

**INFLUENCE OF DISTRIBUTED SOIL LANDSCAPE UNITS ON BARE SOIL
EVAPORATION DYNAMICS**

BY

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DECLARATION

I hereby declare that this thesis has been solely written by myself and that it reflects my own research work. This work has neither in whole nor in part been presented for another degree elsewhere. The works of other researchers have been duly cited and appropriately referenced. All assistances received in executing this project have been acknowledged.



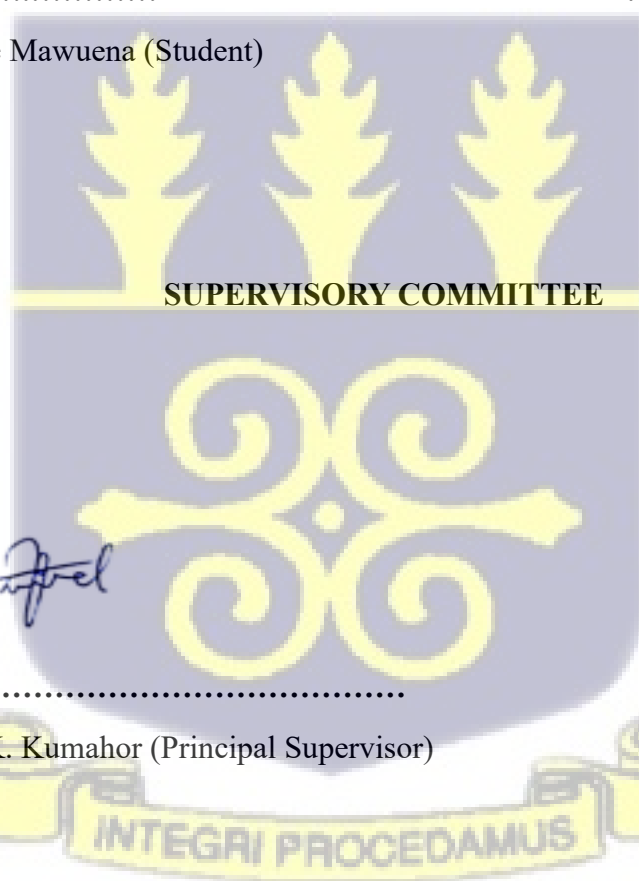
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Date

DEDICATION

This work is dedicated to the Almighty God for His unending grace, which has sustained me throughout these years. I also dedicate this work to my dear father, Chris Atsu Oklu, and my beloved mother, Felicia Ama Oklu, for their unwavering love and immense support.



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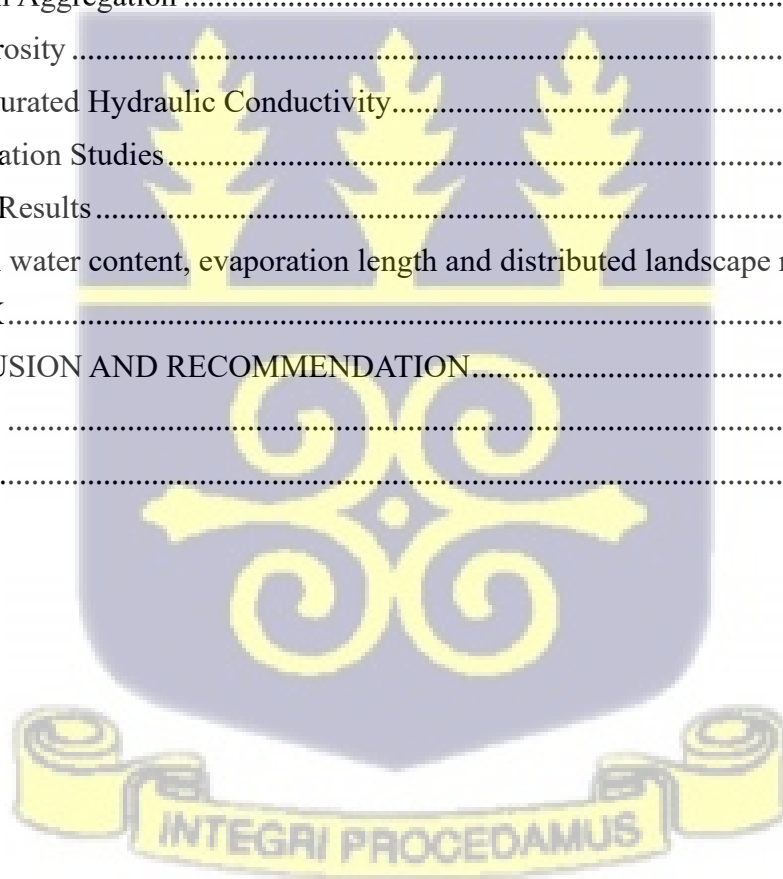
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TABLE OF CONTENTS

DECLARATION.....	1
DEDICATION	2
ACKNOWLEDGEMENT	3
LIST OF FIGURES	7
LIST OF TABLES	8
ABSTRACT.....	15
CHAPTER ONE	15
1.0 INTRODUCTION.....	17
1.1 Background.....	17
1.2 Problem statement and hypothesis	19
1.3 Objectives	22
CHAPTER TWO	23
2.0 LITERATURE REVIEW	23
2.1 Bare soil evaporation	23
2.2 Quantifying evaporation at different scales	24
2.2.1 Pore scale considerations	24
2.2.2 Soil evaporation at column scale	24
2.2.3 Soil evaporation at field scale	25
2.3 Influence of soil properties on bare soil evaporation	26
2.3.1 Texture	26
2.3.1.1 Influence of silt fraction on evaporation	27
2.3.1.2 Influence of Sand fraction on evaporation	27
2.3.1.3 Influence of clay fraction on evaporation	28
2.3.2 Bulk Density	29
2.3.3 Organic Carbon	29
2.3.4 Hydraulic Conductivity.....	30
2.3.5 Soil aggregate content.....	31
2.3.6 Porosity	32
2.3.7 Field capacity	33
2.3.8 Soil Moisture Content	33
2.4 Effect of atmospheric conditions on bare-soil evaporation	34
2.4.1 Temperature	34
2.4.2 Humidity	35

2.4.3 Wind Speed	36
2.4.4 Solar Radiation.....	36
2.4.5 Precipitation	37
2.5 Methods for determining bare soil evaporation.....	38
2.6 Modelling soil evaporation.....	39
2.6.1 Simulating evaporation processs in HYDRUS 1-D.....	39
2.6.2 Evaporation stages and Critical Water Content ($\theta_{1/2}$)	41
2.7 Mapping of Soil Evaporation Using Geographic Information Systems (GIS).....	43
CHAPTER THREE	45
3.0 MATERIALS AND METHODS.....	45
3.1 Description of Study Area	45
3.1.1 Location and Sampling	45
3.2 Soil properties.....	52
3.2.1 Determining aggregate content (%Aggregate)	52
3.2.2 Determining of Field (ρ_f) and Dry Bulk Density (ρ_b).....	52
3.2.3 Field Moisture Content	53
3.2.4 Organic Carbon.....	53
3.2.5 Soil Particle Size Distribution (Texture).....	54
3.2.6 Field capacity	55
3.3 Soil evaporation.....	56
3.4 Measurement of Saturated Hydraulic Conductivity	58
3.5 Hydrus 1-D Numerical Code.....	59
3.6 Determination of the Critical Water Content (CWC)	60
3.7 Deriving a Semi- Distributed Evaporation Map for the Interior Savannah zone of Ghana.....	60
CHAPTER FOUR.....	63
4.0 RESULTS.....	63
4.1. Study area and soils	63
4.2 Soil properties.....	67
4.2.1 Soil texture	67
4.2.2 Soil bulk density	71
4.2.3 Soil organic carbon	72
4.2.4 Aggregate content	73
4.2.5 Total porosity	73
4.2.6 Field capacity	76

4.2.7 Saturated hydraulic conductivity (K_{sat})	77
4.3 Daily Evaporation Rate	79
4.7 Hydrus -1D simulation and soil hydraulic functions.....	87
4.8 Critical moisture content ($\theta_{1/2}$)	93
4.9 Semi-distributed landscape model.....	94
CHAPTER FIVE	99
5.0 DISCUSSIONS	99
5.1 Weather variability and change.....	99
5.2 Soil of the Northern Strip of Ghana.....	100
5.3 Soil Properties.....	100
5.3.1 Soil Texture	100
5.3.2 Bulk Density	101
5.3.3 Organic Carbon	102
5.3.4 Soil Aggregation	102
5.3.5 Porosity	103
5.3.6 Saturated Hydraulic Conductivity.....	103
5.4 Evaporation Studies.....	104
5.5 Model Results.....	105
5.6 Critical water content, evaporation length and distributed landscape model	105
CHAPTER SIX.....	109
6.0 CONCLUSION AND RECOMMENDATION.....	109
REFERENCES	112
APPENDICES	144



LIST OF TABLES

Table 3. 1 Locations where soil samples were collected	51
Table 4. 1 Satellite climatic data for weather stations across the study area.	67



LIST OF FIGURES

Figure 2. 1 Hypothetical case of stage I (constant rate period, CRP) and stage II (falling rate period, FRP) evaporation characteristics (separated by black dashed line) plotted as evaporation rate (E) and cumulative evaporation (CE).	42
Figure 3. 1 Map showing the locations the soil samples which were collected.	48
Figure 3. 2 Map showing selected soil series.	49
Figure 3. 3 Geometry of soil evaporation columns.....	56
Figure 3. 4 The experimental setup for measurement of soil evaporation.....	57
Figure 3. 5 Figure 3.5 Schematic of a falling head hydraulic conductivity measurement setup.....	59
Figure 3. 6 Workflow for developing the semi-distributed landscape model.....	62
Figure 4. 1 Map of zoom in on the interior agroecological zones (Guinea savanna and Sudan savanna) of Ghana with sampling location (diamond) and location to the closest weather station (trains).....	65
Figure 4. 2 Analysis of satellite weather data (temperature, rainfall, relative humidity) data extracted with reference to the location weather station in the interior savannah zone of Ghana (data source: https://power.larc.nasa.gov/).	66
Figure 4. 3 Box plot of the soil particle size of the soils sampled from the interior savannah zone of Ghana (%Sand, %Silt, %Clay).....	68
Figure 4. 4 Textural triangle of the soils sampled from the interior savannah zone of Ghana (%Sand, %Silt, %Clay)	69
Figure 4. 5 Bar chart of sand content (%) of the various soil series sampled from the interior savannah zone of Ghana.....	69

Figure 4. 6 Bar chart of silt content (%) of the various soil series sampled from the interior savannah zone of Ghana.....	70
Figure 4. 7 Bar chart of clay content (%) of the various soil series sampled from the interior savannah zone of Ghana.....	70
Figure 4. 8 Boxplot of bulk density (g/cm^3), organic carbon (OC) and stone content%(right) for the soils sampled from the interior savannah zone of Ghana.	71
Figure 4. 9 Bar chart of soil bulk density(g/cm^3) of the various soil series sampled from the interior savannah zone of Ghana.	72
Figure 4. 10 Bar char of soil organic carbon (%) content of the various soil series sampled from the interior savannah zone of Ghana.....	74
Figure 4. 11 Bar chart of aggregate content of the various soil series sampled from the interior savannah zone of Ghana.....	74
Figure 4. 12 Boxplot of total porosity, field capacity, and saturated hydraulic conductivity (Ks) of the soils sampled from the interior savannah zone of Ghana.	75
Figure 4. 13 Bar chart of total porosity of the various soil series sampled from the interior savannah zone of Ghana.....	75
Figure 4. 14 Bar chart of Field capacity of the various soil series sampled from the interior savannah zone of Ghana.....	77
Figure 4. 15 Bar chart of saturated hydraulic conductivity of the various soil series sampled from the interior savannah zone of Ghana.....	78
Figure 4. 16 Kpalesawgu soil series: Daily evaporation rates recorded for soil and open water (left), quotient of soil evaporation (middle) and observed (open circles) and modelled (lines; Hydrus-1D) cumulative plotted as a function of days of evaporation.....	79

Figure 4. 17 Mimi Techiman soil series: Daily evaporation rates recorded for soil and open water (left), quotient of soil evaporation (middle) and observed (open circles) and modelled (lines; Hydrus-1D) cumulative plotted as a function of days of evaporation.....	80
Figure 4. 18 Kologu soil series: Daily evaporation rates recorded for soil and open water (left), quotient of soil evaporation (middle) and observed (open circles) and modelled (lines; Hydrus-1D) cumulative plotted as a function of days of evaporation.	80
Figure 4. 19 Sambu Pasga soil series: Daily evaporation rates recorded for soil and open water (left), quotient of soil evaporation(middle) and observed (open circles) and modelled (lines; Hydrus-1D) cumulative plotted as a function of days of evaporation.	80
Figure 4. 20 Nangodi soil series: Daily evaporation rates recorded for soil and open water (left), quotient of soil evaporation (middle) and observed (open circles) and modelled (lines; Hydrus-1D) cumulative plotted as a function of days of evaporation.	81
Figure 4. 21 Pusiga soil series: Daily evaporation rates recorded for soil and open water (left), quotient of soil evaporation (middle) and observed (open circles) and modelled (lines; Hydrus-1D) cumulative plotted as a function of days of evaporation.	81
Figure 4. 22 Wenchi Hilun soil series: Daily evaporation rates recorded for soil and open water (left), quotient of soil evaporation (middle) and observed (open circles) and modelled (lines; Hydrus-1D) cumulative plotted as a function of days of evaporation.....	81

Figure 4. 23 Kpalesawgu Changnalili: Daily evaporation rates recorded for soil and open water (left), quotient of soil evaporation (middle) and observed (open circles) and modelled (lines; Hydrus-1D) cumulative potted as a function of days of evaporation.....	82
Figure 4. 24 Nambari soil series: Daily evaporation rates recorded for soil and open water (left), quotient of soil evaporation (middle) and observed (open circles) and modelled (lines; Hydrus-1D) cumulative potted as a function of days of evaporation.	82
Figure 4. 25 Kintampo soil series: Daily evaporation rates recorded for soil and open water (left), quotient of soil evaporation (middle) and observed (open circles) and modelled (lines; Hydrus-1D) cumulative potted as a function of days of evaporation.	82
Figure 4. 26 Tanchera soil series: Daily evaporation rates recorded for soil and open water (left), quotient of soil evaporation (middle) and observed (open circles) and modelled (lines; Hydrus-1D) cumulative potted as a function of days of evaporation.	83
Figure 4. 27 Lima Volta soil series: Daily evaporation rates recorded for soil and open water (left), quotient of soil evaporation (middle) and observed (open circles) and modelled (lines; Hydrus-1D) cumulative potted as a function of days of evaporation.	83
Figure 4. 28 Techiman Tampu: Daily evaporation rates recorded for soil and open water (left), quotient of soil evaporation (middle) and observed (open circles) and modelled (lines; Hydrus-1D) cumulative potted as a function of days of evaporation.	83

