USCS class and therefore, the soil depositional method can take priority instead. In order to reduce errors due giving too much weight to the wrong soil forming factor, a deeper study should be done into which soil forming factors maybe dominant in an area. This can then be expanded by giving weights to the different soil forming factors so that probability of expecting a certain USCS class can be calculated.

Next, as certain parts of the decision tree requires special judgement, such as when the 'Possible' USCS classes are very different from the final USCS class prediction. In order to deal with this, more guidelines and tools can be provided to aid and standardise the judgement process that the user has to undertake. An example would be to add a part in the decision tree that takes into account keywords found in the the name or description of the unit given in a geologic or soil map. In the future this can also be automated by using AI to match keywords with possible soil types.

In addition, potential is also seen for fine-tuning the decision tree so that it is able to incorporate more detailed maps as input. At the moment, the decision tree has been trained with maps of about 1:500,000 scale, so a future improvement could be to train the decision tree with geologic maps of 1:100,000 and 1:50,000 instead.

In a different direction, the collaboration of the TGH method with Flipsen (2022)'s hyperspectral method showed promise for future work to integrate these two methods. A possible idea is to combine the hyperspectral method with the decision tree so that instead of being two separate methods, the hyperspectral method can be used to train and validate the results of the decision tree and vice versa. In fact, there might also be possibility to integrate other remote sensing techniques such as the use of supervised or unsupervised classification techniques to create soil units with similar characteristics, as this was one of the tasks the TGH approach struggled with. The TGH approach can then be used to combine data sources and knowledge to best describe the soil qualities of the unit. The use of multispectral data (such as Sentinel-1 and Sentinel-2 data) to distinguish geomorphological features such as, the dimensions and type of sand dunes for example, can also be included as a future recommendation.

Another area for future improvement, would be the automatisation of the decision tree model, which could be made into a plugin or tool for GIS programs. The data sources and decision tree model used in this thesis were made with a future possibility of automatisation in mind. However, as there are still parts of the decision tree model that requires human judgement, the method could instead be partially automated, whereby the model asks the user for input whenever a judgement call has to be made.

Next, the results of the decision tree model can be made more reliable by implementing a system to evaluate the confidence level in the results. This can be done by giving confidence score and weights to each decision so that the probability of a certain USCS soil class occurring can be calculated, thus, allowing a quantitative evaluation of the performance of the decision tree to be made. Alternatively, instead of quantifying confidence level, the uncertainty present in the model and terrain can be quantified. This will also allow the model to capture the uncertainties that are inherent with heterogeneous environments.

Last but not least, a landscape evolution module such as LandLab (Shobe, Tucker, & Barnhart, 2017) can be used to visualise how the landscape changed and will change over time. This can be especially useful for quantifying the soil distribution for complicated settings such as river floodplains, where it is hard to predict the grain sizes of floodplain sediments. This will not only give a better understanding of how the landscape came to be what it is today, but can also be used to predict how the landscape will change in the future, which can in turn open doors towards studies in the long term effects of climate change.

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A | Soil critical layer

The critical layer is the layer in the soil that supports the weight of a vehicle. The critical layer's depth varies with the soil type, soil strength profile, vehicle type and weight as well as the number of passes required (Department of the Army, 1994).

Table 7-1. Critical-layer depth variations

Type of Vehicle	Depth of Normal Critical Layer (Inches) 1 Pass F-G Soils*	1 Pass C-G Soils**	50 Passes F-G Soils*	50 Passes C-G Soils**
Tracked vehicles with ground contact pressure less than 4 psi	3 to 9	0 to 6	3 to 9	0 to 6
Wheel load up to 2,000 lb	3 to 9	0 to 6	3 to 9	0 to 6
Wheel load, 2,000 to 10,000 lb	6 to 12	0 to 6	6 to 12	0 to 6
Wheel load over 10,000 lb	9 to 15	0 to 6	9 to 15	0 to 6
Tracked, up to 100,000 lb	6 to 12	0 to 6	6 to 12	0 to 6
Tracked, over 100,000 lb	9 to 15	0 to 6	9 to 15	0 to 6

*Fine-grained soils and remoldable sands
**Coarse-grained soils

NOTE: Vehicle weights are located in Appendix D, along with VCI, and VCI_{50} values for military vehicles.

Figure A.1: This table, taken from Department of the Army (1994), shows the depth of the critical soil layer based on the weight of the vehicle and soil type.

B | USCS classes: Field determination and look-up tables

B.1 List of 26 major and boundary classes used in the NRMM

	USCS Soil Type	Description
	Coarse Grained Soils	
1	GW	Well graded gravel: Gravel-sand mixtures with little fines
2	GP	Poorly graded gravel: Poorly graded gravel-sand mixtures
3	GW-GM	Well graded gravel with silt
4	GW-GC	Well graded gravel with clay
5	GP-GM	Poorly graded gravel with silt
6	GP-GC	Poorly graded gravel with clay
7	GM	Silty gravel: Gravel-sand-silt mixtures
8	GC	Clayey gravel: Gravel-sand-clay mixtures
9	GC-GM	Silty clayey gravel
10	SW	Well graded sand
11	SP	Poorly graded sand
12	SW-SM	Well graded sand with silt
13	SW-SC	Well graded sand with clay
14	SP-SM	Poorly graded sand with silt
15	SP-SC	Poorly graded sand with clay
16	SM	Silty sand
17	SC	Clayey sand
18	SC-SM	Silty clayey sand
	Fine Grained Soils	
19	CL	Lean clay
20	CL-ML	Silty clay
21	ML	Silt
22	OL	Organic silts and silty clays with low plasticity
23	CH	Fat clay
24	MH	Elastic silt
25	OH	Organic clays with medium to high plasticity
	Highly organic soils	
26	PT	Peat or muck

Figure B.1: This list, taken from Wasfy and Jayakumar (2021), shows 26 USCS soil classes which consist of major as well as boundary soil classes. The original list was published in the ASTM (2011) Standard, D2487.

B.2 Field tests to predict USCS classes

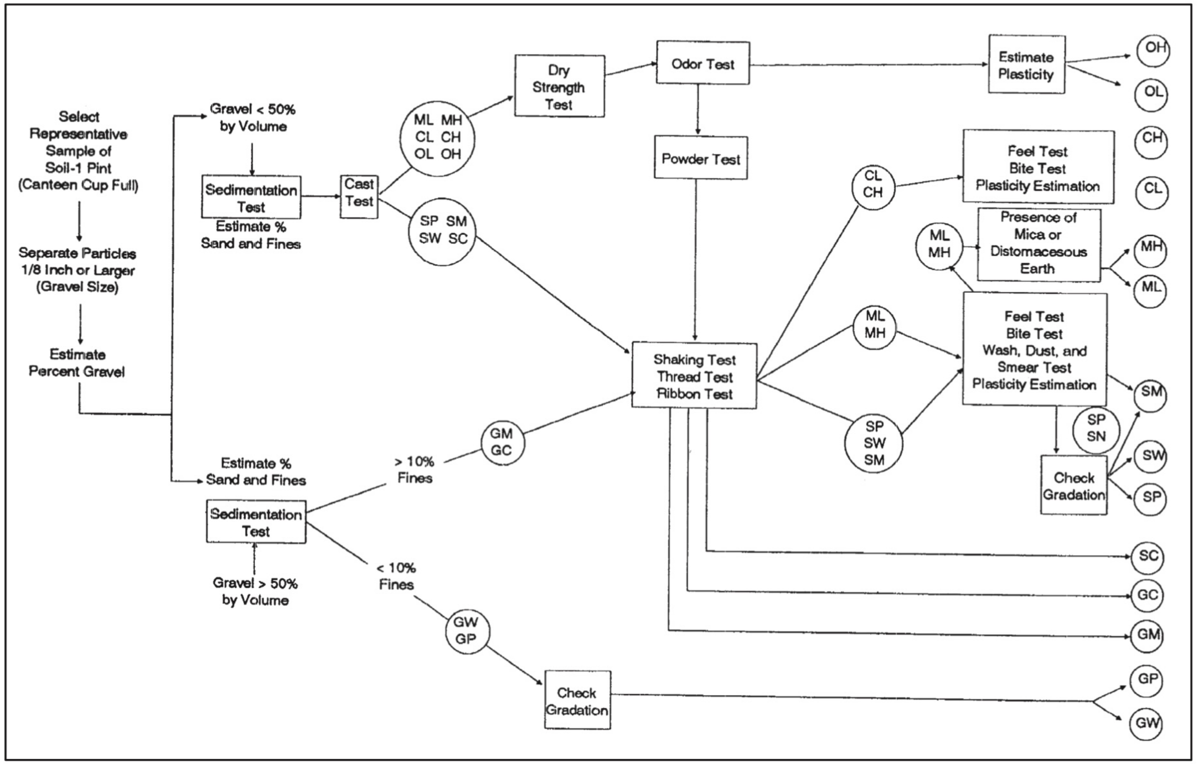

Figure B.2: Suggested procedure by U.S. Department of the Army (2012) for a quick field identification of USCS soil class.

The techniques used for field identifications include the sedimentation test, cast test, dry strength test, odor test, powder test, wet shaking test, thread test, ribbon test, shine test, feel test, grit test, wash, dust and smear test and finally a field plasticity estimation. A short description of each of these tests can be found in Chapter 5 of the (Department of the Army, 2012) handbook.

B.3 Look-up tables correlating USCS classes to various engineering characteristics

Major Division		Letter		Symbol		Name	Value as Subgrade When not Subject to Frost Action	Value as Subbase When not Subject to Frost Action	Value as base When not Subject to Frost Action	Potential Frost Action	Compressibility and Expression	Drainage Characteristics	Compaction Equipment	Unit Dry Weight Pounds Per Cubic foot	Typical Design Values	
				Hatching	Color										CBR	Subgrade Modulus k, Pounds Per Cubic Inch
(1)	(2)	(3)		(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
Coarse-grained soils	Gravel and gravelly soils	GW			Red	Well-graded gravels or gravel sand mixtures, little or no fines	Excellent	Excellent	Good	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired roller, steel-wheeled roller	125-140	40-80	300-500
		GP				Poorly graded gravels or gravel sand mixtures, little or no fines	Good to excellent	Good	Fair to good	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired roller, steel-wheeled roller	110-140	30-60	300-500
		GM	d		Yellow	Silty gravels, gravel-sand-silt mixtures	Good to excellent	Good	Good to fair	Slight to medium	Very Slight	Fair to poor	Rubber-tired roller, sheepsfoot roller, close control of moisture	125-145	40-60	300-500
			u				Good	Fair	Poor to not suitable	Slight to medium	Slight	Poor to practically impervious	Rubber tired roller, sheepsfoot roller	115-135	20-30	200-500
		GC				Clayey gravels, gravel-sand-clay mixtures	Good	Fair	Poor to not suitable	Slight to medium	Slight	Poor to practically impervious	Rubber tired roller, sheepsfoot roller	130-145	20-30	200-500
	Sand and sandy soils	SW			Red	Well-graded sands or gravelly sands, little or no fines	Good	Fair to good	Poor	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired roller	110-130	20-40	200-400
		SP				Poorly graded sands or gravelly sands, little or no fines	Fair to good	Fair	Poor to not suitable	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired roller	105-135	10-40	150-400
		SM	d		Yellow	Silty sands, sand-silt mixture	Fair to good	Fair to good	Poor	Slight to high	Very slight	Fair to poor	Rubber-tired roller, sheepsfoot roller, close control of moisture	120-135	15-40	150-400
			u				Fair	Poor to fair	Not suitable	Slight to high	Slight to medium	Poor to practically impervious	Rubber tired roller, sheepsfoot roller	100-130	10-20	100-300
		SC				Clayey sands, sand-silt mixtures	Poor to fair	Poor	Not suitable	Slight to high	Slight to medium	Poor to practically impervious	Rubber tired roller, sheepsfoot roller	100-135	5-20	100-300
Fine-grained soils	Silts and clays LL<50	ML			Green	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands, or clayey silts with slight plasticity	Poor to fair	Not suitable	Not suitable	Medium to very high	Slight to medium	Fair to poor	Rubber-tired roller, sheepsfoot roller, close control of moisture	90-130	15 or less	100-200
		CL				Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays	Poor to fair	Not suitable	Not suitable	Medium to high	Medium	Practically impervious	Rubber tired roller, sheepsfoot roller	90-130	15 or less	50-150
		OL				Organic silts and organic silt-clays of low plasticity	Poor	Not suitable	Not suitable	Medium to high	Medium to high	Poor	Rubber tired roller, sheepsfoot roller	90-105	5 or less	50-100
	Silts and clays LL>50	MH			Blue	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts	Poor	Not suitable	Not suitable	Medium to very high	High	Fair to poor	Sheepsfoot roller, rubber tired roller	80-105	10 or less	50-100
		CH				Inorganic clays of high plasticity, fat clays	Poor to fair	Not suitable	Not suitable	Medium to very high	High	Practically impervious	Sheepsfoot roller, rubber tired roller	90-115	15 or less	50-150
		OH				Organic clays of medium to high plasticity, organic silts	Poor to very poor	Not suitable	Not suitable	Medium to very high	High	Practically impervious	Sheepsfoot roller, rubber tired roller	80-110	5 or less	25-100
High organic soils		Pt			Orange	Peat and other highly organic soils	Not suitable	Not suitable	Not suitable	Medium to very high	Very high	Fair to poor	Compaction not practical	—	—	—

Figure B.3: Characteristics of USCS classes taken from U.S. Department of the Army (2012) handbook.

B.4 Conversion table for USDA to USCS soil classes

This correlation was made using the USCS classification overlaid onto the USDA triangle as shown in Figure B.4. The USDA triangle is the triangle that classifies soils into their respective USDA textural class based on the percentage of sand, silt and clay. This triangle was used by García-Gaines and Frankenstein (2015) as a mapping scheme between the USDA and USCS classes.

Figure 5. USCS classification mapped onto the USDA triangle by Ayers et al. (2011).

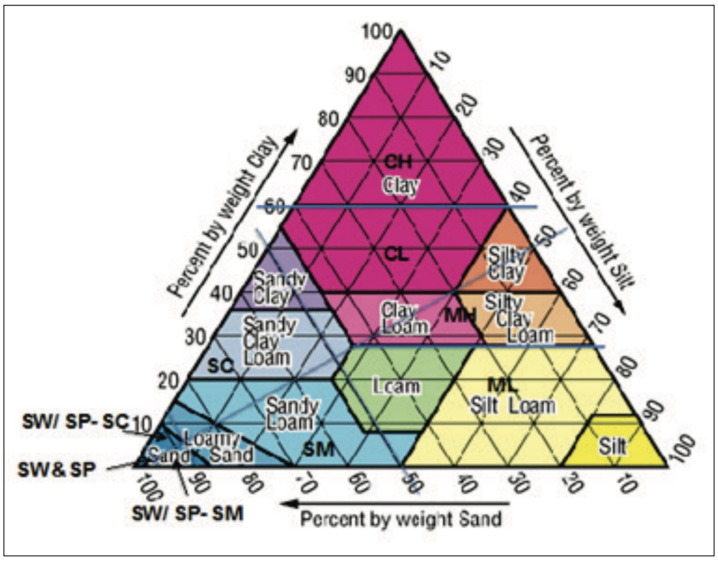

Figure B.4: USCS classification mapped onto the USDA triangle, made by Ayers et al. (2011), taken from García-Gaines and Frankenstein (2015).

Table 11. USCS fit for USDA based on Ayers et al. (2011) data (Garcia-Gaines and Frankenstein 2015).

USDA Classification	USCS Classification	
	Most Probable	Possible
Sand	SW, SP	--
Loamy Sand	SM	SC
Sandy Loam	SM	--
Sandy Clay Loam	SC	--
Sandy Clay	SC	CL
Loam	ML	--
Silt Loam	ML	--
Silt	ML	--
Clay Loam	CL, MH	--
Silty Clay Loam	MH	--
Clay	CH	CL
Silty Clay	CL, MH	--
Peat	--	--

Figure B.5: Conversion table from USDA to USCS soil classes taken from (Zakikhani et al., 2017).

C | Decision tree

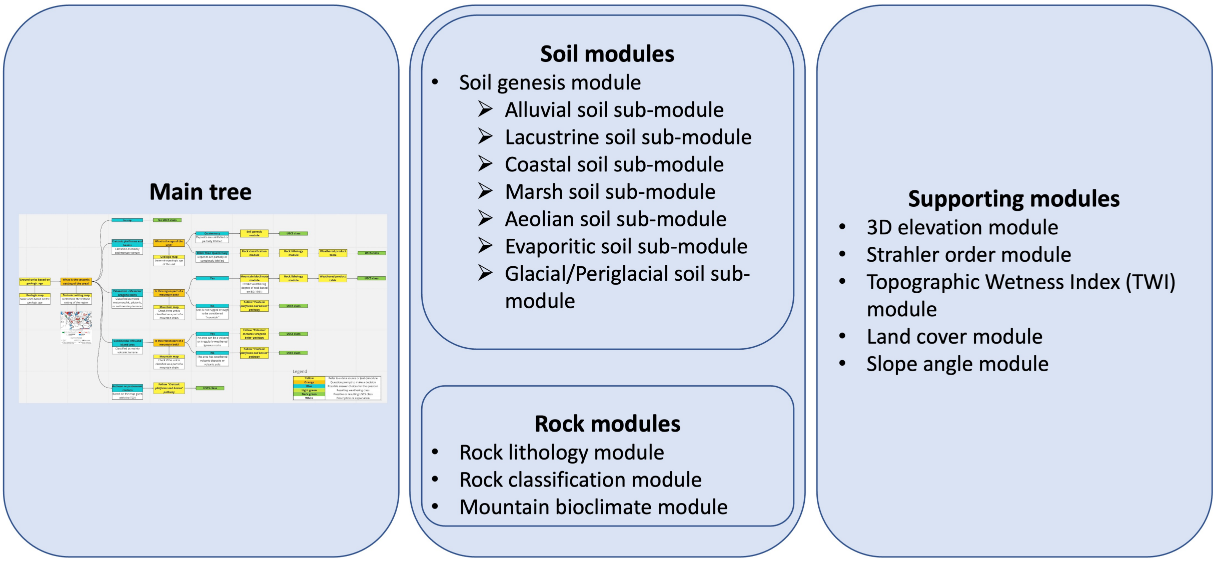

Figure C.1: Illustration showing the three main components of the decision tree. The first component shows the main tree. The second components consists of the soil and rock modules, together with any sub-modules. The third component includes any supporting features that may further improve the prediction results.