Figure 4. 29 Tanina soil series: Daily evaporation rates recorded for soil and open water (left), quotient of soil evaporation (middle) and observed (open circles) and modelled (lines; Hydrus-1D) cumulative potted as a function of days of evaporation.	84
Figure 4. 30 Siare Dagare soil series: Daily evaporation rates recorded for soil and open water (left), quotient of soil evaporation (middle) and observed (open circles) and modelled (lines; Hydrus-1D) cumulative potted as a function of days of evaporation.	84
Figure 4. 31 Temperature and relative humidity (a) and correlation between the potential evaporation and vapor pressure deficit (b) in the screenhouse at the Department of Geography & Resource Development at the University of Ghana.	84
Figure 4. 32 Evaporation rate at stage II versus mean grain diameter (D_g) of soil (note that the annotation is percent sand content; the black dashed line is atmospheric demand threshold according to Or et al., 2013).	86
Figure 4. 33 Evaporation rate at stage II versus mean grain diameter (D_g) of soil (note that the annotation is critical moisture content $\theta_{1/2}$).	87
Figure 4. 34 Tanina Soil series: Moisture characteristics (left) and hydraulic conductivity function (right) derived from evaporation measurement.	88
Figure 4. 35 Siare Dagare soil series: Moisture characteristics (left) and hydraulic conductivity function (right) derived from evaporation measurement.	88
Figure 4. 36 Kpelesawgu soil series: Moisture characteristics (left) and hydraulic conductivity function (right) derived from evaporation measurement.	88
Figure 4. 37 Mimi Techiman soil series: Moisture characteristics (left) and hydraulic conductivity function (right) derived from evaporation measurement.	89

Figure 4. 38 Techiman Tampu soil series: Moisture characteristics (left) and hydraulic conductivity function (right) derived from evaporation measurement.	89
Figure 4. 39 Kolingu soil series: Moisture characteristics (left) and hydraulic conductivity function (right) derived from evaporation measurement.	89
Figure 4. 40 Sambu Pasga soil series: Moisture characteristics (left) and hydraulic conductivity function (right) derived from evaporation measurement.	90
Figure 4. 41 Nangodi soil series: Moisture characteristics (left) and hydraulic conductivity function (right) derived from evaporation measurement.	90
Figure 4. 42 Pusiga soil series: Moisture characteristics (left) and hydraulic conductivity function (right) derived from evaporation measurement.	90
Figure 4. 43 Tanchera soil series: Moisture characteristics (left) and hydraulic conductivity function (right) derived from evaporation measurement.	91
Figure 4. 44 Kpalesawgu Changnalili soil series: Moisture characteristics (left) and hydraulic conductivity function (right) derived from evaporation measurement.	91
Figure 4. 45 Nambari soil series: Moisture characteristics (left) and hydraulic conductivity function (right) derived from evaporation measurement.	91
Figure 4. 46 Measured $\theta_{1/2}$ versus grain size fraction (%sand, %silt and %clay), versus measured $\theta_{1/2}$ versus predicted $\theta_{1/2}$ (predicted CMC from pedo-transfer function and observed from evaporation curves).	94
Figure 4. 47 Bar chart of critical moisture content of the various soil series of the soil series sampled from the interior savannah zone of Ghana.	94
Figure 4. 48 A semi distributed landscape model of bulk density of the soil series sampled from the interior savannah zone of Ghana.	95
Figure 4. 49 A semi distributed landscape model of clay content of the soil series sampled from the interior savannah zone of Ghana.	96

Figure 4. 50 A semi distributed landscape model of sand content of the soil series sampled from the interior savannah zone of Ghana.....	96
Figure 4. 51 Geological map showing the Northern strip of Ghana (after Nude and Arhin, 2009).....	97
Figure 4. 52 A semi distributed landscape model of the critical moisture content of the soil series sampled from the interior savannah zone of Ghana.....	97
Figure 4. 53 A semi distributed landscape model of the Evaporation Depth of the soil series sampled from the interior savannah zone of Ghana.	98



ABSTRACT

Bare soil evaporation is the process of water vaporization from the soil surface without any vegetation cover. It is a significant component of the global water cycle and can have major implications for agriculture, water resource management, and climate change. Quantifying evaporation rates at both local and global levels can inform water management decisions, particularly in agriculture, in the face of climate change. This study presents an evaporation experiment conducted in a screenhouse over 25 days using soil samples from different series and locations in the northern strip (northern interior (Guinea) savannah zone). The research aimed to: (1) Investigate the effect of different soil types on the evaporation of bare soils from northern Ghana; (2) Derive cumulative water characteristics (CWCs) and Critical Water Content (t_{crit}); (3) Validate the Hydrus 1-D model for simulating bare soil evaporation; and (4) Develop a bare soil evaporation map for the northern strip (northern interior (Guinea) savannah zone) of Ghana. To achieve these objectives, statistical descriptors such as mean, mode, measures of variability (range, interquartile range, variance, and standard deviation), correlation matrix, and textural triangle were employed. Column evaporation measurements were used to derive cumulative water content and critical water content (t_{crit}). The soils were packed into PVC columns (15 cm height, 9 cm diameter) and weighed every 12 hours over the 25-day period. Simultaneously, temperature and relative humidity in the screenhouse were recorded. Inverse modelling, prediction, and regression were used to validate the Hydrus 1-D model for simulating evaporation of bare soils. Maps and raster calculations in QGIS were used to generate semi-distributed landscape models for water management in cultivated soils in the interior savannah zone of Ghana. The study revealed that soil texture and bulk density significantly influence soil evaporation, with different textures and densities affecting critical

moisture content, porosity, and water transport. Soil texture also reliably predicts the critical water content, marking the transition between stage 1 and stage 2 evaporation. The Hydrus 1-D model, based on the Richards equation, accurately predicted cumulative evaporation and soil moisture characteristics, though it requires measured hydraulic properties for validation. The use of GIS techniques demonstrated the potential for generating landscape models that support informed water management decisions for cultivated soils in Ghana's interior savannah zone. The study recommends the adoption of soil-specific management practices, such as mulching for water conservation and organic fertilization.



CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

The northern strip (northern interior (Guinea) savannah zone) of Ghana lies in the Guinea Savannah zone and stretches from latitudes 7°30'N and 11°3'N, as well as longitudes 0°45'E and 2°82'W, and this spans a landmass of approximately 129,765 km (Incoom et al., 2020). Typically, the ecological zone has wooded grassland and receives an annual rainfall between 800mm to 1000mm, which falls within May to October (Owusu and Weylen, 2009). The soils in the zone derive from ferrallitic parent materials containing appreciable amounts of iron oxides (Da Costa et al., 2015). Despite the common pedogenesis of the soils, considerable heterogeneity exists across the strip. In the western locations, Tanina series dominate whereas in the eastern locations, Sambu Pasga series dominates the landscape. Throughout the year, Temperatures are high and range between 32 °C and 38 °C, supporting high soil evapotranspiration rates (Ghana Meteorological Agency-GMet, 2019). Thus, despite the relatively high rainfall, the annual evapotranspiration far exceeds the rainfall (Incoom et al., 2020), such that based on the FAO (Allen et al., 1998) classification, the locations can be classified as arid and semi-arid. It is worthy of note that due to the unimodal distribution of rainfall, the off-season of 5 to 6 months duration receives no rainfall and coincides with the periods without vegetation cover. Soil desiccation and moisture release is therefore largely determined by bare soil evaporation. Semi-arid lands, such as the interior savannah zone of Ghana, are characterized by two features, viz: the atmospheric evaporative demand is greater than the water supply (e.g., Noy-Meir, 1973; Sala et al., 1992), and

these ecosystems have less than 50% plant cover, which means that bare soil evaporation plays a significant role in their water balance (Burke et al., 1998).

Arid and semiarid regions of the globe, often described as water-limited environments (Parsons & Abrahams, 2009), are typified by limited rainfall and high potential evaporation rates. Precipitation primarily occurs over a few months during the wet season and is infrequent for the remainder of the year, leading to extended periods of drought during the dry season. Within these regions, a significant portion of the rainfall that could have been utilized for crop growth and development is returned to the atmosphere via soil evaporation or drained into aquifers below. In arid and semiarid regions, increase in evaporation might accelerate desertification (Goyal, 2004). The quantification of bare soil evaporation is therefore relevant for the tropical water cycle and underpins water management decision with regards to rainfed agriculture, conservation of soil and water resources, and climate adaptation (Lehmann, 2023). Mellouli et al. (2000) noted that in agricultural lands, evaporative losses can be as high as 30-75% of rainfall total during a crop growing season. Evaporation is the main source of water loss from the soil when the plants are young and with only partial or no canopy cover. This reduces when the plants mature, and canopy cover is achieved (Brock, 1968).

Evaporation however has some benefits which cannot not be overlooked. Where the soil is saturated, evaporation becomes necessary to reduce soil water content to facilitate early planting and reduces surface run-off (Bonsu, 1997) and soil erosion. Along the same lines, evaporation is a key driver of the water and energy balance (Allen et al., 1998, Lehmann, 2023) of the globe.

1.2 Problem statement and hypothesis

The northern strip (northern interior (Guinea) savannah zone) of Ghana has traditionally been used for pastoral agriculture, though some well adapted cereals (i.e., sorghum and millet) and grains (i.e., maize) are cultivated. A number of agricultural challenges require the assessment of bare soil evaporation of these locations. First, the locations are increasingly intensively cultivated by introducing high yielding crops such as maize. The intensification of agriculture in such semi-arid locations requires supplemental irrigation and the optimization of irrigation schemes requires in-depth knowledge of soil evaporation rates. This information is often lacking to guide the water resource management. In the recent agricultural policy of the government to improve irrigation, under the “one village one dam” scheme a number of water reservoirs have apparently been constructed without determination of soil evaporation characteristics. To date, irrigated agriculture in Ghana is less than 2% of the total arable land of Ghana.

Second, bare soil evaporation is influenced by meteorological conditions. As the average global temperature is expected to rise during the next century (IPCC, 2007), the earth is also expected to experience changes including, more erratic rainfall, and increased frequency of drought and flood. It is also expected that temperature increase would lead to increase in evaporation under most of the predicted global warming scenarios (Neriah et al., 2014). In Ghana, Klutse et al. (2021) have indicated warming over the last few decades and temperature is expected to increase in both near (2030-2059) and far (2070-2099) time scales. There is a likelihood of experiencing increasing aridity trends in the Interior Savannah zone of Ghana considering historical trends (Incoom et al. 2020).

Third, apart from climate factors, soil factors are also important determinants of evaporation. Among others, soil texture has also been noted to be a key control on evaporation rates (Merlin et al., 2016; An et al., 2018). A number of studies have shown that evaporation rates from sandy soils were higher than clayey and loamy soils (Lehman, 2023; Bonsu, 1997), and this can be attributed to the large pore sizes of sandy soils. Davarzani et al. (2014) noted that characteristics of porous media such as porosity, angularity, and grain size affect evaporation rates. Given that there is heterogeneity in soils within the northern strip (northern interior (Guinea) savannah zone), it is conceivable that the soils would respond differently under similar evaporative demand of the atmosphere.

Whereas the need for bare soil evaporation information cannot be over-emphasized in the context of agricultural development, there is a general lack of soil evaporation data with regard to the locations of interest. The traditional methods of field observation are prohibitively expensive and time consuming, especially in developing countries. Alternatively, modelling approaches offer tools for assessing soil-atmosphere hydrology. In a number of studies, models such as Penman-Monteith and Priestley-Taylor have been applied to study soil evaporation under varied conditions, especially in temperate countries. Given that models have been successfully employed to simulate the varied soil evaporation situations, it is plausible that model application for soil evaporation assessment is also feasible under tropical conditions, despite the more complex interactions between atmospheric condition (relative humidity, temperature, wind) and soil properties. Hitherto, model application in soil hydrological studies in Ghana is scant.

Furthermore, heterogeneity in soils across suggests that even under the same evaporative demand, soil evaporation and desiccation rates may differ, affecting decisions of the types of agriculture to practice at different locations. In this regard, soil evaporation maps using Geographical Information Systems (GIS) would offer the possibility of facilitating the delineation of soil evaporation intensities sub-zones to guide decision making. The derivation of soil maps could be facilitated using the output of soil evaporation models. The HYDRUS (1D) model (Šimůnek et al., 2005) is particularly effective in simulating soil hydrology including evaporation. Yet, the influence of soil heterogeneity must be considered in using such models. An output of models such as HYDRUS (1D), apart from total soil evaporation are the van Genuchten parameters, α (related to the air-entry) and n (related to pore size distribution) which are linked to front depth at the transition from stage I (atmospheric controlled or potential) to stage II (soil controlled) evaporation (Lehman et al., 2018). Similarly, the critical water content (t_{crit}) can be derived as pedo-transfer function that is texture dependent and hence can reflect the variations of the soils in the zone of study on soil evaporation. It is therefore hypothesized that t_{crit} can be used to assess the evaporation of different soil series in the northern strip (northern interior (Guinea) savannah zone) of Ghana. Given the logistic limitations in carrying out actual field observations, it is further hypothesized that a combination of a modeling approach to soil evaporation assessment and soil evaporation intensity mapping would provide a sound foundation for agricultural planning.

1.3 Objectives

Given the complex interactions between soil and climate factors in determining evaporation and with regard to the hypothesis of this study, the objectives of this study are as follows:

1. Investigate the effect of different soil types on the evaporation of bare soils obtained from the northern strip (northern interior (Guinea) savannah zone) of Ghana.
2. Derive the cumulative water characteristics (CWCs) and critical water content (t_{crit}) as basis of assessing the texture effect on soil evaporation.
3. Validate the Hydrus 1-D model for simulating the evaporation of the bare soils, and
4. Develop a bare soil evaporation map for the northern strip (northern interior (Guinea) savannah zone) of Ghana.



CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Bare soil evaporation

Bare soil evaporation, a crucial component of the hydrologic cycle, refers to the process of water evaporation from bare soil surfaces devoid of vegetation or other coverings (Or et al., 2013). This process plays a significant role in the water and energy balance of terrestrial ecosystems (Lehmann et al., 2018). Approximately 25% of solar energy input is consumed by evaporation, with about 70% of global water loss attributed to bare soil evaporation (Trenberth et al., 2009). The dynamics of bare soil evaporation are influenced by various factors, including soil intrinsic properties such as capillarity and wettability, which affect liquid phase continuity and capillary driving forces (Or et al., 2013).

Numerous studies have investigated bare soil evaporation, including Gardner (1959) pioneering work. Gardner obtained numerical solutions for flow equation in the drying of porous media, assuming an exponential relationship between diffusivity and water content. The rate of drying of laboratory soil columns in an experiment compared well with numerical solutions obtained by Gardner (1959). Subsequent studies by Wythers et al. (1999) and Balugani et al. (2021) examined the influence of soil texture on bare soil evaporation and evaporation through a dry soil layer under different conditions, respectively. Bonsu (1997) explored the concept of desorptivity and the later stages (falling rate period) of evaporation in tropical soils. These studies collectively highlight

the significance of bare soil evaporation in the hydrologic cycle and the importance of understanding its dynamics for managing soil water loss in various ecosystems.