C.1 Main tree

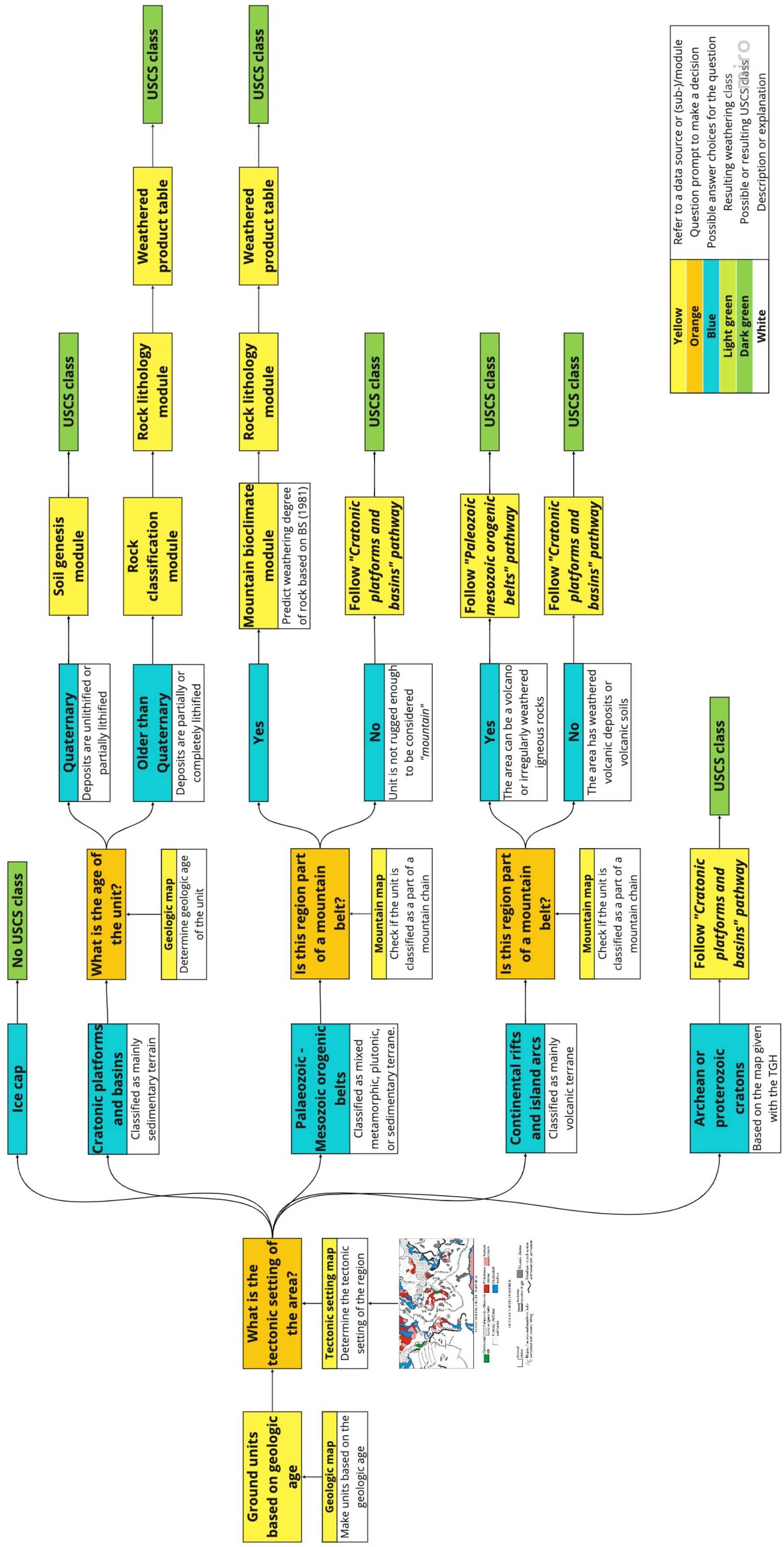

Figure C.2: Main decision tree

C.2 Soil genesis module

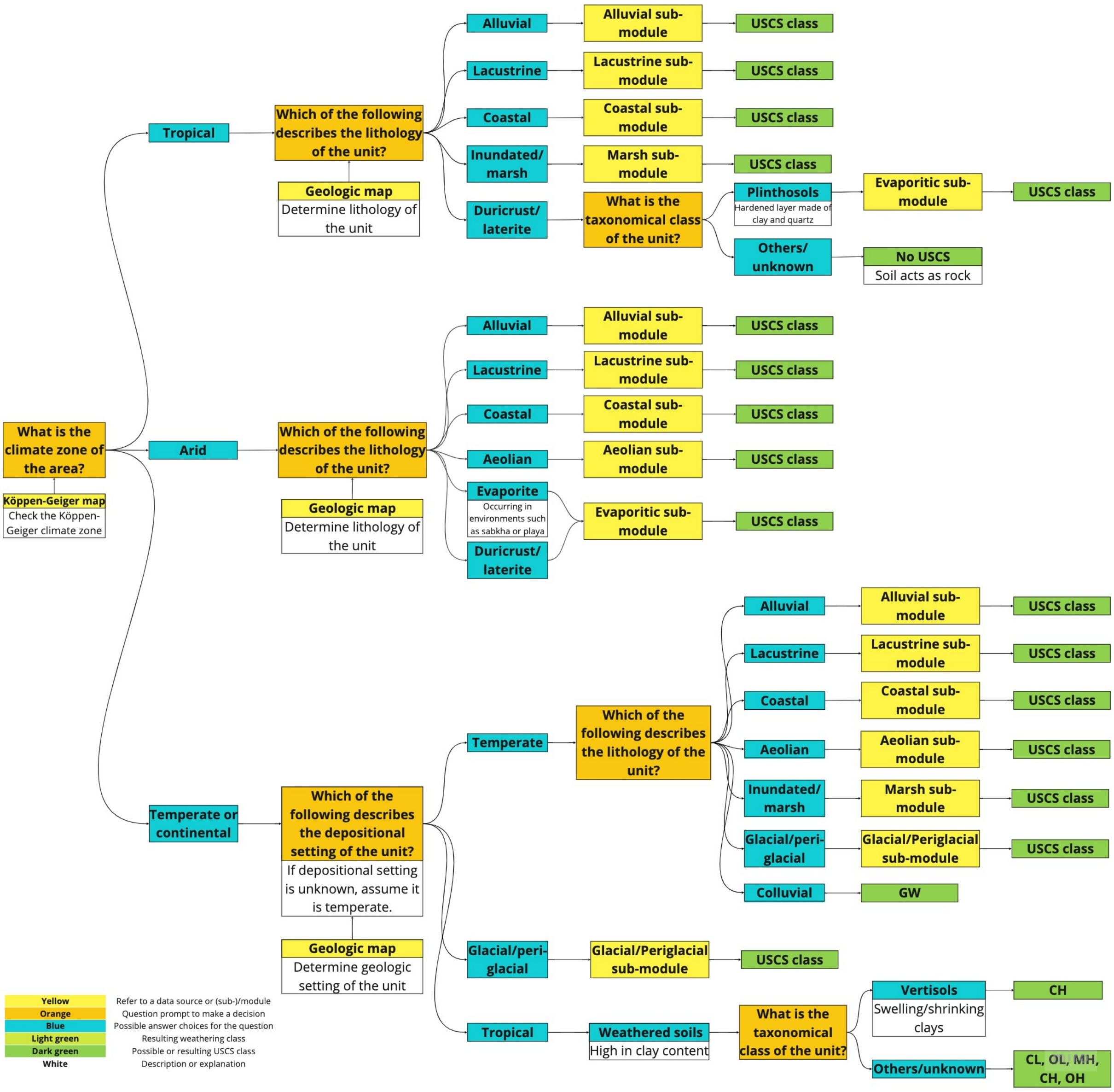

Figure C.3: Soil genesis module which branches out to several other modules depending on the climate and depositional process of the material.

C.2.1 Alluvial soil module

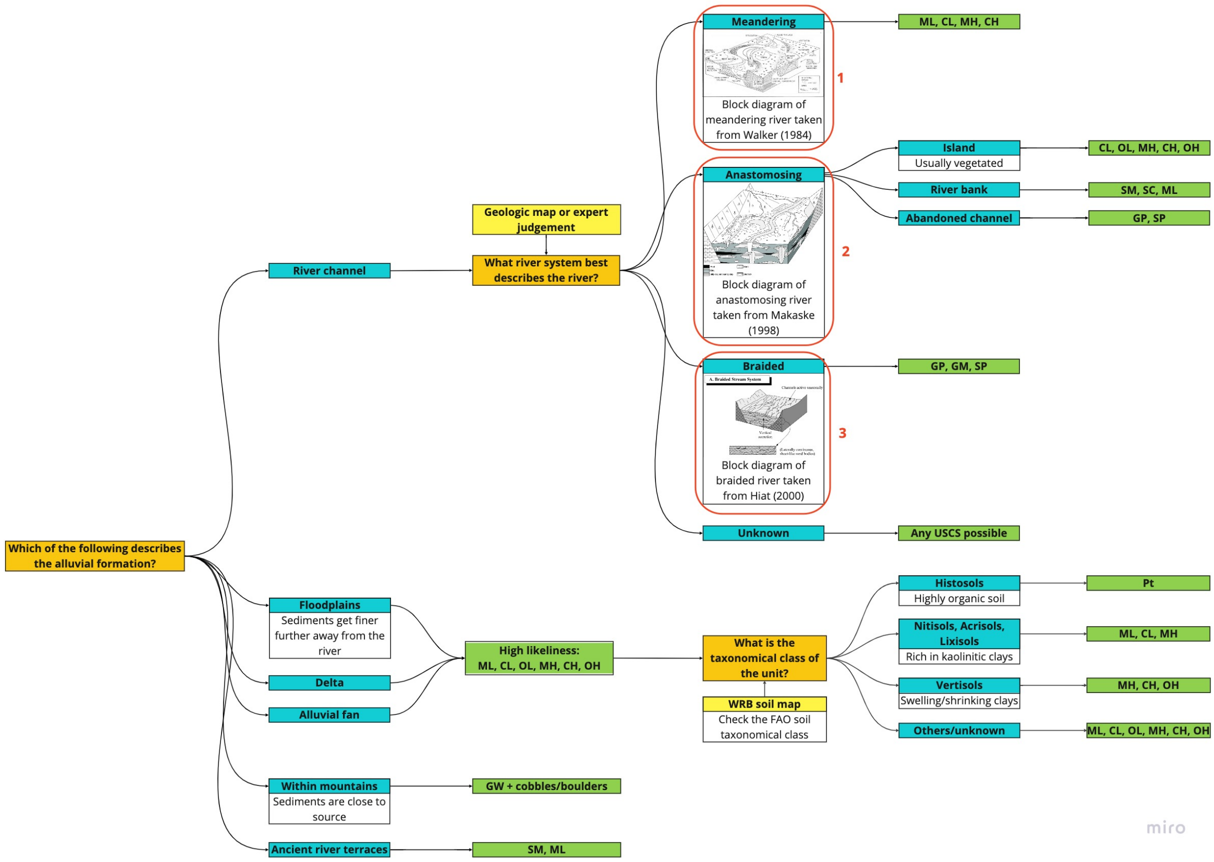

Figure C.4: Alluvial soil module. The block diagrams for meandering, anastomosing and braided river systems will be shown in more detail in the following figures.

Table 3-4. Aggregate types by feature

Feature	*Cobbles*	*Gravels*	*Sands*	*Silts*	*Clays*
Point bar		X	X		
Channel bar		X	X		
Alluvial Terrace	X	X	X		
Oxbow Lake, Clay plug				X	X
Natural levee		X	X	X	
Backswamp				X	X
Delta, Bird's-foot				X	X
Delta, Arcuate		X	X	X	X
Alluvial fan	X	X	X	X	X
Lake bed deposits				X	X
Esker	X	X	X		
Kame	X	X	X		
Kame Terrace	X	X	X		
Outwash Plains		X	X		
Desert Pavement	X	X			
Sand Dunes			X		
Loess				X	

Figure C.5: Table of aggregate type based on geomorphological feature, taken from Department of the Army (2012). This table was used as a guideline in making USCS soil classes predictions.

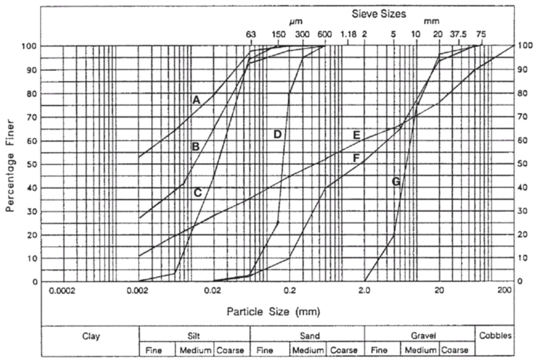

Figure C.6: Typical particle size distribution for various soils: (A) marine clay; (B) alluvial silty clay (estuarine); (C) uniform silt (loess); (D) uniform fine sand (dune); (E) glacial till (boulder clay); (F) sandy gravel (coarse alluvium); and (G) uniform (clean) gravel. Taken from P. G. Fookes et al. (2005). This table was used as a guideline in making USCS soil classes predictions.

Meandering river system

The meandering river system is made up of a main river channel that bends and curves through a valley or plain. There are several components to a meandering river system as can be seen in figure C.7 below. The main components of the river that influence the deposition of sediments are the river channel fill, its floodplains or floodbasins, crevasse splay and deposition on the inner bend of the river.

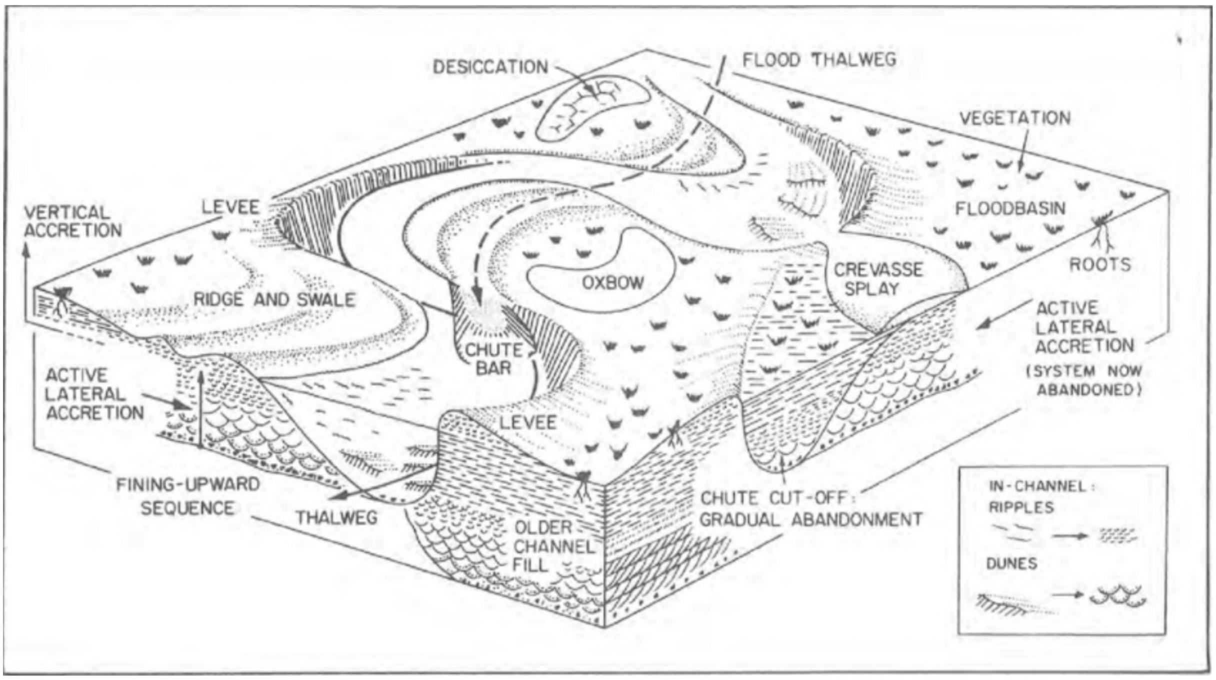

Figure C.7: Block diagram of a meandering river taken from Walker (1984).

Braided river system

Braided river systems are recognized by their shallow, but wide multi-threaded channels, which are usually smaller channels that surround braid bars. Compared to meandering river systems, the sediment load being transported of braided river systems is usually greater. Furthermore, this river system is also subject to rapid changes in structure, especially during floods.

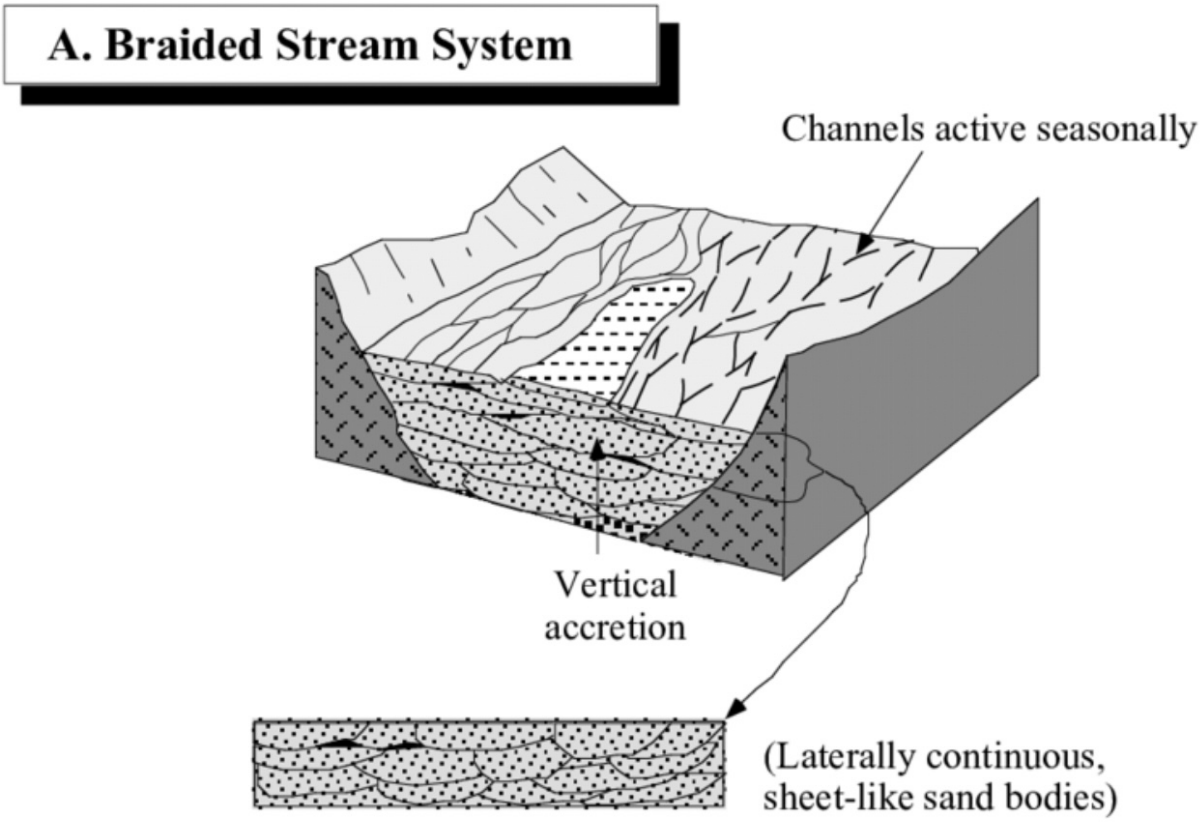

Figure C.8: Block diagram of a braided river takien from Hiatt (2000).

Anastomosing river system

Anastomosing river systems appear similar to braided river systems. The key difference is that anastomosing systems consist of channels that are more permanent than the channels of a braided river system. Furthermore, rather than surround small braid bars, an anastomosing river encloses floodplains. Lastly, the channels of this system can be meandering or braided.

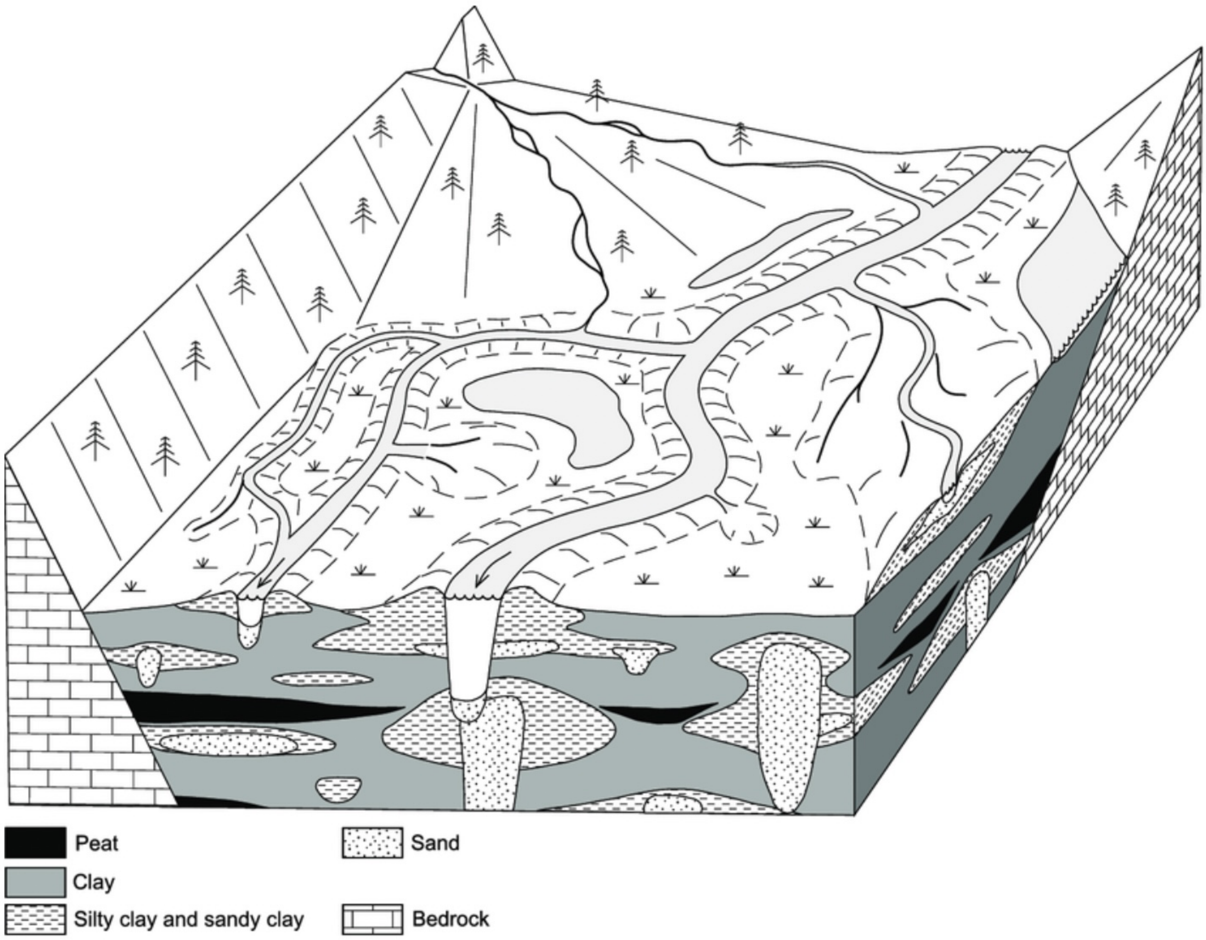

Figure C.9: Block diagram of an anastomosing river taken from Makaske et al. (2017).