2.2 Quantifying evaporation at different scales

2.2.1 Pore scale considerations

The description of pore scale evaporation process considers on the geometry of the pores and liquid phase continuity. This can be analyzed using extracted three-dimensional structures from μ CT imaging and numerical simulation (e.g., Leuther & Diamantopoulos, 2024) and/or pore networks model simulation (Segura, and Toledo, 2005; Nasir et al., 2022; Lu et al., 2021; Wu et al., 2021; Wu et al., 2014; Laurindo and Prat, 1996; Wu and Zhao, 2021). The behavior of liquid in corners and its impact on the rate of evaporation can be studied in individual capillaries with angular cross-sections or in microfluid networks (Ding & Geistlinger, 2021). In microfluid networks, liquid pinned in corners plays a crucial role in maintaining evaporation rate at the early stages (Ding & Geistlinger, 2021). Water will flow to the surface along a capillary pressure difference and maintain evaporation rate at the early stages as long as continuous liquid structures which are stuck in corners persist (Ding & Geistlinger, 2021). The findings from the pore scale studies provide insights into developing the accurate continuum scale models for modelling evaporation in porous media (Wu and Zhao, 2021).

2.2.2 Soil evaporation at column scale

The depth of a soil column has a profound impact on evaporation rates, primarily through its effects on moisture availability, temperature gradients, and capillarity (Balugani et al., 2021). Higher temperatures at the surface can enhance evaporation

rates, but this effect diminishes with depth. Evaporation rates vary with soils with layering (Assouline and Narkis, 2019), as different layers have distinct properties and water contents (Or et al., 2013; Assouline and Narkis, 2019). Soil column depth influence initial and boundary water content conditions which in turn impact evaporation rates and pattern (Or et al., 2013). Soil depth affects soil temperature profiles and heat transfer mechanisms, and this influences evaporation rates (Lehmann, 2023). Careful experimental design and appropriate instrumentation are therefore crucial for accurate measurements and data interpretation and to capture relevant scales and processes (Lehmann, 2023).

2.2.3 Soil evaporation at field scale

Field scale evaporation measurement refers to the methods and techniques used to measure evaporation from the soil surface at a scale larger than soil column (e.g., agricultural fields, watersheds, and ecosystems). This scale and appropriate methods are relevant for understanding evaporation processes. Some common methods include Eddy Covariance (EC) method (Foken et al., 2011). Bowen Ratio (BR) method (Malek & Bingham, 1993), Lysimeters approach (Yan et al., 2012), Remote Sensing (RS) approach (Lehmann, 2023), meteorological observation (Allen et al., 1998; Wythers et al., 1999), Soil Moisture Network (SMN) approach (Allen et al., 1998), Energy Balance (EB) method (Allen et al., 1998). The EC method measures the exchange of water vapor and energy between the soil and atmosphere using sensors mounted on a tower. The BR method estimates evaporation by measuring the ratio of sensible heat to latent heat fluxes. Lysimeters, particularly weighing types, measure water loss from the soil through evaporation and drainage and estimate evaporation based on mass conservation. Satellites and aerial imagery can estimate evaporation using both thermal

and microwave data. Arrays of soil moisture sensors monitor water content and infer evaporation. Meteorological parameters can be used together with empirical models to estimate field scale evaporation. The energy balance approach estimates evaporation by closing the energy balance at the soil surface and inferring evaporation from latent heat. Very often, a combination of methods is to improve accuracy of evaporation estimates.

2.3 Influence of soil properties on bare soil evaporation

2.3.1 Texture

Evaporation is influenced by both atmospheric demand and soil particle size, with soil texture playing a crucial role in determining soil porosity and permeability (An et al., 2018; Amooh and Bonsu, 2015; Merlin et al., 2016; Lehmann et al., 2018). Fine-grained soils exhibit low initial evaporation rates but their higher cumulative evaporation due to high water storage capacity (Or et al., 2013). In contrast, coarse soils dry out more rapidly at the initial stages, but loose there conductivity very quickly and due to lower moisture in the dry end (Teh et al., 2023). Only a few laboratory studies on the influence of soil texture on evaporation have been conducted on Ghanaian soils (e.g., Amooh and Bonsu, 2015). Amooh and Bonsu (2015) showed that soil moisture diffusivity was highest in soils with high organic matter and clay content, whereas desorptivity was lower in coarse-textured soils with low organic matter and clay content. The study demonstrated that soil texture and organic matter content significantly affect evaporative soil moisture loss. Sandy soil textures exhibit larger pore sizes and lower water holding capacities, resulting in higher evaporation rates initial rates compare to silty or clayey soil textures (Amooh and Bonsu, 2015). Soils with higher organic matter content exhibit higher moisture retention capacities and lower evaporation rates (Amooh and Bonsu, 2015).

2.3.1.1 Influence of silt fraction on evaporation

Silt content, defined as the proportion of fine particles (20-63 micrometers in diameter) in soil composition (Matus, 2021), plays a crucial role in determining soil properties and behavior. Numerous studies have investigated the impact of silt content on soil strength and behavior, revealing its significant influence on soil properties such as carbon and nitrogen storage levels (Matus, 2021). Liu et al. (2021) found that silt content affects the strength of soft soils, exhibiting a transitional behavior between sand and clay. Silty soils possess a higher water-holding capacity compared to sandy soils (Masood and Ali, 2023), making them less susceptible to evaporation (Beck-Broichsitter et al., 2023). Wythers et al. (1999) observed that soils with higher silt content exhibit lower evaporation rates. van Donk (2010) noted that increasing silt content can improve soil structure, leading to higher infiltration rates and reduced surface runoff, consequently reducing evaporation. Evaporation from sand and silt loam soils can account for up to 30% of evapotranspiration during crop irrigation (van Donk, 2010). It is worth of note that factors such as soil moisture, temperature, and air movement also influence evaporation rates, making it challenging to solely attribute evaporation differences to only silt content (Wythers et al., 1999).

2.3.1.2 Influence of Sand fraction on evaporation

Sand particle size refers to the diverse range of individual sand grain sizes present in a sand sample. Sand is a granular material comprising fragments of minerals and rocks, characterized by particles varying in size between 0.075mm and 4.75mm (Anderson and Block, 1962). Notably, sand is highly porous and permeable, with larger pores compared to finer soil types like clay or silt (Mahmoodlu et al., 2016). These larger pores facilitate enhanced movement of air and water within the soil, leading to

increased initial evaporation rates (Hussary et al., 2022; Liu et al., 2022; Mahdavi et al., 2021). Sandy soils exhibit poor water-holding capacity relative to clay or loam soils, resulting in faster drying at the initial evaporation stages (Ibrahimi and Alghamdi, 2022). Additionally, sandy soils have lower heat capacity and higher thermal conductivity compared to other soils, influencing evaporation rates (Chen-hui et al., 2011; Ghuman and Lal, 1985).

2.3.1.3 Influence of clay fraction on evaporation

The clay content of soil, defined as the fraction of particles smaller than 2 μm , is a critical soil property that significantly influences various aspects of soil behavior, including hydraulic properties, water fluxes, and soil fertility (Loiseau et al., 2019; Shabou et al., 2015). Clay content plays a vital role in determining soil hydrological characteristics, salinity, and nutrient availability (Zhao et al., 2017). The large specific surface area of clay particles (Singh et al., 2019) also impacts the storage potential of carbon and nitrogen in soils (Matus, 2021). Notably, soils with higher clay content exhibit lower initial evaporation rates compared to soils with lower clay content (Phogat et al., 2016; Yang et al., 2022). The water-holding capacity of clay soils is higher than that of sandy soils due to their small particle size and ability to retain water in interstitial spaces (Huntley, 2023), allowing them to store more water and therefore higher cumulative evaporation. Additionally, swelling and shrinking clay soils can develop vertical cracks which are preferential pathways for evaporation of horizontal cracks which act as barrier to soil evaporation (Churchman and Velde, 2019).

2.3.2 Bulk Density

Bulk density is a critical soil property that is related to sorting, packing and degree of compaction of soil particles (Mobilian and Craft, 2022). Bulk density has a profound impact on soil evaporation (Assouline, 2006; Goldberg-Yehuda et al., 2024), as higher bulk density soils have smaller interparticle spaces and reduced evaporation. Various factors, including soil texture, organic matter content, and structure influence soil bulk density (Mobilian and Craft, 2022). Higher bulk density often indicates soil compaction, which reduces pore space. Thus, compacted soils are likely to exhibit a hardpan layer that impedes water flow and retention, ultimately affecting evaporation rates (Ni et al. 2018). The influence of bulk density on soil evaporation is more pronounced in sandy soils, which have larger pore spaces and are more susceptible to compaction (Mobilian and Craft, 2022). Additionally, higher bulk density increases pore network tortuosity (Masis-Meléndez et al., 2015), impeding water movement and decreasing evaporation (Zhang et al., 2021). Furthermore, higher bulk density can reduce soil thermal conductivity (Abu-Hamdeh and Reeder, 2000), leading to reduced rate of soil surface warming and subsequently reduce evaporation (Abu-Hamdeh and Reeder, 2000; Shiozawa and Campbell, 1990). Soil tillage reduced soil bulk density, and this is expected to increase evaporation (Assouline, 2006). Increased bulk density also results from soil compaction due to solute migration and salt precipitation (Goldberg-Yehuda et al., 2022).

2.3.3 Organic Carbon

Soil organic carbon (SOC) plays a crucial role in maintaining soil health and function, including influencing soil evaporation (Farooqi et al., 2021). SOC affects soil evaporation by enhancing soil structure through aggregation, and improving water

holding capacity, thereby reducing evaporation (Berryman et al., 2020; Sharma et al., 2013). Additionally, SOC acts as a sponge, absorbing and retaining water, further reducing evaporation (Berryman et al., 2020). Several studies have found a strong negative correlation between soil organic carbon and temperature (e.g., Follett et al., 2012; Hike et al., 2017; Yan et al., 2017; Li et al., 2020). The darkening effect of SOC also decreases soil surface albedo, reducing solar radiation reflectance, and leading to higher soil temperatures and increased evaporation (Dobos, 2020; Genesio et al., 2012). Numerous studies have investigated the relationship between SOC and soil evaporation. Kayler et al. (2018) examined soil evaporation and organic matter turnover, indicating that SOC can improve soil water retention, potentially reducing evaporation rates. Amooah and Bonsu (2015) found that soils with substantial organic matter content exhibited improved water holding capacity, and reduced evaporation. The impact of SOC on soil evaporation is more pronounced in sandy soils, which are more susceptible to compaction and have lower water holding capacity compared to clay soils (Huang and Hartemink, 2020).

2.3.4 Hydraulic Conductivity

Soil hydraulic conductivity (K) is a fundamental property that quantifies the ability of soil to transmit water (Klute, 1965). It is influenced by soil texture, structure, and organic matter content, and plays a crucial role in soil water movement and evaporation (Hillel, 2003; Sarki et al., 2014). Soil hydraulic conductivity exerts a significant impact on soil evaporation through several mechanisms. Firstly, it controls the rate of water movement to the soil surface, determining how quickly water can migrate from deeper soil layers to the surface, where it can evaporate (Klute, 1965). Soils with higher hydraulic conductivity exhibit higher evaporation rates when water content is high

(Zhang et al., 2016). However, once large pores are emptied, water transport in finer soils (e.g., clay) can surpass that of coarse-textured soils.

Secondly, soil hydraulic conductivity affects soil surface temperature (Saha and Tripathi, 1979), influencing the rate of heat transfer from deeper soil layers to the surface (Hopmans and Dane, 1986). Soils with higher hydraulic conductivity values exhibit warmer surface temperatures, leading to increased evaporation (Saha and Tripathi, 1979). Lastly, soil hydraulic conductivity influences soil water holding capacity (Bhardwaj et al., 2007). Soils with higher hydraulic conductivity have lower water holding capacities (Bhardwaj et al., 2007; Ravina and Magier, 1984), which can lead to increased evaporation.

2.3.5 Soil aggregate content

Soil aggregation refers to the process by which soil particles coalesce to form larger units, known as soil aggregates (Goss and Kay, 2005). These aggregates play a crucial role in maintaining soil health and function, including influencing soil evaporation (Goss and Kay, 2005; Négyesi et al., 2021). The porous structure of soil aggregates facilitates the movement of air and water through the soil, thereby improving soil structure and reducing evaporation (Goss and Kay, 2005; Négyesi et al., 2021). Soil aggregates exert a positive impact on soil evaporation through several mechanisms. Firstly, they create a more porous soil structure, enhancing water drainage and reducing evaporation (Goss and Kay, 2005; Négyesi et al., 2021). Secondly, soil aggregates prevent soil surface crusting, which can impede water infiltration and increase evaporation (Goss and Kay, 2005; Négyesi et al., 2021). Furthermore, soil aggregates increase the soil's water-holding capacity and reduce evaporation rates (Goss and Kay, 2005; Négyesi et al., 2021). The larger pore spaces between aggregates allow water to

infiltrate deeper into the soil, reducing the amount of water available for evaporation from the soil surface (Goss and Kay, 2005; Négyesi et al., 2021). Additionally, the presence of aggregates protects the soil surface from direct exposure to wind and sunlight, further reducing evaporation rates (Goss and Kay, 2005; Négyesi et al., 2021). Empirical evidence supports the significance of soil aggregates in reducing soil evaporation. Boyle et al. (1989) investigated the characteristics of soil evaporation and temperature under aggregate mulches created by burrowing ants. Their findings revealed that the presence of aggregates on the soil surface significantly reduced the rate of soil evaporation.

2.3.6 Porosity

Soil porosity, volume of void to volume of soil (Hao et al., 2008), plays a crucial role in determining the availability of space for water and air in soil. Soil texture, structure, and organic matter content influence porosity (Hao et al., 2008). Soil porosity exerts a significant impact on soil evaporation by controlling the rate of water movement to the soil surface (Lipiec et al., 2006). Specifically, it determines the velocity at which water can migrate across the soil profile to the surface, where it can evaporate (Lipiec et al., 2006). Soils with higher porosity exhibit higher cumulative evaporation (An et al., 2018). Furthermore, soil porosity influences soil surface temperature (Howe and Smith, 2021). It affects the rate of heat transfer from deeper soil layers to the surface (Wang and Fox, 2020). Consequently, soils with higher porosity exhibit warmer surface temperatures, leading to increased evaporation (Howe and Smith, 2021). In addition, soil porosity impacts soil water holding capacity (Batista et al., 2018; Cameron and Buchan, 2006). It determines the amount of water that the soil can retain (Batista et al., 2018; Cameron and Buchan, 2006). Soils with higher porosity have lower water holding

capacities, which can lead to increased initial evaporation rate (Batista et al., 2018; Cameron and Buchan, 2006).

2.3.7 Field capacity

Soil field capacity (FC) refers to the maximum amount of water that a soil can retain against gravity (Peters, 1965). This critical parameter serves as an indicator of soil water availability and is employed in irrigation scheduling to ensure that plants receive adequate water to meet their needs. Field capacity represents the total amount of water that the soil can hold against gravity (Peters, 1965), thereby controlling the rate of water movement to the soil surface and determining the amount of water available for evaporation (Cassel and Nielsen, 1986). Soils with higher field capacity exhibit increased water availability for evaporation (Cassel and Nielsen, 1986), resulting in higher evaporation rates. Moreover, field capacity influences soil surface temperature and the rate of heat transfer through the soil to the soil surface (Zhang et al., 2022). Soils with higher field capacity exhibit cooler surface temperatures (Zhang et al., 2022), which can lead to reduced evaporation. Additionally, field capacity affects soil water holding capacity, serving as a measure of the soil's ability to retain water (Karahan et al., 2014). Soils with higher field capacity exhibit lower evaporation rates due to their increased water retention capabilities (Karahan et al., 2014).

2.3.8 Soil Moisture Content

Soil moisture exerts a significant influence on evapotranspiration, the combined process of evaporation from the soil surface and transpiration, from plants (Zhang et al., 2022). Soil moisture content controls the rate of water movement to the soil surface, with soils having higher moisture content exhibiting higher evaporation rates (An et al.,

2018). Merlin et al. (2016) noted that a critical moisture content exists at which soil evaporation process transitions from stage I to stage II and this was further confirmed by Lehmann et al. (2018). Additionally, soil moisture content influences soil vapor pressure, with soils having higher moisture content exhibiting higher water vapor pressure (Alexander and Haring, 2002), which can lead to increased evaporation. Soil moisture content also affects the temperature and humidity of the lower atmosphere. Thus, at low soil moisture levels, a larger portion of incoming solar radiation is directed towards increasing the sensible heat flux from the soil, thereby restricting evapotranspiration and further leading to a rapid increase in surface air temperature (Zhang et al., 2022).

2.4 Effect of atmospheric conditions on bare-soil evaporation

The relationship between atmospheric conditions and soil evaporation is complex and interdependent. Atmospheric conditions, such as temperature, humidity, wind speed, and solar radiation, directly influence the rate of soil evaporation (Allen et al., 1998).

2.4.1 Temperature

Temperature is a key driver of soil evaporation (Novák and Novák, 2012). Some evaporation models, for example: Dalton's Law (1802), Penman's Equation (1948), Thornthwaite's Model (1948), Hamon's Method (1961), Hargreaves' Equation (1975), Priestley-Taylor Model (1972), Makkink's Equation (1957) and Turc's Method (1961) use temperature solely or together with other environmental variables to estimate evaporation. As temperature increases, the kinetic energy of water molecules in the soil also increases, leading to enhanced evaporation rates (Ali and Ali, 2010). Elevated

temperatures amplify the vapor pressure deficit (VPD) between the soil surface and the atmosphere, further increasing evaporation (Ali and Ali, 2010; Novák and Novák, 2012). Seasonal temperature fluctuations significantly influence soil evaporation, with peak rates occurring in warm periods and diminished rates in cold seasons (Milly, 1984). Numerous studies have investigated the impact of soil temperature on bare soil evaporation. For instance, a bench-scale assessment revealed that soil temperature has a direct influence on bare soil evaporation, with the effect diminishing as soil temperature decreases (Liu et al., 2020). An investigation into the effects of temperature rise on pan and soil evaporation found that a 1°C increase in soil temperature corresponds to approximately a 10% increase in soil surface evaporation rate, underscoring the significant impact of temperature on soil evaporation dynamics (Kidron and Kronenfeld, 2015).

2.4.2 Humidity

Relative humidity (RH) exhibits an inverse relationship with soil evaporation (Chakraborty and Derby, 2018). Elevated RH levels diminish the vapor pressure gradient, thereby reducing the rate of water evaporation from the soil (Chakraborty and Derby, 2018). In arid and dry regions characterized by low atmospheric humidity experience heightened soil evaporation rates, which can significantly impact water availability and ecosystem well-being (Stewart and Broadbridge, 1999). Numerous studies have investigated the effect of relative humidity on soil evaporation. For instance, Liu et al. (2013) conducted a comprehensive analysis of the responses of soil evaporation rates to air temperature and air humidity, revealing that relative humidity exerts a profound influence on soil evaporation dynamics.

2.4.3 Wind Speed

Wind can have a profound impact on soil evaporation, as it facilitates the transport of water vapour away from the soil surface, thereby enhancing evaporation rates (Poulsen, 2022). Increase in wind speed increases soil moisture loss through the modification (thinning) of the evaporation boundary layer with increasing wind speed (Cuxart, and Boone, 2020). Very often, the influence of wind is represented as aerodynamic resistance and thus applied on the border between the air flow and permeable media [e.g., Bittelli et al., 2008; Camillo and Gurney, 1986; Novak, 2010; van de Griend and Owe, 1994]. For example, evaporation rate (E) can be determined by (Davarzani et al., 2014):

$$E = \frac{1}{r_s + r_v} ((\rho_v)_{pm} - (\rho_v)_{ff}) \quad [2.1]$$

where r_s is the soil surface resistance for water vapor transport, r_v is the aerodynamic resistance for water vapor, $(\rho_v)_{pm}$ is the vapor density immediately below the soil surface (in porous medium), and $(\rho_v)_{ff}$ is the vapor density immediately above the soil surface.

2.4.4 Solar Radiation

Solar radiation serves as a primary energy source driving soil evaporation (Or et al., 2013; Tong et al., 2022). By warming the soil surface, solar radiation provides the necessary energy to facilitate the conversion of liquid water into vapor (Novák and Novák, 2012; Tong et al., 2022). The amount of solar radiation that reaches the earth's surface influences the rate of evaporation in the following ways: (1) solar radiation warms the surface, increasing the temperature and kinetic energy of water molecules, making it easier for them to escape into the air, (2) solar radiation supplies the energy required for evaporation, with higher radiation levels resulting in faster evaporation rates., (3) solar radiation influences the vapor pressure of water, with higher radiation

levels leading to increased vapor pressure and enhanced evaporation, (4) solar radiation can reduce humidity by increasing evaporation, which in turn affects the atmosphere's capacity to hold moisture, and (5) solar radiation can influence wind patterns and atmospheric circulation, which can transport water vapor away from the evaporation site, promoting further evaporation. Understanding the influence of solar radiation on evaporation is crucial for soil water management.

2.4.5 Precipitation

Precipitation events can temporarily suppress soil evaporation by saturating the soil, leading to a reduction in evaporation rates (Allen et al., 1998; Eberbach et al., 2019). However, subsequent evaporation rates are influenced by antecedent soil moisture levels, and atmospheric conditions including temperature relative humidity and wind (An et al., 2018). The frequency and intensity of precipitation events in a region have a profound impact on its overall soil evaporation patterns, shaping the dynamics of soil water availability and ecosystem functioning (Cui et al., 2022). Sorman and Abdulrazzak (1995) conducted a comprehensive analysis to estimate actual evaporation using precipitation and soil moisture data. Their findings revealed that the determination of direct evaporation from the surface is strongly influenced by existing soil conditions, physical parameters, and seasonal rainfall and soil moisture distribution. These findings highlight the complex interplay between precipitation, soil moisture, and evaporation, underscoring the need for continued investigation into these critical processes.

2.5 Methods for determining bare soil evaporation.

Various methods exist for determining bare soil evaporation, including lysimeters, meteorological methods, and energy balance methods (Li et al., 2020; Qiu et al., 1998). Lysimeters, which are large containers of soil, measure evapotranspiration, the combined loss of water from the soil surface and through plant transpiration (Courtin and Bliss, 1971; Moorhead, 2018). Weighing lysimeters calculate evapotranspiration by measuring the change in weight of the soil and container over time, while non-weighing lysimeters use alternative methods, such as measuring water level changes in a reservoir (Moorhead, 2018). Micrometeorological methods, like the Eddy covariance method (Foken et al., 2011), use atmospheric variable measurements to calculate evaporation. Energy balance methods, including the Bowen ratio method (Malek and Bingham, 1993), calculate evaporation using radiation component measurements at the soil surface. Other methods include soil moisture sensors, evaporation pans, and porous plate evaporimeters (Zazueta and Xin, 1994; Eagleman, 1967). Comparative studies have evaluated the effectiveness of these methods. For instance, Yan et al. (2012) compared three methods for estimating soil evaporation in a bare field and found that the k ratio and bulk equation produced a good fit with observation data, while the complementary relationship generated larger deviations. Balugani et al. (2018) tested various approaches to estimate soil evaporation through a dry soil layer in a semi-arid region and found that the pore-scale conceptual model provided the closest estimates to Eddy covariance measurements during the dry season. These studies highlight the complexities of measuring bare soil evaporation and the need for careful consideration of method selection and validation.

2.6 Modelling soil evaporation

Many studies have proposed various analytical or semi-analytical mathematical models based on the Richards equation for modeling evaporation process (e.g., Novak, 1988; Nasser et al., 2020; Menziani et al., 2007; Teng et al., 2013; Teng et al., 2019; Yamanaka and Yonetani, 1999). Apart from this, the growing computational ability provides the avenue of modelling evaporation processes numerically by applying the theory of the coupled heat and moisture transport in variable saturated soils (Philip and de Vries, 1957) and was later extended by other researchers (Milly, 1984; Nassar & Horton, 1997; Vanderborght et al., 2017). The theory has successfully been tested against experimental observations (Sakai et al., 2011). Very recently, Iden, et al. (2022) showed that for typical laboratory evaporation experiments, an isothermal flow model can accurately simulate bare soil evaporation experiments, but only if hydraulic conductivity curve is augmented with an isothermal vapor diffusion model (Peters, 2013). Currently, there are several numerical codes, for example, soil-vegetation-atmosphere transfer (SVAT) model, Simultaneous Heat and Water (SHAW) model, and HYDRUS, developed for simulating coupled water and heat flow in the vadose zone. HYDRUS-1D is a widely used finite element model for simulating one-dimensional movement of water, heat, and multiple solutes in variably saturated porous media (Simunek et al., 2016) and is applied widely in the study of unsaturated zone process.

2.6.1 Simulating evaporation process in HYDRUS 1-D

The HYDRUS (1D) numerical code (Simunek et al., 1998) is one of the most widely used numerical codes for simulating evaporation from soils. The code uses finite difference scheme to solve the Richards equation, a partial differential equation that describes water movement in porous media given by:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[K \left(\frac{\partial \psi}{\partial z} \right) \right] - S \quad [2.2]$$

where, θ is the volumetric water content; t is time; z is the spatial coordinate (depth) and ψ is the water pressure head, K is unsaturated hydraulic conductivity (Šimůnek et al. 2008). Finally, S is the sink term [T-1] to account for root-water uptake, defined as (Feddes, 1978). In our case root water uptake is zero since we do not consider cropped field. The HYDRUS-1D model uses the van Genuchten (1980) model to describe the soil moisture characteristic given:

$$S_e(\psi_m) = \frac{\theta(\psi) - \theta_r}{\theta_s - \theta_r} = \left[\frac{1}{1 + (\alpha|\psi|)^n} \right]^m \quad [2.3]$$

where θ is the volumetric water content, θ_r is the residual volumetric water content, θ_s is the saturated volumetric water content, α is a parameter that determines the air entry value, n is a parameter that is related to pore size distribution, and m is an empirical parameter that is related to n via the relation $1-1/n$. Further on, the Mualem (1976) model is used to describe the hydraulic conductivity function given by:

$$K(\theta) = K_s S_e^\tau \left[1 - \left(1 - S_e^{1/m} \right)^m \right]^2 \quad [2.4]$$

where K_s is the saturated hydraulic conductivity, τ is tortuosity factor, and m is an empirical parameter related to pore size distribution n . The HYDRUS-1D code has been used to simulate: (1) the transport of soil water isotopes with evaporation fractionation (Zhou et al., 2021), (2) soil water dynamics and the response of different reference evapotranspiration models to crop evapotranspiration under a rainfed condition (Ndule et al., 2021), (3) partitioning of evaporation into transpiration, and soil evaporation and interception (Sutanto et al., 2012). Hydrus-1D has also been used to predict some soil hydraulic parameters from soil water evaporation (Mohammed et al., 2021). By

simulating water flow in variably saturated media, HYDRUS-1D can provide insights into the dynamics of soil evaporation and its interaction with other hydrological processes.

2.6.2 Evaporation stages and Critical Water Content ($\theta_{1/2}$)

The soil evaporation process can be described as a two-stage process: Stage I, characterized by a constant and high evaporation rate, and Stage II, marked by a decreasing evaporation rate as the soil surface dries out (Or et al., 2013) and this is depicted in a hypothetical case (Figure 2.1). Stage I evaporation occurs when soil water is non-limiting, and capillary conduction maintains water supply to the evaporating surface. This stage is influenced by factors such as soil moisture content (Abu-Hamdeh, 2003), temperature (Howell et al., 1993), wind speed (Wang et al., 2007), and solar radiation (Rana and Katerji, 2000). Stage II evaporation is influenced by the same factors as Stage I with moisture availability in soil exerting a strong control on evaporation rates. Both stages are crucial for various applications, including agricultural water management (Allen et al., 1998), hydrological modeling (Shuttleworth, 2007), and climate modeling (Trenberth et al., 2007). However, challenges persist due to the complexity of soil-plant-atmosphere interactions (Katerji and Rana, 2006), limited data availability (Liu et al., 2007), and uncertainty in model parameters (Shuttleworth, 2007). To further our understanding and prediction of evaporation, research should focus on integrating GIS techniques to improve evaporation estimation (Kalma et al., 2008) and developing more advanced models to account for complex soil-plant-atmosphere interactions (Katerji and Rana, 2006). The depth of the drying front at the end of Stage I evaporation is determined by the range

of hydraulically connected pores in the soil. Soil water characteristics can provide valuable information for predicting the depth of the drying front and mass loss during Stage I evaporation, which can be useful for estimating regional-scale evaporative water losses.

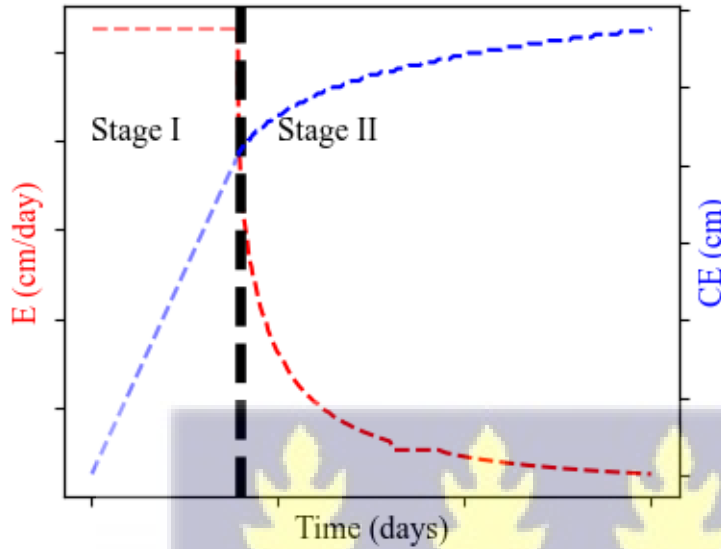


Figure 2. 1 Hypothetical case of stage I (constant rate period, CRP) and stage II (falling rate period, FRP) evaporation characteristics (separated by black dashed line) plotted as evaporation rate (E) and cumulative evaporation (CE).