C.2.2 Lacustrine soil module

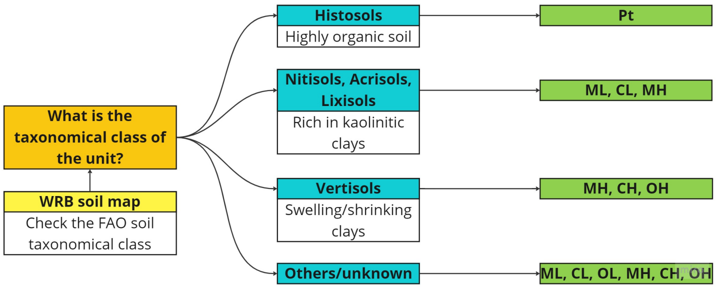

Figure C.10: Lacustrine soil module

C.2.3 Coastal soil module

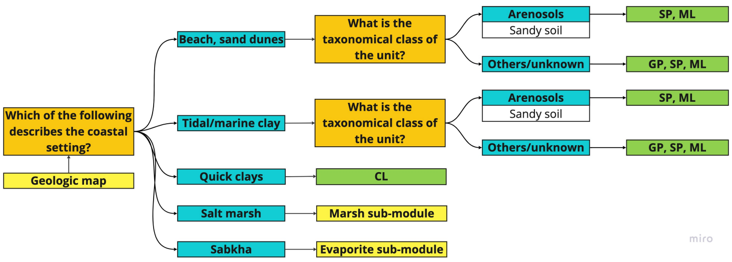

Figure C.11: Coastal soil module

C.2.4 Marsh soil module

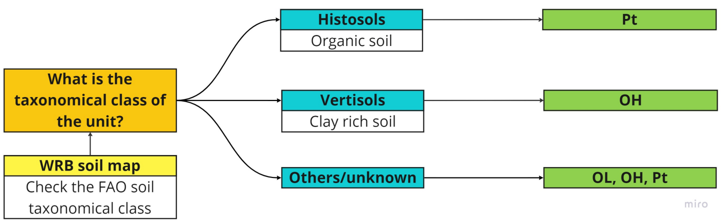

Figure C.12: Marsh soil module

C.2.5 Aeolian soil module

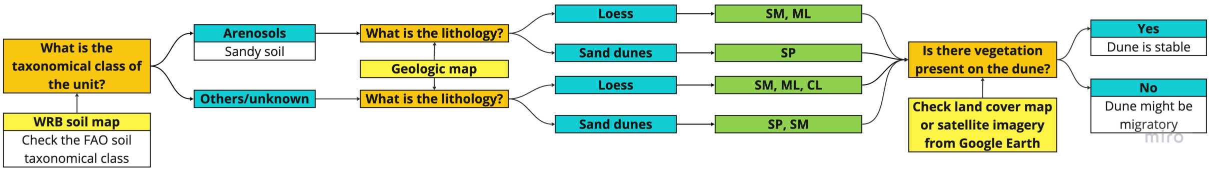

Figure C.13: Aeolian soil module

C.3 Rock classification module

C.3.1 Rock lithology module

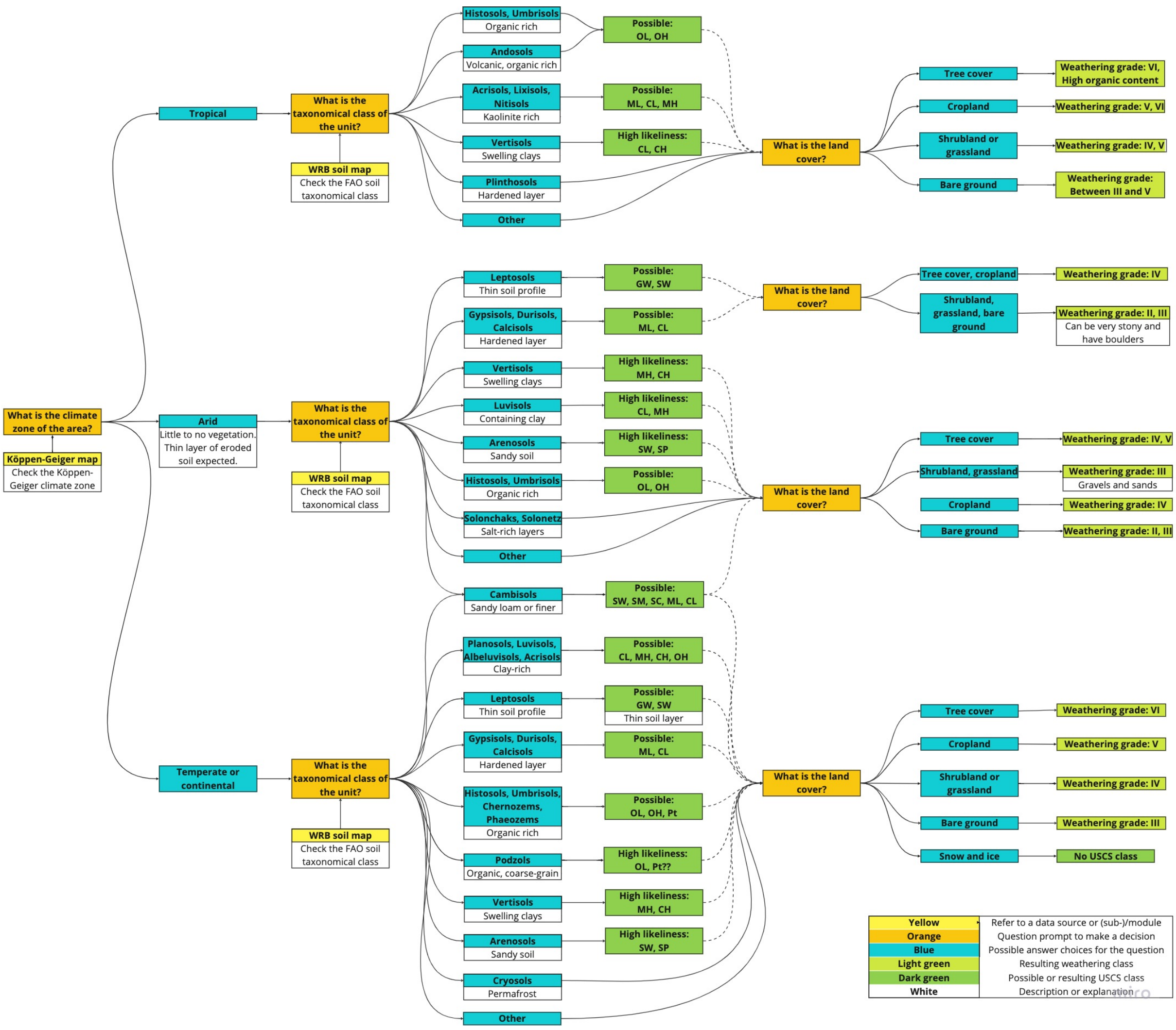

Figure C.14: Rock classification module

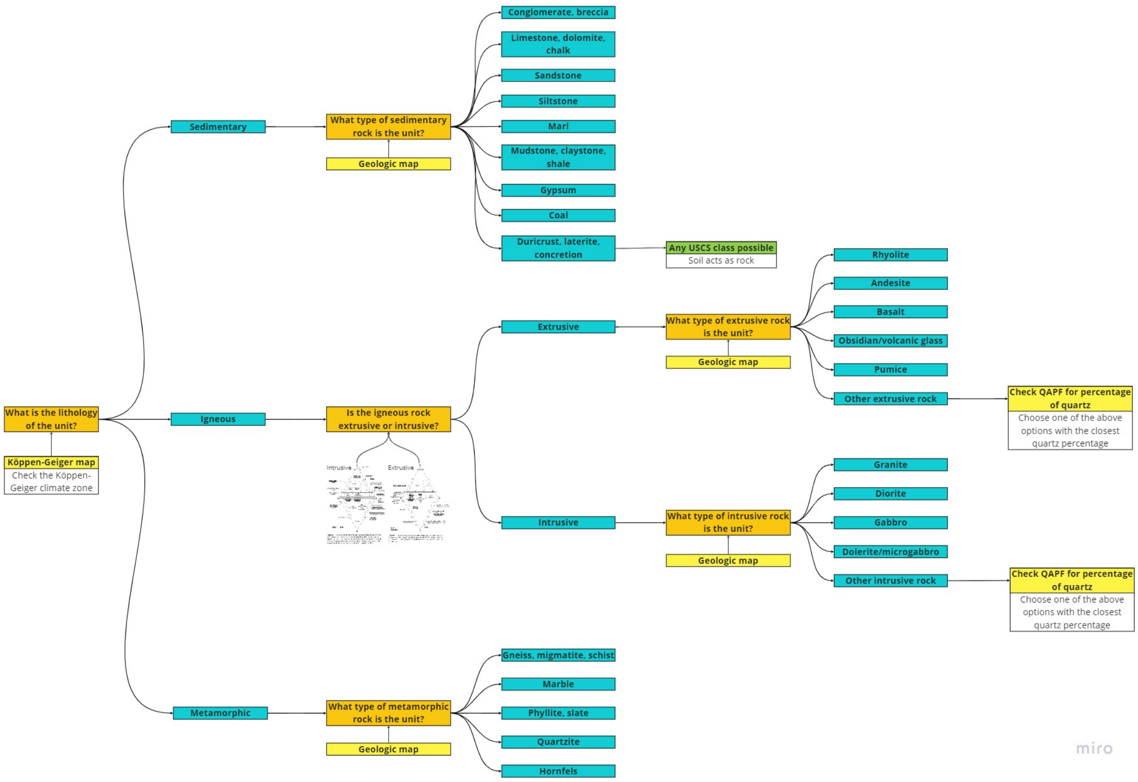

Figure C.15: Rock lithology module

C.3.2 Weathering grades description

Weathering grade / Rock type	I	II	III (Thin soil layer)	IV (Thin soil layer)	V (Soil profile present)	VI (Developed soil profile)
	Rock		**Soil matrix between corestones**		**Residual soil**	
Weathering state	**Fresh rock**	**Slightly weathererd rock**	**Moderately weathered, partly disintegrated rock**	**Highly weathered, disintegrated rock**	**Completely weathered to immature soil**	**Residual soil**
Description	Bare rock exposed on the surface. The properties of the rock are same as the parent material.	Rock may be slightly weathered and is weaker than fresh rock. A thin layer of topsoil exists.	Less that 50% of the rock has disintegrated. Irregular weathering patterns and corestones may be present. Mostly mechanical weathering. Duricrusts may be present.	More than 50% of the rock has disintegrated to soil. Irregular weathering patterns and corestones may be present. Mostly mechanical weathering.	Rock has underwent complete mechanical weathering and some degree of chemical weathering. Soil may still have mineralogical features of parent rock.	Rock has underwent complete mechanical, chemical and biogical weathering such that soil is no longer like parent material. Humus layer or duricrusts may be present.
Conditions for weathering	Rock is geologically young and is part of a mountain bioclimate range.	Arid climates or mountain bioclimates that does not experience as much chemical weathering.	Rocks in arid climates that have experienced weathering in previous climates.	Meditteranean climate. Arid to temperate.	Temperate or continental.	Hot and humid environment.
Uniformity of weathering	No weathering	Slight weathering, depends on fracture patterns	Irregular weathering	Irregular weathering	Soil like, with occasional rocks	Complete weathering
Vegetation expected	Little to none	Bare ground but may have sparse grass or shrubs	Grass, shrubs or agriculture	Grass or shrubs	Can be completely vegetated or used for agriculture	Can be completely vegetated or used for agriculture
Consequences for trafficability	Depends on the ruggedness or steepness of the terrain	Depends the steepness of the terrain	Depends on the presence of large boulders and the plasticity of the soil matrix.	Depends on the presence of large boulders and the plasticity of the soil matrix.	Depends on the presence of organic matter or clay	Depends on the presence of organic matter or clay

Figure C.16: Description of weathering grades used in this thesis.