Merlin et al. (2016) developed a pedo-transfer equation function to predict $\theta_{1/2}$ at which evaporation transitions from stage I to stage II evaporation given by:

$$\theta_{1/2} = 0.20 + 0.28 \times [\%Clay] - 0.16 \times [\%Sand] \quad [2.5]$$

where $\theta_{1/2}$ is the critical moisture content, %Clay is the percentage of clay particles, and %Sand is the percentage of sand particles in the soil. The $\theta_{1/2}$ has been reported to be dependent on soil texture (Merlin et al., 2016).

Lehmann (2008) also proposed a framework for predicting characteristic length, L_G , affecting evaporative drying of porous media with input parameters deriving from the van Genuchten (1980) and Mualem (1976) models given by:

$$L_G = \frac{1}{\alpha(n-1)} \left(\frac{2n-1}{n} \right)^{(2n-1)/n} \left(\frac{n-1}{n} \right)^{(n-1)/n} \quad [2.6]$$

where α and n are van Genuchten (1980) parameters relating to pore size distribution and entry pressure respectively. Further on the evaporation front depth, L_C , can be predicted from the relation:

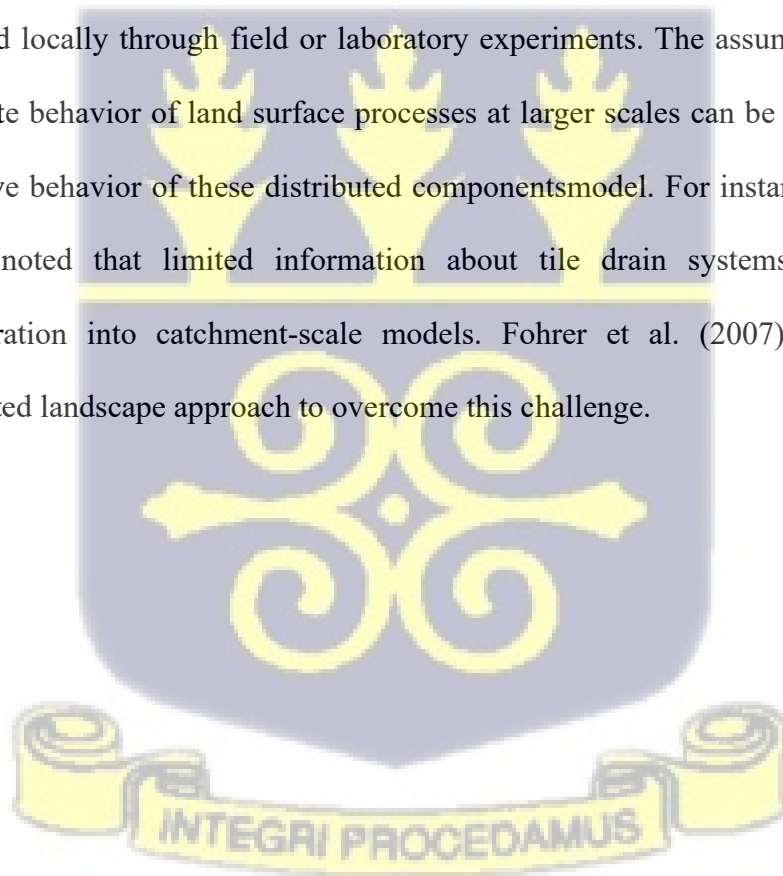
$$L_C = \frac{L_G}{1 + e_o/K(\theta)} \quad [2.7]$$

where e_o is stage I evaporation rate, K is hydraulic conduction as a function of moisture content (θ). Lehmann et al. (2018) examined factors influencing Stage I and II evaporation, including soil moisture, environmental conditions, and soil texture, and highlighted the importance of evaporation in agricultural water management, hydrological and climate modeling, while emphasizing the need for improved models and integrated approaches like GIS for better evaporation estimation.

2.7 Mapping of Soil Evaporation Using Geographic Information Systems (GIS)

Geographic Information Systems (GIS) is increasingly being used in agriculture and geoenvironmental sciences to address various challenges. GIS has proven effective in crop yield estimation and forecasting (Priya & Shibasaki, 2001; Chaudhari et al., 2010), enabling precision agriculture to optimize irrigation, fertilization, and pest control through spatial data analysis (Oshunsanya et al., 2017). Studies have shown that GIS-based precision agriculture can lead to improved agricultural productivity and sustainability. Additionally, GIS has been applied in pest and disease monitoring (Dong et al., 2019), land use planning, and supply chain management (Ghosh et al., 1996; Stewart & Janssen, 2014; Sharma et al., 2018), allowing for targeted measures to prevent infestations, reduce chemical pesticide use, and minimize environmental

impact. However, challenges persist, including data availability and quality issues (Sogbedji & McIsaac, 2002), highlighting the need for continued research and development to fully harness the potential of GIS in agriculture. In catchment hydrology, the prevailing approach to developing predictive models for landscape processes, such as land-use change, has been reductionist in nature. This approach involves breaking down complex systems into their smallest components to understand the whole. The appeal of this approach lies in its theoretical simplicity and apparent conceptual clarity. For instance, creating a predictive model typically begins with the selection of fundamental physical processes believed to dominate at a specific point. The parameters used in these equations have clear physical meanings and can be observed locally through field or laboratory experiments. The assumption is that the aggregate behavior of land surface processes at larger scales can be derived from the collective behavior of these distributed components model. For instance, Fohrer et al. (2007) noted that limited information about tile drain systems hindered their incorporation into catchment-scale models. Fohrer et al. (2007), thus proposed distributed landscape approach to overcome this challenge.



CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Description of Study Area

3.1.1 Location and Sampling

The experiment was conducted in a screenhouse located at the University of Ghana, Department of Geography. For this study, soils were sampled from the interior Savannah zone of Ghana, mainly Guinea savannah, excluding the Sudan Savannah and portions of Bono East and Oti regions. The interior Savannah zone of Ghana covers seven (7) administrative regions, namely: Upper West, Upper East, Northeast, Northern, Savannah, Bono East, and Oti. Geographically, the interior savannah zone extends between latitudes 7°30'N and 11°3'N, as well as longitudes 0°45'E and 2°82'W, and this spans a landmass of approximately 129,765 km², representing an estimated 54% of total area of Ghana (Incoom et al., 2020). The map of the sampling area, the dominant soil types and sampling locations are shown in Figs. 3.1, 3.2 and Table 4.1, respectively.

The climatic conditions of the interior savannah range from semi-arid characteristics in the northern-most parts to semi-humid attributes in the central areas, ultimately transitioning into a humid climate in the southern-most parts. The meteorological conditions are mainly governed by two prominent air masses: firstly, the North-East Trade Winds (Harmattan), originating from the Sahara Desert, manifesting as hot, dry, and laden with dust; and secondly, the South-West Monsoon, deriving from the Atlantic

Ocean and characterized by cold and moist winds as they blow from the southern direction (Incoom et al., 2020). A considerable portion of the interior savannah zone, which includes the Guinea and Sudan savannah, experiences a unimodal rainy season (Ghansah et al., 2018), characterized by erratic and unpredictable rainfall patterns, exhibiting substantial variations regarding its onset and cessation, quantity, and spatial distribution from one season to the next. Notably, significant differences are observed between successive seasons, particularly concerning the timing of onset, spatial extent, and total precipitation (Kasei et al., 2014). Mean monthly temperature ranges from 27°C to 36°C in the northern-most aeras and 24°C to 34°C in the southern-most areas of the interior savannah (Ghansah et al., 2018; Kasei et al., 2014).

Agriculture, mainly crops, and livestock, is the dominant land-use activity within the study area (Ofosu et al., 2014). Crop cultivation is predominantly subsistence, and rainfed farming and a few commercial farms (Ofosu et al., 2014). Consequently, during the rainy season, numerous small-holder fields are dispersed throughout the region. The primary crops cultivated during this period include sorghum (*Sorghum bicolor*), millet (*Pennisetum glaucum*), maize (*Zea mays*), groundnuts (*Arachis hypogaea*), rice (*Oryza sativa*), yam (*Dioscorea alata*), cowpea (*Vigna unguiculata*), Bambara beans (*Vigna subterranea*), alongside certain vegetable varieties. Given that agriculture is mainly rain-fed, farming operations are primarily limited to the wet season, with minimal (irrigated) to no farming activities taking place during the dry season.

The predominant vegetation type in the area primarily comprises Savannah landscapes, characterized by vast grasslands interspersed with trees and shrubs, including species such as baobab, shea, mango, and neem. In the southernmost parts of the interior savannah, the vegetation transitions to dry forests, characterized by a sparse distribution of tall trees, with shrubs and grasses thriving beneath their canopy (Aziz & Obuobie, 2017). A location referenced sampling method was adopted where a soil map (obtained from Soil Research Institute-CSRI) was loaded in QGIS (version 3.22.10).



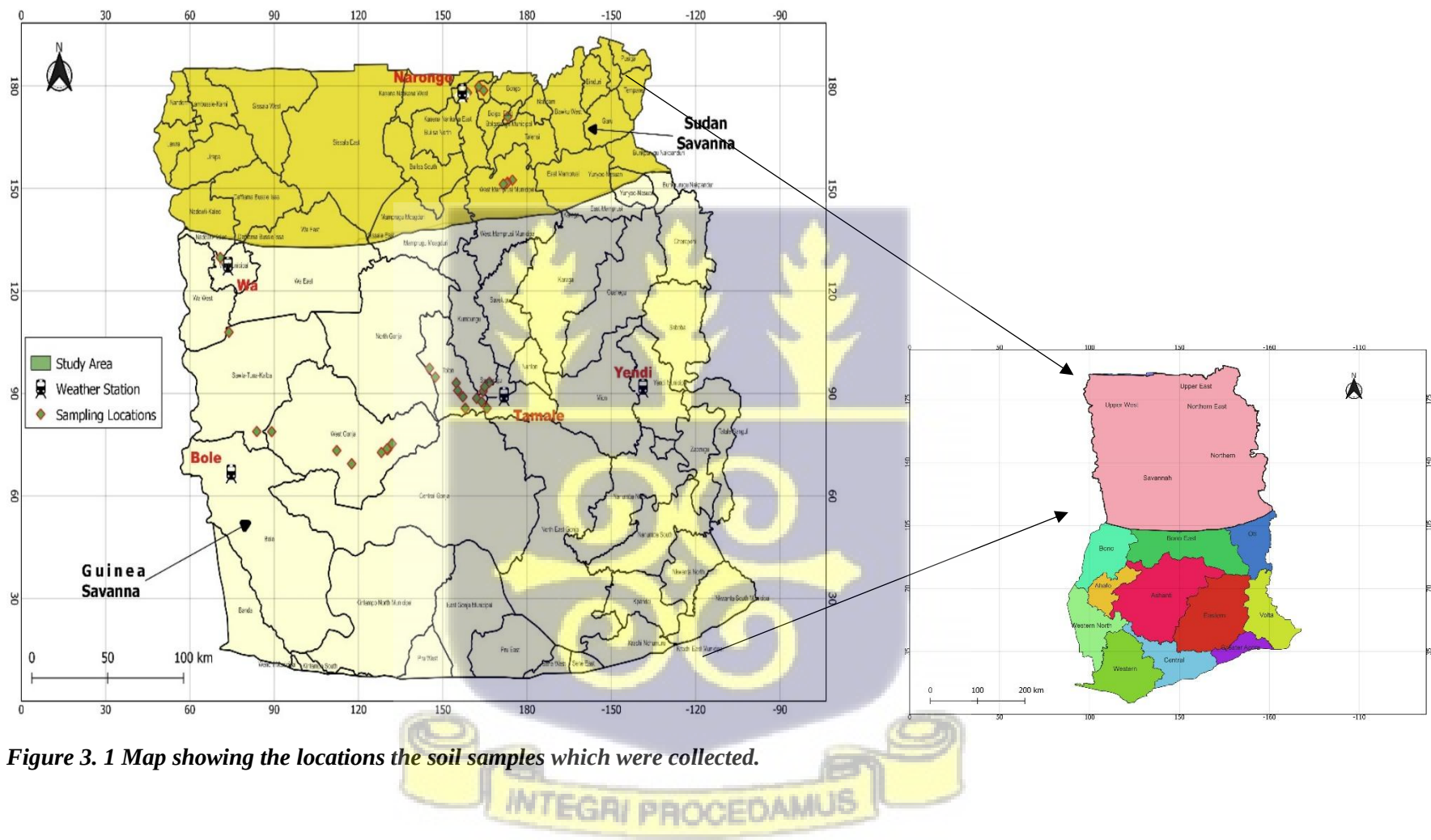


Figure 3. 1 Map showing the locations the soil samples which were collected.

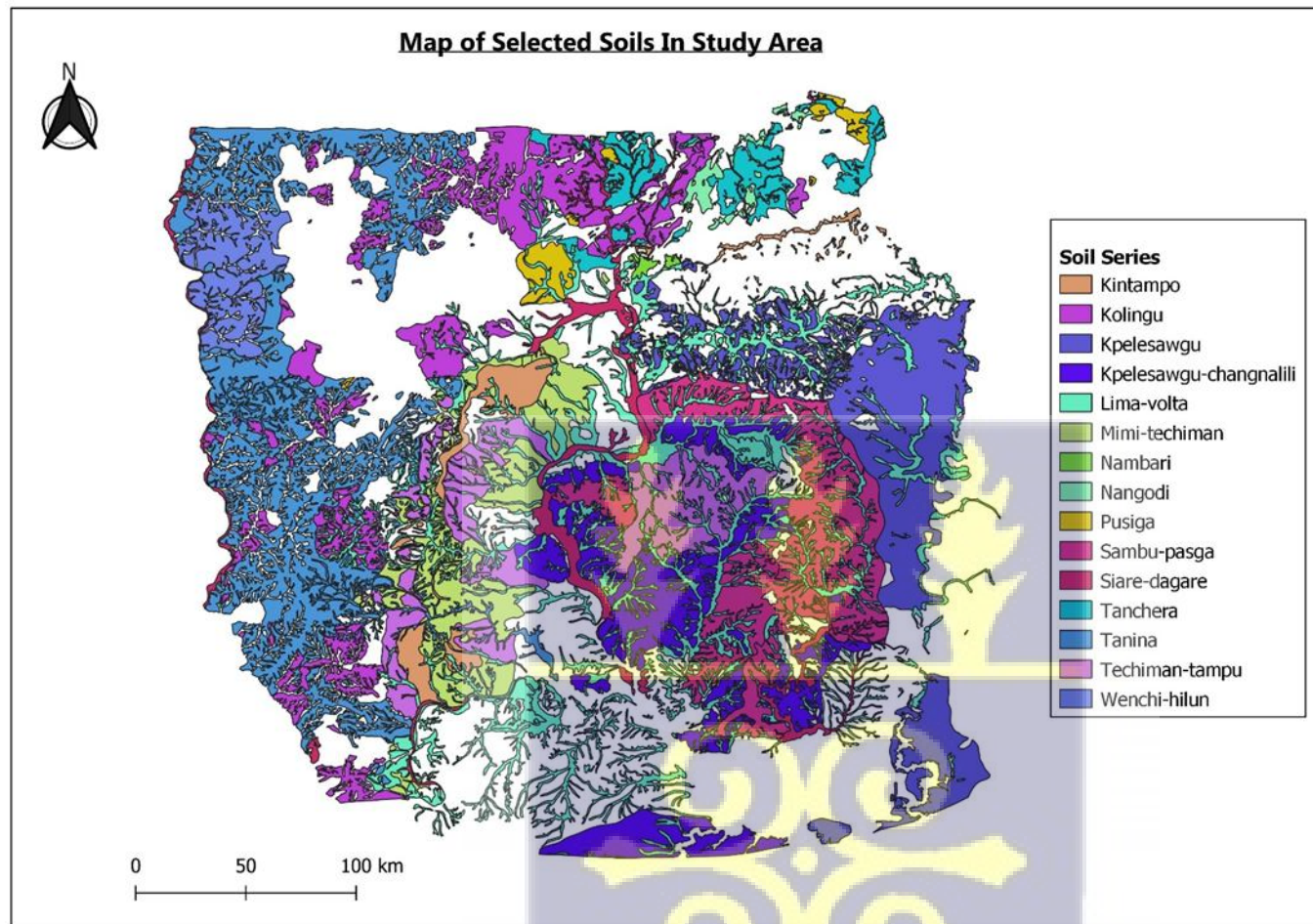


Figure 3. 2 Map showing selected soil series.