C.3.3 Weathered rock table

Weathering grade Rock type	I	II	III (Thin soil layer)	IV (Thin soil layer)	V (Soil profile present)	VI (Developed soil profile)
Conglomerate, breccia	Fresh rock **No USCS**	Slight discolouration **GW + boulders**	Slightly eroded/fractured **GW, GM, GC + boulders**	Heavily fractured **GW, GM, GC + boulders**	Coarse-grained material **GW, GM, GC**	Poorly sorted, gravelly soil **GW, GM, GC, OH**
Limestone, dolomite, chalk	Fresh rock **No USCS**	Slight dissolution **GW + boulders**	Karst formations, little soil **GW, SW, SM, SC**	Heavy karsting **GW, SW, SM, ML**	Chalky, stony soil **GW, SW, SM, ML, CL, MH**	Loamy, clayey soil **ML, CL, OL, MH, CH, OH**
Sandstone	Fresh rock **No USCS**	Slight discolouration **GW, SW + boulders**	Thin layer eroded rock **GW, GM, SW, SM,**	Thin layer eroded rock **GW, GM, SW, SM**	Sand-rich soil **SW, SM, SC**	Sandy soil **SW, SM, SC, OL**
Siltstone	Fresh rock **No USCS**	Slight discolouration **GW, SW + boulders**	Thin layer eroded rock **GW, SM, ML**	Thin layer eroded rock **GW, SM, ML**	Silt, sand, clay **SM, SC, MH, ML**	Silty soil **MH, ML, OL**
Marl	Fresh rock **No USCS**	Slight dissolution **GW + boulders**	Karst formations **GW, SM, ML, MH**	Heavy karsting **GW, SM, ML, MH**	Silt rich **ML, MH, CH**	Loamy, clayey, swelling soil **MH, CH, OL**
Mudstone, claystone, shale	Fresh rock **No USCS**	Slight discolouration **GW, SW + boulders**	Thin layer eroded rock **GW, SW, ML, MH, CL**	Thin layer eroded rock **GW, SW, ML, MH, CL**	Clay rich soils, some pieces **CH, CL**	Clay rich soils **CH, CL, OH, OL**
Gypsum	Fresh rock **No USCS**	Slight dissolution **No USCS**	Thin layer eroded rock **GW, SW + boulders**	Thin layer soil/humus **ML, CL, OL, MH**	Thin layer soil/humus **ML, CL, OL, MH, CH, OH**	Salt-rich soils/concretions **ML, CL, OL, MH, CH, OH**
Coal	Fresh rock **No USCS**	Slight erosion **GW, SW**	Thin layer eroded rock **GW, ML**	Thin layer eroded rock **GW, ML, OL**	Small coal pieces and ash **GW, ML, OL**	Highly flammable ash **ML, OL**
Rhyolite	Fresh rock **No USCS**	Fractured rock **GW + boulders**	Irregular/deep weathering **GW, SW, SM + boulders**	Corestones and saprolite **GW, GM, SM, ML**	Regolith **ML, CL, OL, MH**	Mostly silt with some clay **ML, CL, OL, MH**
Andesite	Fresh rock **No USCS**	Fractured rock **GW + boulders**	Irregular/deep weathering **GW, SW, SM + boulders**	Corestones and saprolite **GW, GM, GC, SM, ML**	Regolith **ML, CL, OL, MH**	Mostly silty loam or loam **ML, CL, OL, MH**
Basalt	Fresh rock **No USCS**	Fractured rock **GW + boulders**	Irregular/deep weathering **GW, SW, SC + boulders**	Corestones and saprolite **GW, GM, GC, SC, ML**	Regolith **ML, CL, OL, MH, CH, OH**	Clay rich soil **ML, CL, OL, MH, CH, OH**
Obsidian, volcanic glass	Fresh rock **No USCS**	Fractured rock **GW, SW + boulders**	Irregular/deep weathering **GW, SW + boulders**	Corestones and saprolite **GW, GM, SW, SM**	Regolith **SW, SM, ML**	Black sand **SW, SM, ML**
Pumice/scoria	Fresh rock **No USCS**	Fractured rock **GW + boulders**	Irregular/deep weathering **GW, SW + boulders**	Corestones and saprolite **GW, SW, SM, SC**	Regolith **ML, CL, MH**	Organic clay **CL, OL, CH, OH**
Granite	Fresh rock **No USCS**	Fractured rock **GW + boulders**	Irregular/deep weathering **GW, SW, SM, SC+boulders**	Corestones and grus **GM, GC, SM, SC**	Grus **SC, ML, CL, OL, MH**	Sandy clay or clayey sand **SC, ML, CL, OL, MH**
Diorite	Fresh rock **No USCS**	Fractured rock **GW + boulders**	Irregular/deep weathering **GW, SW, SC + boulders**	Corestones and saprolite **GM, GC, SM, SC**	Regolith **SC, ML, CL, OL, MH**	Loamy clay **SC, ML, CL, OL, MH**
Gabbro	Fresh rock **No USCS**	Fractured rock **GW + boulders**	Irregular/deep weathering **GW, SW, SC + boulders**	Corestones and saprolite **GM, GC, SM, SC**	Regolith **ML, CL, MH**	Loamy clay **ML, CL, OL, MH, CH, OH**
Dolerite/microgabbro	Fresh rock **No USCS**	Fractured rock **GW + boulders**	Irregular/deep weathering **GW, SW, SC + boulders**	Corestones and saprolite **GM, GC, SM, SC**	Regolith **ML, CL, MH, CH**	Shrinking/swelling clays **CL, MH, CH, OH**
Gneiss, migmatite, schist	Fresh rock **No USCS**	Fractured rock **GW + boulders**	Irregular/deep weathering **GW, SW + boulders**	Corestones and grus **GM, GC, SM, SC**	Grus **SC, ML, CL, OL, MH**	Silty sands, loam or clay **ML, CL, OL, MH, CH, OH**
Marble	Fresh rock **No USCS**	Slight dissolution **GW + boulders**	Irregular/deep weathering **GW, SW + boulders**	Corestones and grus **GW, SW, SM**	Saprolite **GM, GC, SM, ML, CL, MH**	Loamy soil **ML, CL, OL, MH, CH, OH**
Phyllite, slate	Fresh rock **No USCS**	Fractured rock **GW + boulders**	Irregular/deep weathering **GW, SW + boulders**	Platy pieces **GC, SC, SM, ML**	Clay matrix **SM, SC, ML, CL, OL, MH, CH, OH**	Clay rich soil **CL, OL, CH, OH**
Quartzite	Fresh rock **No USCS**	Fractured rock **GW + boulders**	Often sand rich **GW, SW + boulders**	Coarse grained **GW, SW, SM**	Coarse grained **GW, SM, SC, ML**	Sandy soils **SM, SC, ML, CL, OL, MH,**
Hornfels	Fresh rock **No USCS**	Fractured rock **GW + boulders**	Irregular/deep weathering **GW, SW + boulders**	Coarse stony soil **GW, SW, SM**	Can be anything **SM, SC, ML, CL, OL MH, CH, OH**	Fine grained **ML, CL, OL, MH, CH, OH**

Figure C.17: Weathered rock table

D | Maps used

D.1 Overview of data used

Data type	Scale	Source
Geologic map	-	Geologic maps are usually specific to the study area and can be found in national databases.
Tectonic setting map	1:35,000,000	Geologic Survey of Canada
Taxonomical soil map	1:500,000	SoilGrids.org
Köppen-Geiger climate map	1:55,000,000	Found in the paper by Kottek et al. (2006). Köppen-Geiger map
Mountain bioclimate map	1:10,000	GMBA website
Land cover map	1:10,000	WorldCover
DEM	30m accuracy	SRTM Downloader Plugin

Table D.1: Table showing data sources used in the decision tree model.

D.2 World tectonic setting map

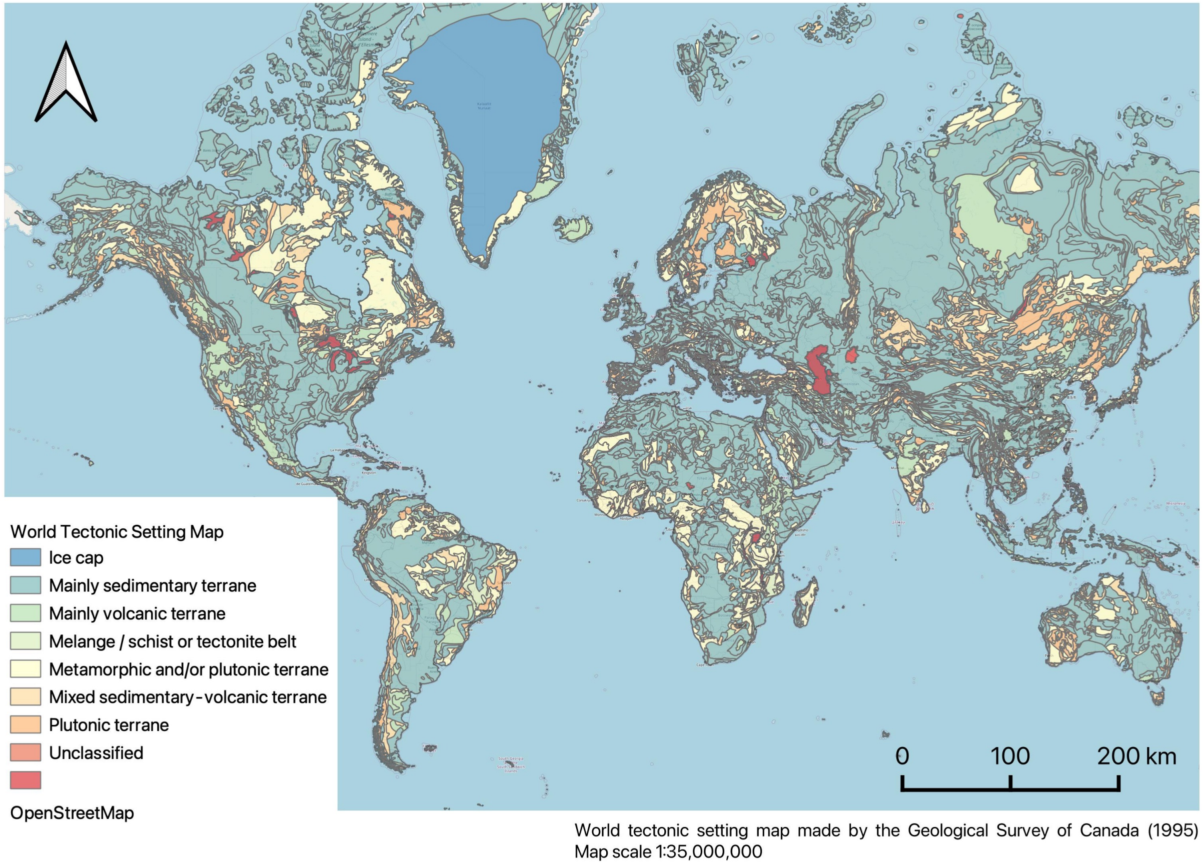

Figure D.1: World tectonic setting map made by Geological Survey of Canada in 1995, taken from usgs.gov.

D.3 Köppen-Geiger climate classification scheme

In order to define the Köppen-Geiger climate classes, the following equations have to be used:

Type	Description	Criterion
A	**Equatorial climates**	$T_{min} \geq +18$ °C
Af	Equatorial rainforest, fully humid	$P_{min} \geq 60$ mm
Am	Equatorial monsoon	$P_{ann} \geq 25\,(100-P_{min})$
As	Equatorial savannah with dry summer	$P_{min} < 60$ mm in summer
Aw	Equatorial savannah with dry winter	$P_{min} < 60$ mm in winter
B	**Arid climates**	$P_{ann} < 10\,P_{th}$
BS	Steppe climate	$P_{ann} > 5\,P_{th}$
BW	Desert climate	$P_{ann} \leq 5\,P_{th}$
C	**Warm temperate climates**	-3 °C $< T_{min} < +18$ °C
Cs	Warm temperate climate with dry summer	$P_{smin} < P_{wmin}$, $P_{wmax} > 3\,P_{smin}$ and $P_{smin} < 40$ mm
Cw	Warm temperate climate with dry winter	$P_{wmin} < P_{smin}$ and $P_{smax} > 10\,P_{wmin}$
Cf	Warm temperate climate, fully humid	neither Cs nor Cw
D	**Snow climates**	$T_{min} \leq -3$ °C
Ds	Snow climate with dry summer	$P_{smin} < P_{wmin}$, $P_{wmax} > 3\,P_{smin}$ and $P_{smin} < 40$ mm
Dw	Snow climate with dry winter	$P_{wmin} < P_{smin}$ and $P_{smax} > 10\,P_{wmin}$
Df	Snow climate, fully humid	neither Ds nor Dw
E	**Polar climates**	$T_{max} < +10$ °C
ET	Tundra climate	0 °C $\leq T_{max} < +10$ °C
EF	Frost climate	$T_{max} < 0$ °C

Figure D.2: Key to calculate Köppen-Geiger climate zones for the main climates and subsequent precipitation conditions, taken from the paper by Kottek et al. (2006).