Soil samples were collected from thirty-eight different locations within the study area. The soil samples were collected from a depth of 0-20cm, which is known to be crucial for assessing various soil properties (Ferguson et al., 2007). The collected soil samples were labelled and placed in Ziplock bags to ensure proper identification and preservation of samples during transportation to the laboratory. The samples were analysed for bulk density (ρ_b), particle size distribution (ρ_s), soil moisture content (θ), aggregate content (%Aggregate), field capacity (θ_{FC}), saturated hydraulic conductivity (K_{sat}), and soil organic carbon (OC) content. Soil samples were homogenized by crushing and sieved through a 2-mm sieve to obtain fine earth fraction.



Table 3. 1 Locations where soil samples were collected

Administrative ID	LATITUDE	LONGITUDE	Soil Series	Geology
1	9.2358	-2.2372	Tanina	Granite
19	9.1764	-1.5178	Tanina	Voltaian
36	9.1486	-1.5437	Tanina	Alluvial
2	10.900	-1.0666	Techim	Granite
5	9.4784	-0.9361	Techim	Voltaian
12	9.0776	-1.7595	Techim	Voltaian
16	10.450	-0.8536	Techim	Voltaian
26	9.4878	-0.4618	Techim	Voltaian
29	10.091	-2.5445	Techim	Granite
3	10.882	-1.0796	Lima-	Granite
14	10.460	-0.8283	Lima-	Voltaian
23	9.4342	-0.9739	Lima-	Voltaian
4	9.0778	-1.7585	Tanche	Voltaian
6	10.471	-0.7990	Kintam	Alluvial
13	10.451	-0.8539	Kintam	Voltaian
7	9.3513	-0.9505	Namba	Voltaian
11	10.911	-0.9706	Namba	Birimian
15	9.3999	-1.0129	Namba	Shale,
22	9.1427	-1.8488	Namba	Granite
37	10.910	-0.9700	Namba	Birimian
8	9.1336	-1.5823	Kpeles	Voltaian
30	10.456	-0.8322	Kpeles	Voltaian
9	9.4063	-1.0950	Wenchi	Alluvial
32	9.4750	-1.1349	Wenchi	Shale,
10	9.7243	-2.4923	Pusiga	Granite
17	9.3814	-0.9825	Nango	Voltaian
20	9.5034	-1.2592	Nango	Shale,
18	10.463	-0.7900	Sambu	Voltaian
24	9.4564	-0.9652	Sambu	Voltaian
27	9.3505	-1.0811	Sambu	Voltaian
35	9.7243	-2.4927	Sambu	Granite
25	10.090	-2.5449	Koling	Granite
31	10.931	-1.0008	Koling	Alluvial
3			u	sediments
34	10.782	-0.8271	Koling	Granite
21	9.4370	-1.1257	Mimi-	Shale,
38	9.2364	-2.3268	Mimi-	Granite
28	10.456	-0.8319	Kpeles	Voltaian
33	9.1480	-1.5485	Siare-Dagare	Voltaian sandstone

3.2 Soil properties

3.2.1 Determining aggregate content (%Aggregate)

Aggregate content was determined by weighing 500g of air-dried soil and passing it through a 2mm sieve (Boateng et al., 2013) and the amount of soil sample remaining on the top of 2mm sieve was expressed as a percentage of the total sample to determine the aggregate content. The aggregate particles were collected from the sieve and weighed.

$$\%Aggregate = \frac{W_s}{W_t} \times 100\% \quad [3.1]$$

where W_s and W_t are weight of aggregate and total weight of soil respectively. The fine earth fraction (less than 2mm) was placed in plastic bags, labelled and sent to the laboratory for the determination of other physiochemical parameters.

3.2.2 Determining of Field (ρ_f) and Dry Bulk Density (ρ_b)

Field and dry bulk densities were determined using the core sampler method (Grossman & Reinsch, 2002). A cylindrical core sampler (height = 5 cm; volume = 98.17cm³) was pushed vertically into the soil to obtain a sample. The collected soil sampled was gently pushed out into labelled Ziplock bags, sealed, and transferred to the laboratory. The samples were weighed, dried at 105°C for 24 hours, and reweighed. The recorded field and oven dry weights were used to determine ρ_{bf} and ρ_b . Field bulk density was calculated using:

$$\rho_f = \frac{M_s}{V_t} \quad [3.2]$$

where M_s and V_t are mass of soil (field) and total volume of soil respectively. Dry bulk density was calculated using the relation:

$$\rho_b = \frac{M_o}{V_t} \quad [3.3]$$

where M_s and V_t are mass of soil and total volume of soil respectively.

3.2.3 Field Moisture Content

The soils whose wet weights were determined during sampling in the field were brought to the laboratory for soil moisture determination. The procedure followed that of the ASTM D 2216 standard (Rasti et al., 2020). The procedure involved weighing soil samples and subsequently subjecting them to a drying process in an oven for a duration of 24 hours, at a controlled temperature of 105°C. Once the drying process was complete, thus constant weight is attained, the soil samples were placed in a desiccator for a period and weighed after cooling, and the recorded weights were used to calculate moisture content given by:

$$\theta_g(\%) = \frac{W_w - W_{od}}{W_{od}} \times 100 \quad [3.4]$$

where W_s and W_{od} are weight of wet soil and weight of dry soil respectively. The volumetric moisture content was converted to volumetric given by:

$$\theta_v(\%) = \theta_g \times \rho_b \quad [3.5]$$

3.2.4 Organic Carbon

Organic carbon was determined using the wet combustion method (Walkley & Black, 1934). Ten (10) ml of 1 N potassium dichromate ($K_2Cr_2O_7$) solution and twenty (20) ml concentrated sulphuric acid (H_2SO_4) were added to 0.5 g of soil (fine earth fraction). The flask was swirled to ensure full contact of the soil with the solution after which it

was allowed to stand for 30 min and two hundred (200) ml of distilled water was added to stop the reaction. The unreduced $K_2Cr_2O_7$ remaining in solution after the oxidation of the oxidizable organic material in the soil sample was titrated with 0.2 N ammonium ferrous sulphate, $(NH_4)_2Fe(SO_4)_2$, solution after adding 10 ml of orthophosphoric acid and barium diphenylamine sulphate (0.16 %) indicator.

$$\%SOC = 0.003 \times \frac{10(V_B - V_T)}{V_B} \times \frac{100}{M_s} \quad [3.6]$$

where, V_B , V_T , and M_s are volume of $(NH_4)_2Fe(SO_4)_2$ required to titrate the blank sample, volume of $(NH_4)_2Fe(SO_4)_2$ required to titrate the soil sample, and mass of soil sample respectively.

3.2.5 Soil Particle Size Distribution (Texture)

The modified Bouyoucos hydrometer method by Day (1965) was used to determine the particle size distribution. The soil samples were analysed for clay, silt, and sand content. Forty grams (40 g) of the 2 mm sieved fine earth fraction was weighed into a beaker and 60 ml of 6% H_2O_2 was added to oxidize the organic matter. 100 ml of 5% Calgon solution (Sodium hexametaphosphate) was then added to the content and mixed. The 5% Calgon (sodium hexametaphosphate) solution was prepared by weighing 50 g and dissolved it in 1000ml of water, using the 1000 ml volume metric flask. The solution was placed in a mechanical shaker to shake for 2 (two) hours. The soil sample was removed from the shaker and placed into a 45-micron sieve to wash out the sand fraction. The washed sand fraction was transferred into a moisture can. The moisture can, with the soil, was oven dried for 24 hours at 105 °C. The remaining silt and clay fraction was washed into a measuring cylinder and was made up to the 1000ml

mark. The suspension was agitated vigorously with the plunger and immediately shaking was stopped, the time was noted. The temperature of the soil solution was recorded after equilibration. A hydrometer (ASTM 15 2H) was then placed into the suspension and the first and second readings were noted after 5 minutes and 5 hours respectively. The various fractions are calculated as follows.

$$\text{Sand}\% = \frac{\text{Weight of oven dried Sand}}{\text{Total Weight of Soil}} \times 100\% \quad [3.7a]$$

$$\text{Clay}\% = \frac{\text{Five hour Reading}}{\text{Total Weight of Soil}} \times 100\% \quad [3.7b]$$

$$\text{Silt}\% + \text{Clay}\% = \frac{\text{Five mins Readings}}{\text{Total Weight of Soil}} \times 100\% \quad [3.7c]$$

$$\text{Silt}\% = \%(\text{Silt} + \text{Clay}) - \% \text{Clay} \quad [3.7d]$$

The textural classes were determined using the textural triangle.

3.2.6 Field capacity

Field capacity was defined as the amount of water held in soil after excess water has drained from the soil. This state is usually attained within 2-3 days after rainfall or irrigation (Zettl et al., 2011). The soil samples were packed into core samplers using their bulk density and saturated for 48 hours and allowed to drain for 3 days after the saturated weight was obtained. The sample was allowed to drain from the bottom after the initial weight was taken while the top of the column was covered to exclude evaporation. The weight of the saturated soil was taken again on the third day. The soil was oven dried at 105°C for 24 hours, allowed to cool in a desiccator and the weight was taken and used to calculate for the field capacity.

$$\theta_g(\%) = \frac{W_w - W_{od}}{W_{od}} \times \rho_b \quad [3.8]$$

where W_s (after 3 days of drainage), W_{od} and ρ_b are weight of wet soil and weight of dry soil and bulk density respectively.

3.3 Soil evaporation

Air-dried soil samples were carefully packed into cylindrical polyvinyl chloride pipe (PVC) columns of height 15 cm and diameter 9.54 cm. The columns were packed bearing in mind the measured field bulk densities. To ensure uniformity in packing the columns were tapped gently at the sides during packing. The packed columns were saturated for a period of 72 hours from the bottom to avoid air entrapment.

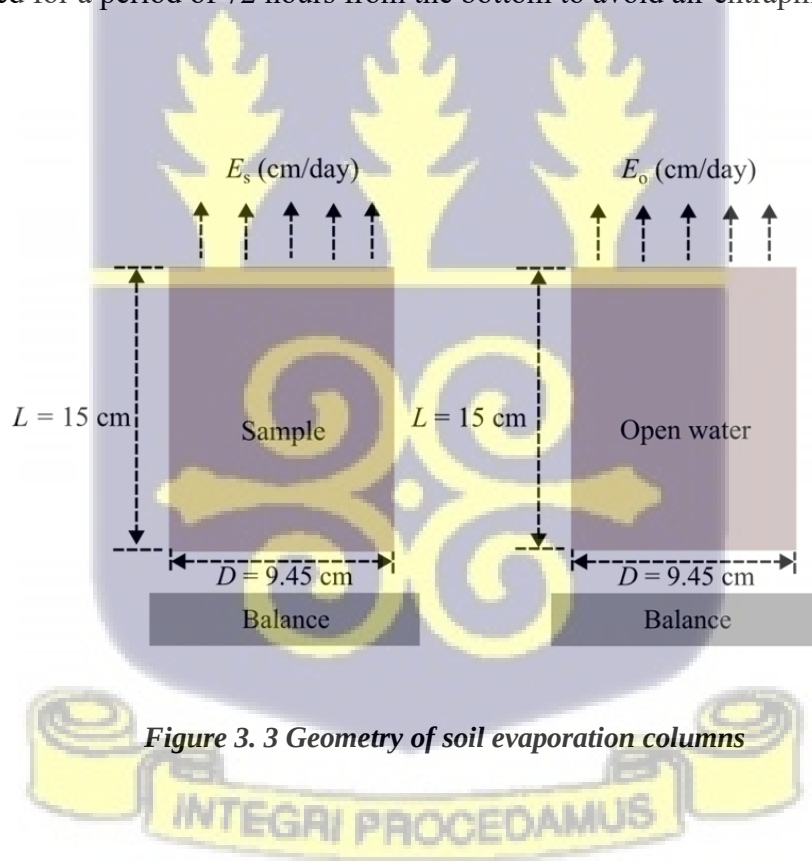


Figure 3. 3 Geometry of soil evaporation columns



Figure 3. 4 The experimental setup for measurement of soil evaporation.