Type	Description	Criterion
h	Hot steppe / desert	$T_{ann} \geq +18$ °C
k	Cold steppe /desert	$T_{ann} < +18$ °C
a	Hot summer	$T_{max} \geq +22$ °C
b	Warm summer	not (a) and at least 4 $T_{mon} \geq +10$ °C
c	Cool summer and cold winter	not (b) and $T_{min} > -38$ °C
d	extremely continental	like (c) but $T_{min} \leq -38$ °C

Figure D.3: Key to calculate Köppen-Geiger temperature classification, taken from the paper by Kottek et al. (2006).

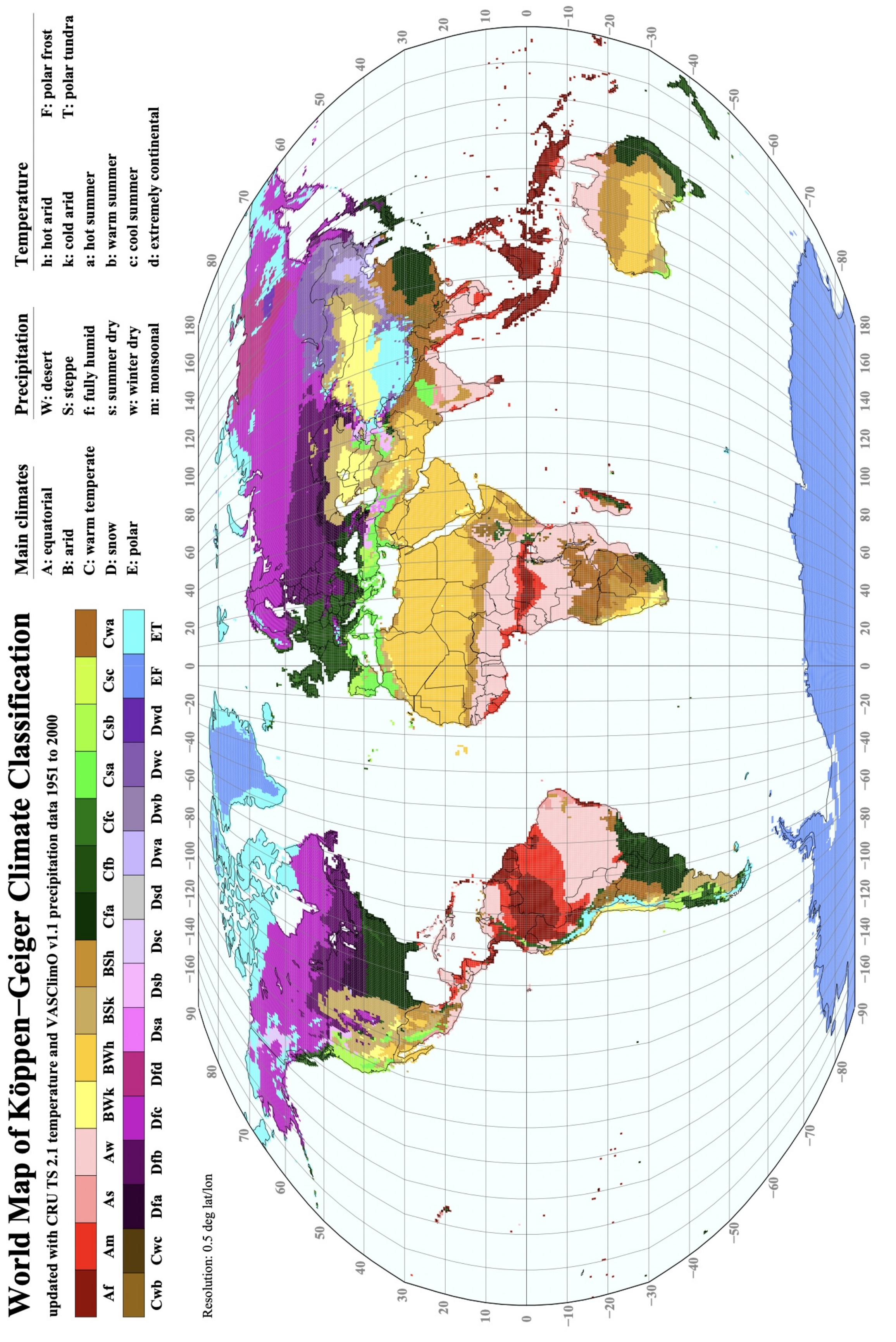

Figure D.4: Climate zones of the world based on Köppen-Geiger climate classification scheme, taken from the paper by Kottek et al. (2006).

D.4 WRB soil map

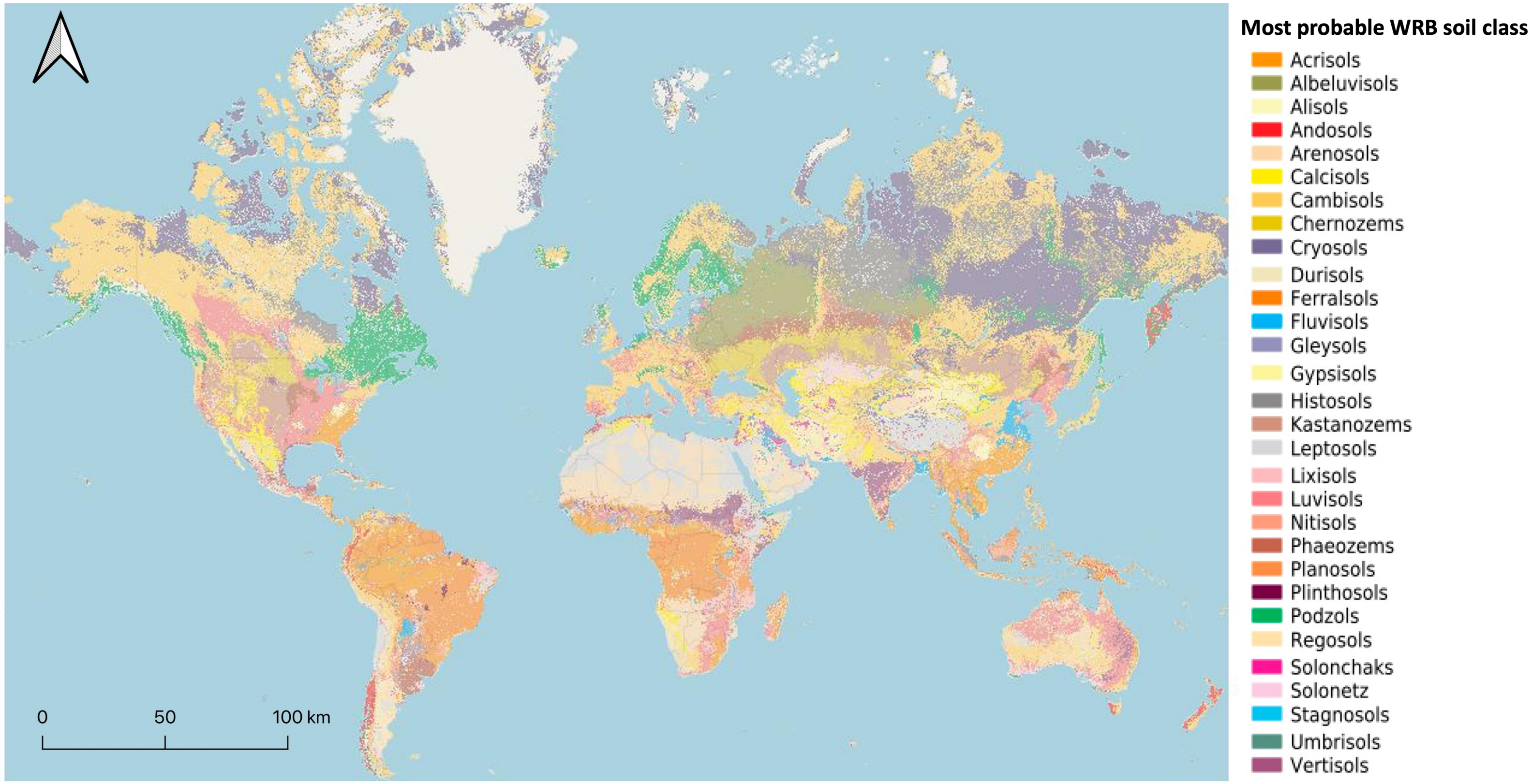

Figure D.5: Soil map showing the most probable taxonomical soil classes, taken from SoilGrids.org.

D.5 Mountain bioclimatic zone

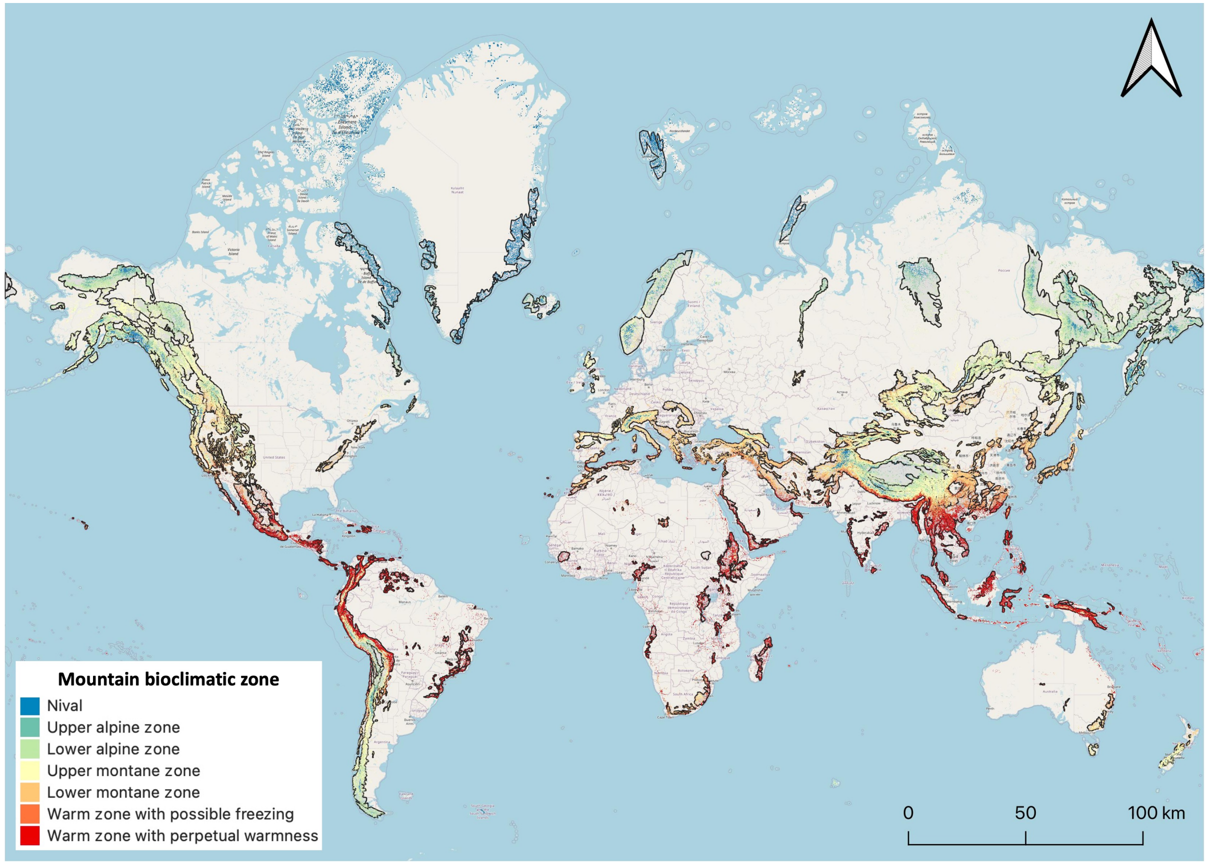

Figure D.6: World mountain bioclimatic zone map, taken from GMBA website.