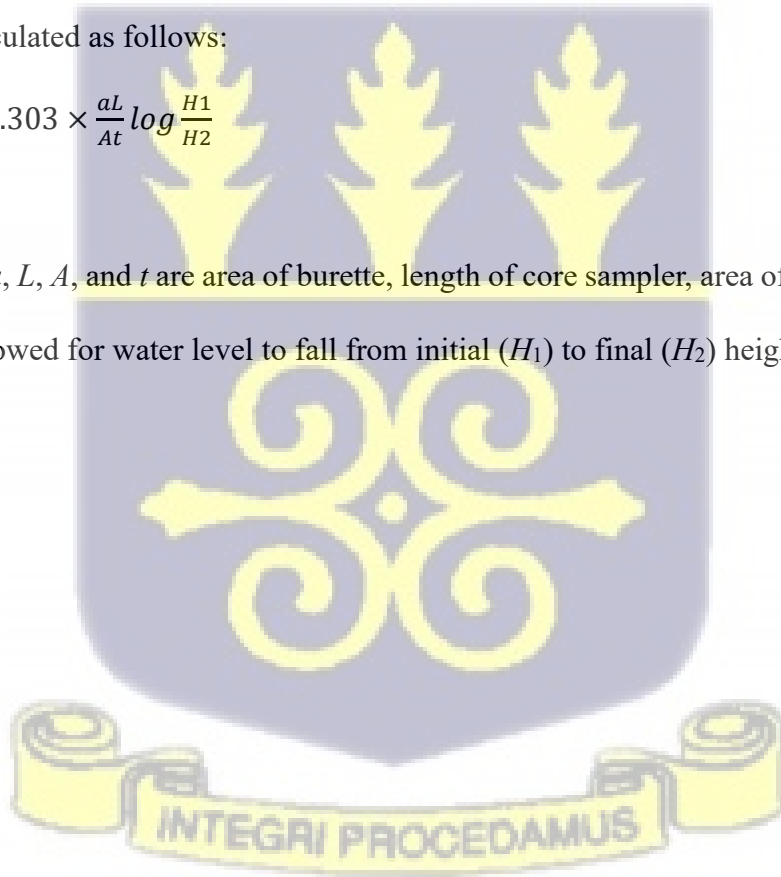
Upon quasi full saturation, the bottom of the sample was sealed, and the initial weights taken after the samples were cleaned off excess water. The experiment was conducted in a greenhouse, where evaporation measurement weight of samples was taken at 12-hour interval over a total duration of 25 days. Additionally, a logger was installed in the greenhouse to monitor temperature and humidity. To compare soil evaporation with potential (open water) evaporation, evaporation from open water reservoir (Figure 3.3) subjected to the same boundary condition in terms of temperature and relative humidity of air as the soil columns was also measured. When no weight loss under laboratory condition was observed, the samples were oven dried at 105°C for 24 hours and the moisture content determined. The oven-dried samples were weighed, and these recorded weights were subsequently used to calculate the final moisture content of the soil samples.

3.4 Measurement of Saturated Hydraulic Conductivity

The saturated hydraulic conductivity (K) of soil samples was determined using the falling head method (Woessner & Poeter, 2020). The procedure involved packing the soil samples into a core sampler of height 5 cm and diameter 8.5 cm. The sample saturated from the bottom for 48 hours. A permeable cloth material covered the base and top of the core sampler, allowing water to pass through. To perform the falling head test, the saturated soil sample was placed on a sample holder, and an attached burette filled with water was allowed to exfiltration through the sample (Figure 3.5). The initial and final levels of the water and the time that elapsed was noted. The burette was refilled, and the test was repeated for three to four times. The hydraulic conductivity was calculated as follows:

$$K = 2.303 \times \frac{aL}{At} \log \frac{H_1}{H_2} \quad [3.9]$$

where, a , L , A , and t are area of burette, length of core sampler, area of soil sample, and time allowed for water level to fall from initial (H_1) to final (H_2) height respectively.



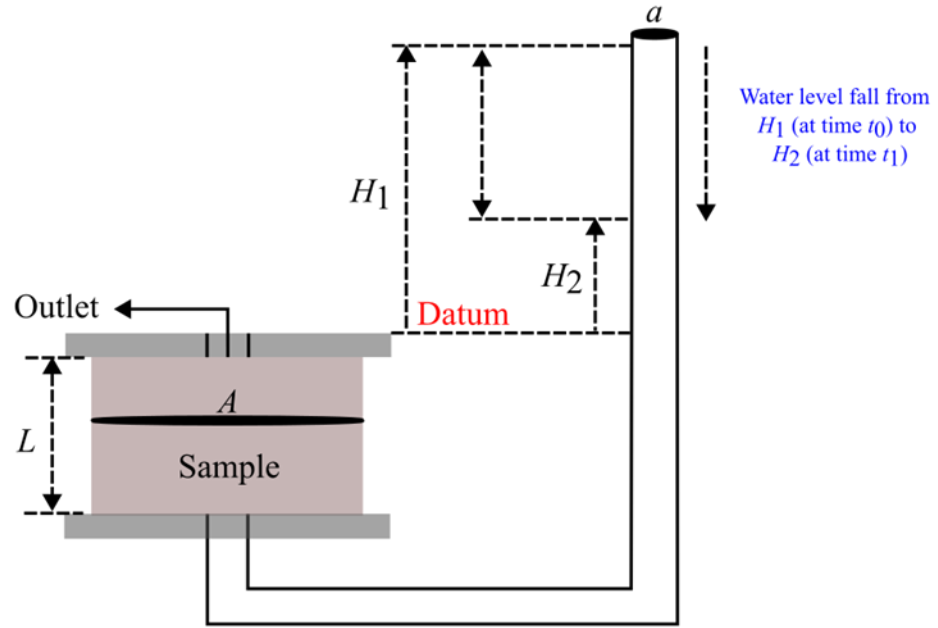


Figure 3. 5 *Figure 3.5 Schematic of a falling head hydraulic conductivity measurement setup*

3.5 Hydrus 1-D Numerical Code

The Richards equation, in Hydrus 1-D, was used to simulate evaporation (Bezerra-Coelho et al., 2018; Šimůnek et al., 2016):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[K(\theta) \left(\frac{\partial h_m}{\partial z} + 1 \right) \right] \quad [3.10]$$

where, $\partial h_m / \partial z$ is matric potential gradient, $K(\theta)$ is the unsaturated hydraulic conductivity K as a function of moisture content (θ) of the soil. The geometry (depth, $z = 15$ cm) of the soil evaporation column was discretised into 101 steps and for each soil, the boundary and initial conditions were determined and input into the model.

Comparisons were made between the HYDRUS evaporation output and those measured in the laboratory. The agreement between the simulated and observed was based on r^2 . The soil hydraulic properties obtained from inverse modeling were derived following the van Genuchten (1980):

$$\theta = \frac{\theta(h_m) - \theta_r}{\theta_s - \theta_r} = [1 + (\alpha h_m)^n]^{-(1-1/n)} \quad [3.11]$$

where, θ is the volumetric water content of the soil, θ_r is the residual volumetric water content, θ_s is the saturated volumetric water content, $1/\alpha$ is a parameter that determines air entry point of sample, n is another parameter that determines pore size distribution, h_m soil water potential and m is a fitting parameter. The Mualem (1976) conductivity function, $K(\theta)$, is given by:

$$K(\theta) = K_s \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^\tau \left[1 - \left(1 - \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^{1/m} \right)^m \right]^2 \quad [3.12]$$

where, K_s is the saturated hydraulic conductivity, θ_r is the residual volumetric water content, θ_s is the saturated volumetric water content, τ is tortuosity factor, m is a parameter derived from the van Genuchten (1980) model.

3.6 Determination of the Critical Water Content (CWC)

The graphs of the soil evaporation with time enabled the determination of the two stages of evaporation. For each soil, the CWC was determined. Also, the soil texture data for the soils were used to estimate the CWC using a pedotransfer function proposed by Merlin et al. (2016) in equation 2.5, where f_{clay} , and f_{sand} are the fraction of sand and clay respectively. The CWC from the evaporation curves and from equation 3.12 were compared. The agreement between observed and calculated CWC was based on r^2 .

3.7 Deriving a Semi- Distributed Evaporation Map for the Interior Savannah zone of Ghana.

Soil landscape models are useful tools for predicting soil properties and the evolution of soil in time and in space (Vanwalleghem et al., 2013; Sangchyoswat et al., 2002; Zolfaghari et al., 2022; Florinsky et al., 2002)). Soil-landscape models can be used to predict the spatial distribution of soil properties at the surface horizon across a

landscape (Huggett, 1975). These models can also be used to predict soil properties such as clay, silt, sand, ironstone, and thickness of the surface horizon from the original terrain attributes for an area (Zolfaghari et al., 2022). Landscape models, where continuous, provide a more detailed representation of landscape characteristics but require more data and computational resources. On the other hand, distributed landscape models are more straightforward and efficient but may oversimplify complex relationships. Furthermore, a semi-distributed landscape model is a hybrid approach that combines elements of both continuous and distributed landscape models. It aims to balance the trade-offs between model complexity, data requirements, and computational efficiency (Dupas et al., 2019). In this study, soil properties, including soil bulk density, critical water content, and evaporation rate and transition time to stage to evaporation were lumped into discrete area to create a digital landscape model. This approach has been exemplified for the simulation of hydrologic fluxes (e.g., Pai et al., 2012). In this study, the smallest spatial units (i.e., soil series) may not be continuous, and there is no routing among them (Kalcic et al., 2015) but must be linked to provide continuous information on a spatial soil process. The procedure to achieve this is summarized in Figure 3.6. The procedure for implementing such a model involves the following steps: (1) defining the study area and boundaries, (2) discretize the landscape into smaller units (e.g., soil units), (3) Initialization of the digital landscape with soil process data (e.g., bulk density, critical water content, evaporation rate and evaporation depth) and post-processing, (4) visualize and analyse the results using GIS. In step (1) study area and boundaries becomes a region of interest, thus the interior savannah zone of Ghana. In step (2), similar landscape units which are clustered are reclassified to have same attribute. Step (3) required data initialization and further errata calculation to derive expected output. a region of interest (ROI) was digitized out

of the soil map, (2) the soil map was vectorized and reclassified (same soil series belonging to the same soil clustered map unit), (3) the reclassified map units were rasterized, (4) correct (exclude) for other spatial attributes (e.g., water bodies, other land use types such urban or forest). (5) generated maps based on the desired soil property or from raster calculator.

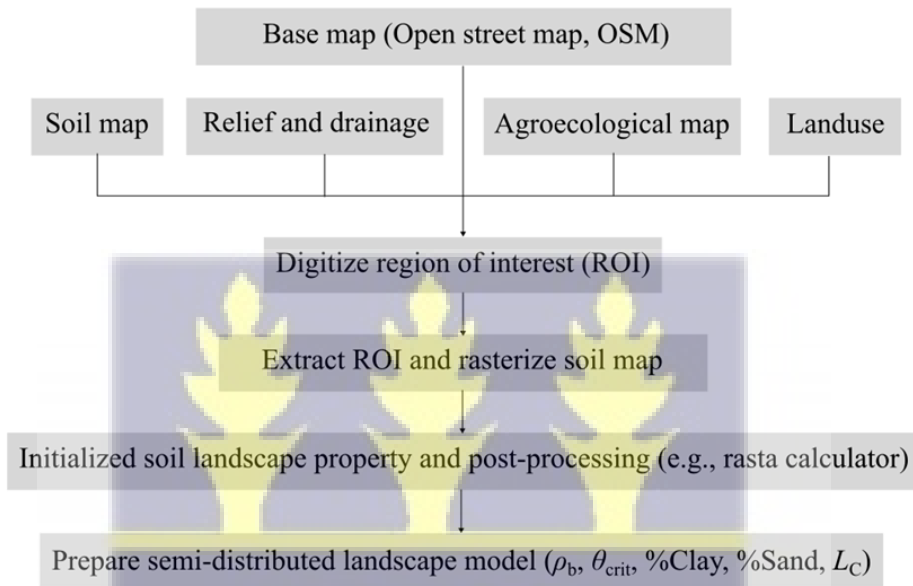


Figure 3. 6 Workflow for developing the semi-distributed landscape model.

CHAPTER FOUR

4.0 RESULTS

4.1 Study area and soils

The study site, the interior savannah zone of Ghana (Figure 4.1), has five Meteorological stations. Satellite climate data (<https://power.larc.nasa.gov/>) was obtained for rainfall, temperature, relative humidity, wind speed, was used to calculate reference evaporation (ET_o) following the Penman-Monteith approach (e.g., Allen et al., 1998). A plot of rainfall, ET_o, relative humidity, and temperature are shown in Figure 4.2 and a summary of the minimum and maximum values are also shown in Table 4.1. The coldest month is in August respectively for all the location, but the values varied amongst the different location. The hottest months March respectively for all the location except Navrongo (hottest month occurring in April), but the values varied amongst the different location. Also, the wettest month is in August for all locations with P/ET surplus occurring in over 3 to 5 months depending on the location. Remarkably, Tamale and Yendi showed about a 5-month period of rainfall surplus. Soil moisture deficits are expected from October to May (Bole), November to May (Tamale, Yendi, Wa), and October to June (Navrongo). Cropping windows generally overlap with rainfall-ET_o surplus windows (Figure 4.2).

Fifteen (15) soil series were sampled from the study site (Figure 4.1). This includes Tanina, Techiman-Tampu, Lima-Volta, Tanchera, Kintampo, Nambari, Kpelesawgu-Changnalili, Wenchi-Hilun, Pusiga, Nangodi, Sambu-Pasga, Kologu, Mimi-Techiman, Kpelesawgu, and Siare-Dagare. These soils derive from various geological formations,

including Granite, Voltain sandstone, Alluvial sediments, Birrimian greenstones, Voltaian shale, and Shale, Mudstone, Sandstone. During sampling (i.e., February 21-25, 2023), the soil was dry with a moisture content ranging from 0.23% to 11.48% (mean: 1.14%).



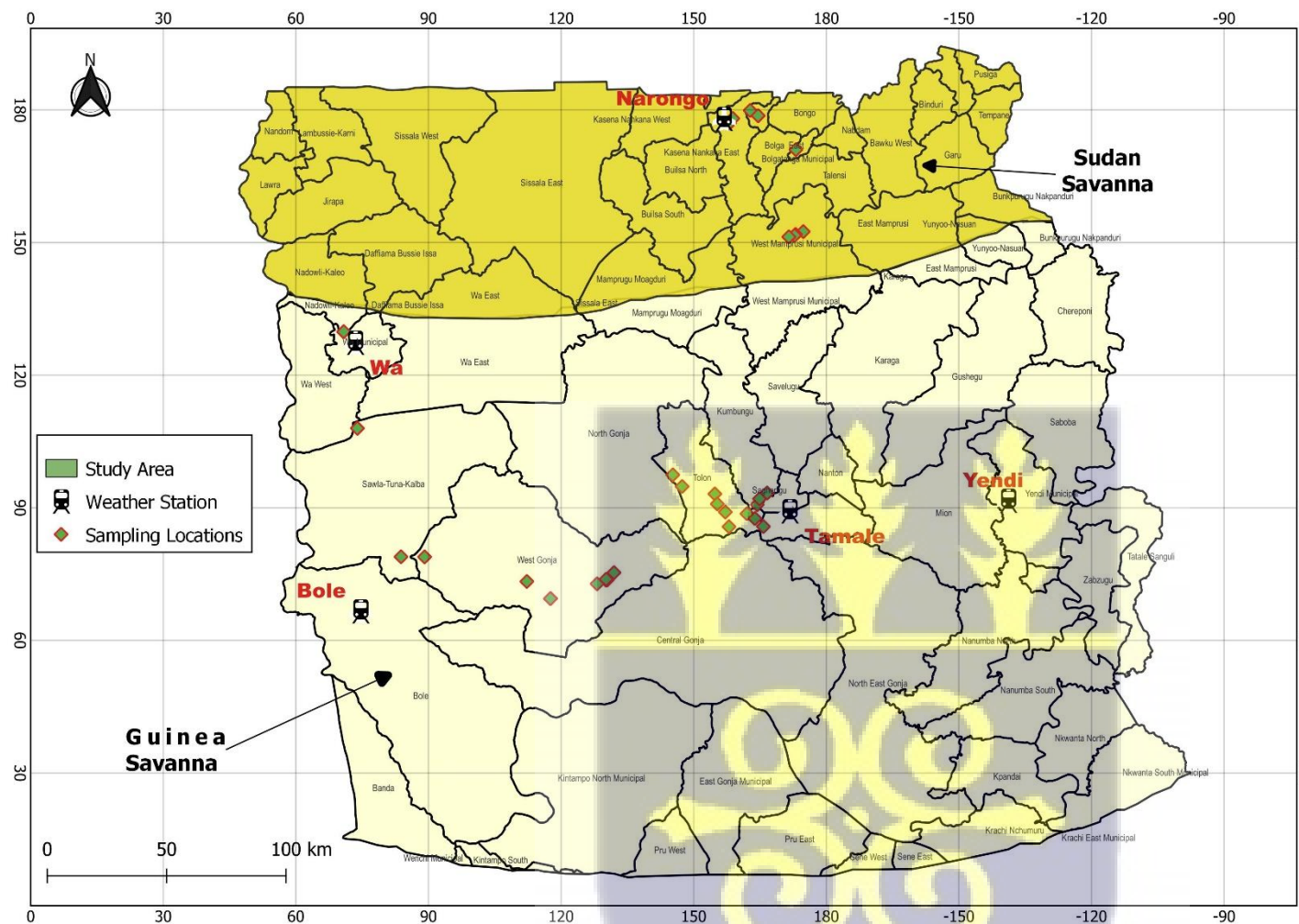


Figure 4. 1 Map of zoom in on the interior agroecological zones (Guinea savanna and Sudan savanna) of Ghana with sampling location (diamond) and location to the closest weather station (trains).