D.6 Pilot study: Mali

Data type	Scale	Source
Geologic map	1:500,000 1:1,500,000	Both maps are scanned maps from the Royal Museum of Central Africa in Belgium
Tectonic setting map	1:35,000,000	Geologic Survey of Canada
Taxonomical soil map	1:500,000	SoilGrids.org
Köppen-Geiger climate map	1:55,000,000	Found in the paper by Kottek et al. (2006). Köppen-Geiger map
Mountain bioclimate map	1:10,000	GMBA website
Land cover map	1:10,000	WorldCover
DEM	30m accuracy	SRTM Downloader Plugin

Table D.2: List of maps used in the Mali pilot study.

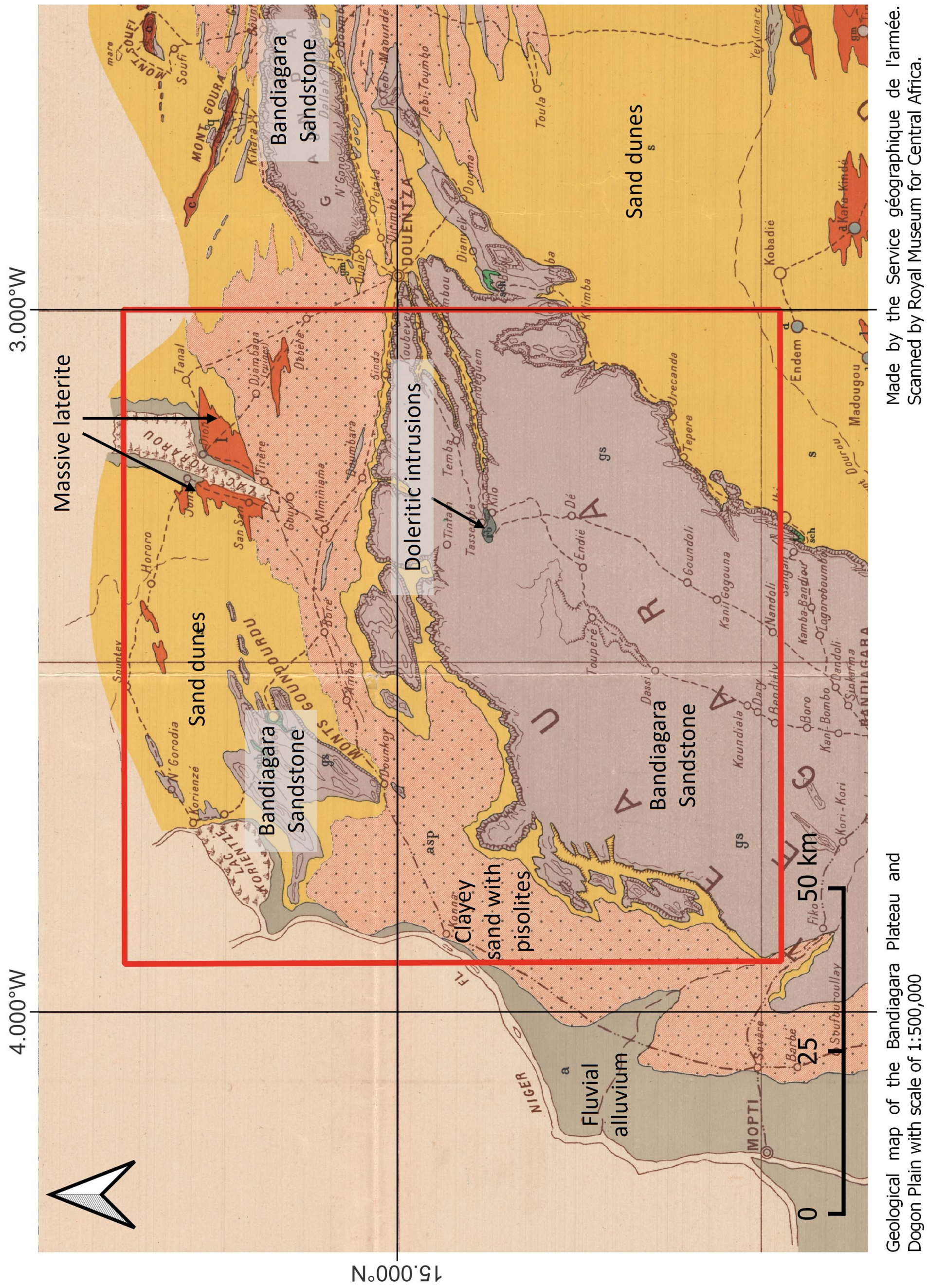

Figure D.7: Map with scale 1:500,000, made in 1934. This map is available in the Royal Museum for Central Africa in Belgium.

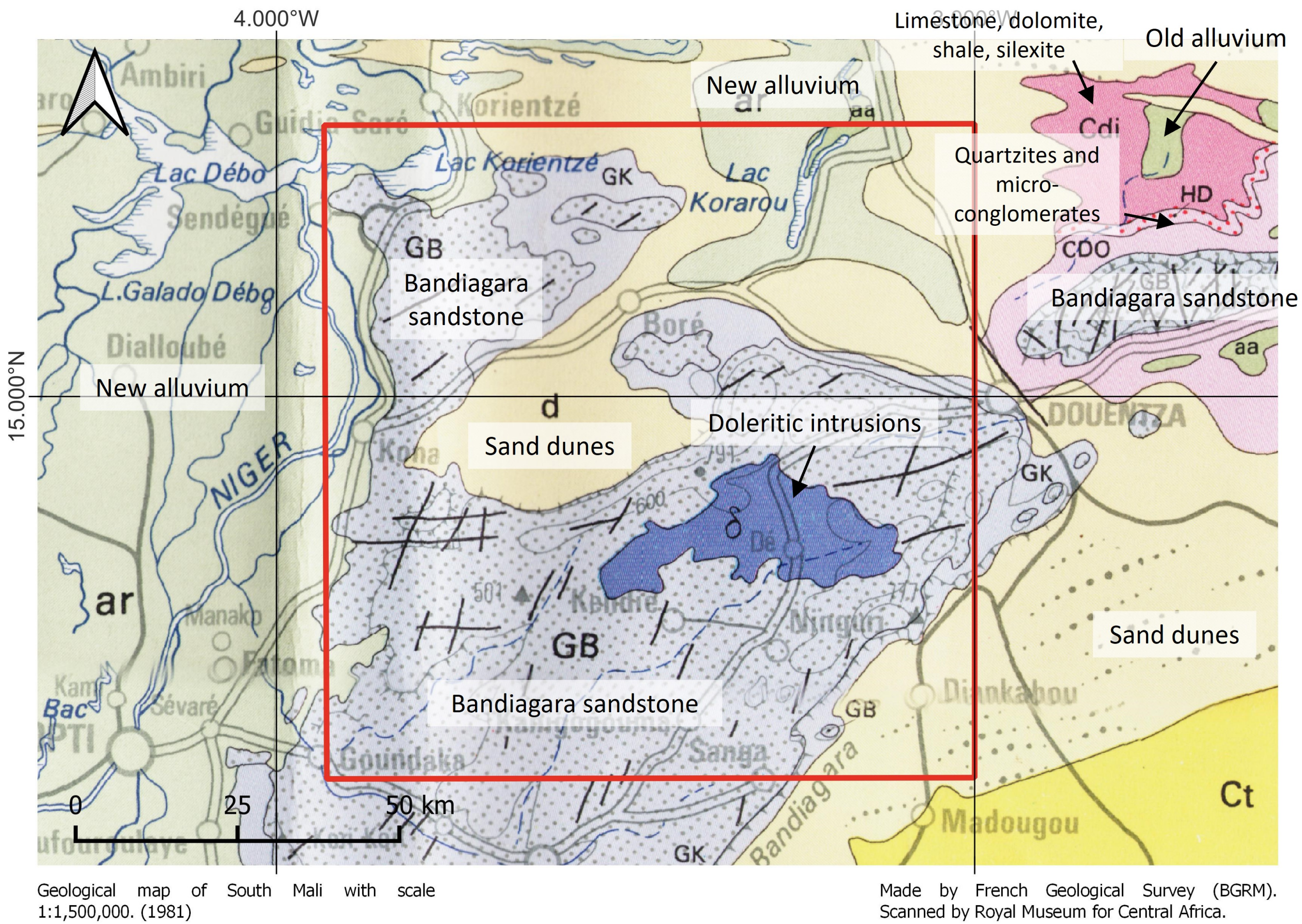

Figure D.8: Map with scale 1:1,500,000, made in 1981. This map is available in the Royal Museum for Central Africa in Belgium.

Figure D.9: Location 1 (Damagari, Mali)

Figure D.10: Location 2 (along the Niger River)

D.7 Pilot study: Spain

Data type	Scale	Source
Geologic map	1:1,000,000 1:1,000,000	Geologic Map of Spain LNEG (WMS link)
Tectonic setting map	1:35,000,000	Geologic Survey of Canada
Taxonomical soil map	1:500,000	SoilGrids.org
Köppen-Geiger climate map	1:55,000,000	Found in the paper by Kottek et al. (2006). Köppen-Geiger map
Mountain bioclimate map	1:10,000	GMBA website
Land cover map	1:10,000	WorldCover
DEM	30m accuracy	SRTM Downloader Plugin

Table D.3: List of maps used in the Spain pilot study.

D.8 Validation study: Netherlands

Data type	Scale	Source
Geologic map	1:600,000	Dutch geologic map (DINOLoket)
Tectonic setting map	1:35,000,000	Geologic Survey of Canada
Taxonomical soil map	1:500,000	SoilGrids.org
Köppen-Geiger climate map	1:55,000,000	Found in the paper by Kottek et al. (2006). Köppen-Geiger map
Mountain bioclimate map	1:10,000	GMBA website
Land cover map	1:10,000	WorldCover
DEM	30m accuracy	SRTM Downloader Plugin

Table D.4: List of maps used in the Netherlands validation study.