Figure 4. 2 Analysis of satellite weather data (temperature, rainfall, relative humidity) data extracted with reference to the location weather station in the interior savannah zone of Ghana (data source: <https://power.larc.nasa.gov/>).

Table 4. 1 Satellite climatic data for weather stations across the study area.

	Temp (mm)		RH (%)		P (mm)		ETo (mm)	
	Min	Max	Min	Max	Min	Max	Min	Max
Navrongo	24.8	31.9	20.7	84.4	1.6	234.0	91.1	285.0
Wa	25.0	30.5	27.8	82.6	2.1	218.4	100.3	283.7
Yendi	25.1	29.9	40.8	85.1	2.7	217.7	88.9	249.9
Bole	25.3	29.9	32.5	82.6	3.0	175.6	98.5	275.7
Tamale	25.1	30.2	38.8	84.0	2.5	204.8	90.8	250.7

4.2 Soil properties

4.2.1 Soil texture

The particle size analysis results are presented in Figures 4.3 and 4.4. The minimum sand, silt and clay were 7.0, 1.0, and 7.5% respectively whereas the maximum sand, silt and clay contents were 91.2, 73.2, and 27.5% respectively. The average sand, silt and clay content were 59.7, 27.5, and 12.8% indicative of sandy loam soil. The standard deviation from the mean sand, silt and clay values were 20.45, 18.73, and 3.53%. Overall, sand content was highest, followed by silt and then clay. In the lower quartile, sand, silt content and clay content were 49.3, 11.7, and 10%. The median values for sand, silt and clay 64.9, 23.8, and 12.5%. In the upper quartile, sand, silt and clay content were 76.2%, 36.7%, and 15%. The coefficient of variability for sand, silt and clay were 34.2%, 68.1%, and 27.6%, indicating that silt content was the most variable. The Lima-Volta series had the lowest sand content at 7%, while the Kintampo series had the highest sand content at 98.2%. The Kintampo series also had the lowest silt content at 1.3%, while the Techiman-Tampu series had the highest silt content at 73.2%. The Kintampo series had the lowest clay content at 7.5%, whereas the Lima-Volta series had the highest clay content at 27.5%. The soils can be classified into three general classes, viz: sands (i.e., sand and loamy sand), loams (i.e., sandy loam, loam, and silty loam), and silt. The colors of the markers in Figure 4.4 indicate the same soil series and

therefore may share a common parent material. It is notable that the soils exhibit heterogeneity in soil texture even within the same soil series, indicating variability and diversity in their textural characteristics.

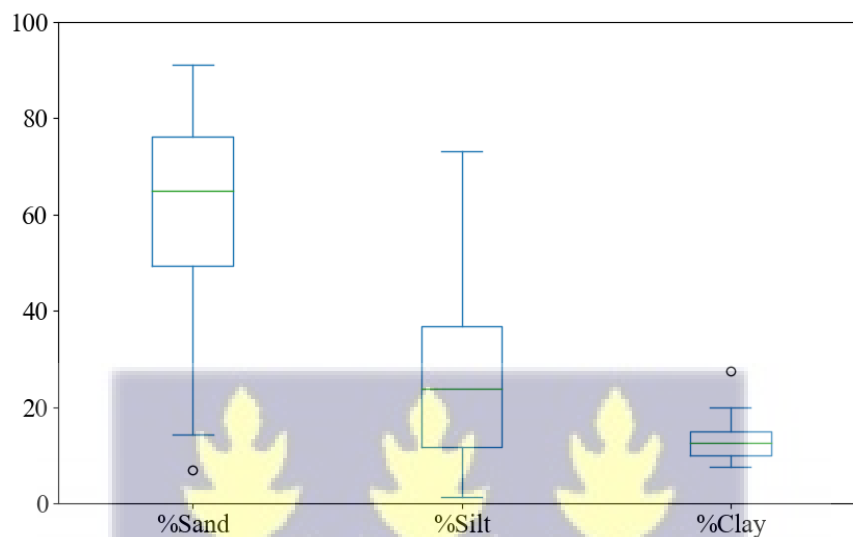


Figure 4. 3 Box plot of the soil particle size of the soils sampled from the interior savannah zone of Ghana (%Sand, %Silt, %Clay).



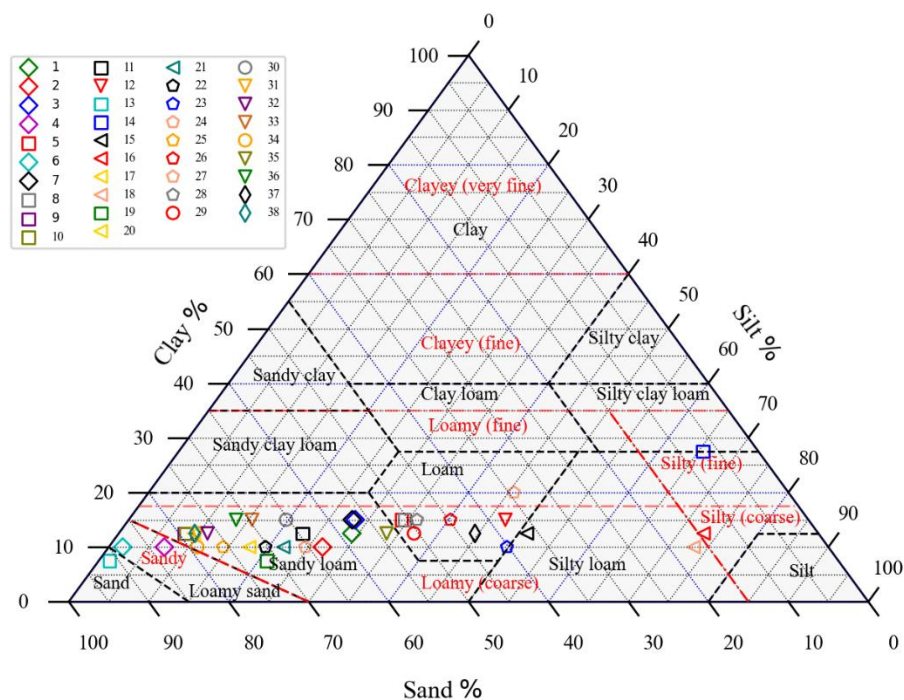


Figure 4. 4 Textural triangle of the soils sampled from the interior savannah zone of Ghana (%Sand, %Silt, %Clay)

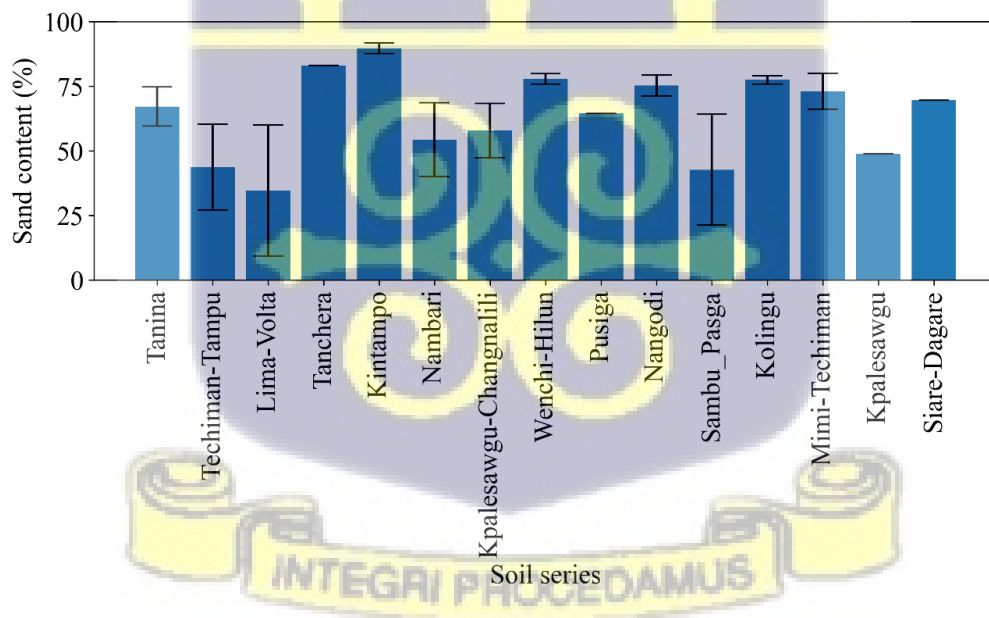


Figure 4. 5 Bar chart of sand content (%) of the various soil series sampled from the interior savannah zone of Ghana.

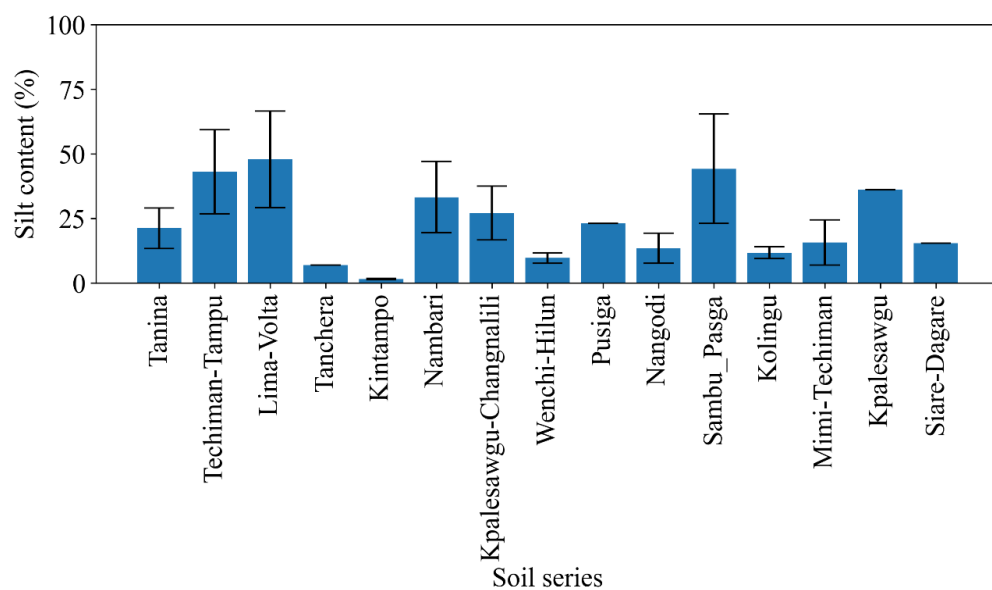


Figure 4. 6 Bar chart of silt content (%) of the various soil series sampled from the interior savannah zone of Ghana.

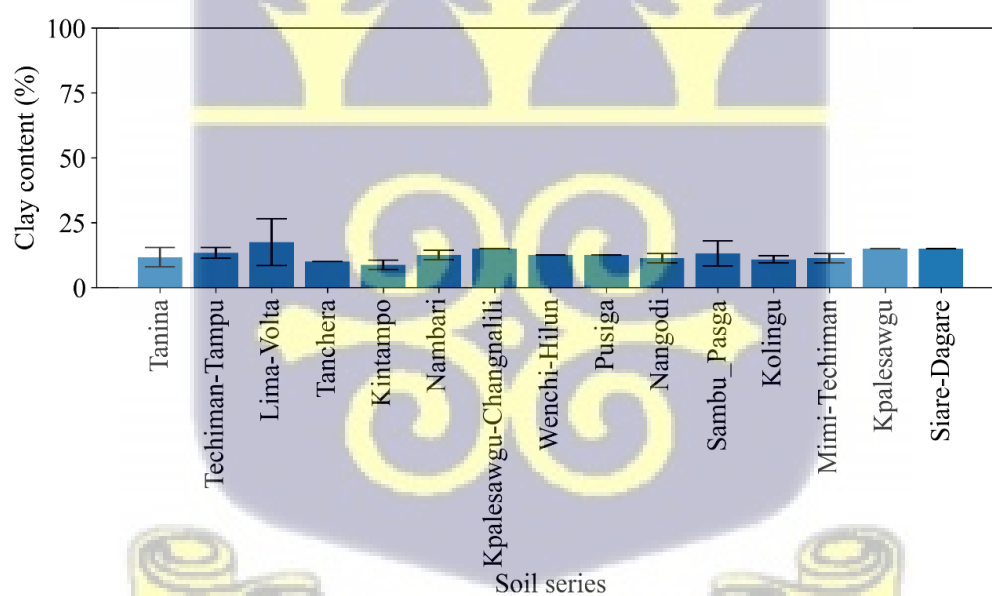


Figure 4. 7 Bar chart of clay content (%) of the various soil series sampled from the interior savannah zone of Ghana.

4.2.2 Soil bulk density

Figure 4.8 (left) presents a boxplot of the field bulk density values for the sampled soils, revealing notable variations among the soil series. The Tanina soil series had the lowest bulk density, with a value of 0.94 g/cm^3 , while the Techiman-Tampu series had the highest bulk density, at 1.60 g/cm^3 . The average and median bulk densities were both 1.30 g/cm^3 , indicating a relatively consistent central tendency. The lower and upper quartile bulk densities were 1.23 and 1.35 g/cm^3 , respectively. The standard deviation was 0.11 , and the coefficient of variation was 8.3% , indicating a relatively low level of variability. Figure 4.9 shows a visual representation of the distribution of bulk density among the various soil series, offering a clearer picture of the differences and patterns that exist.

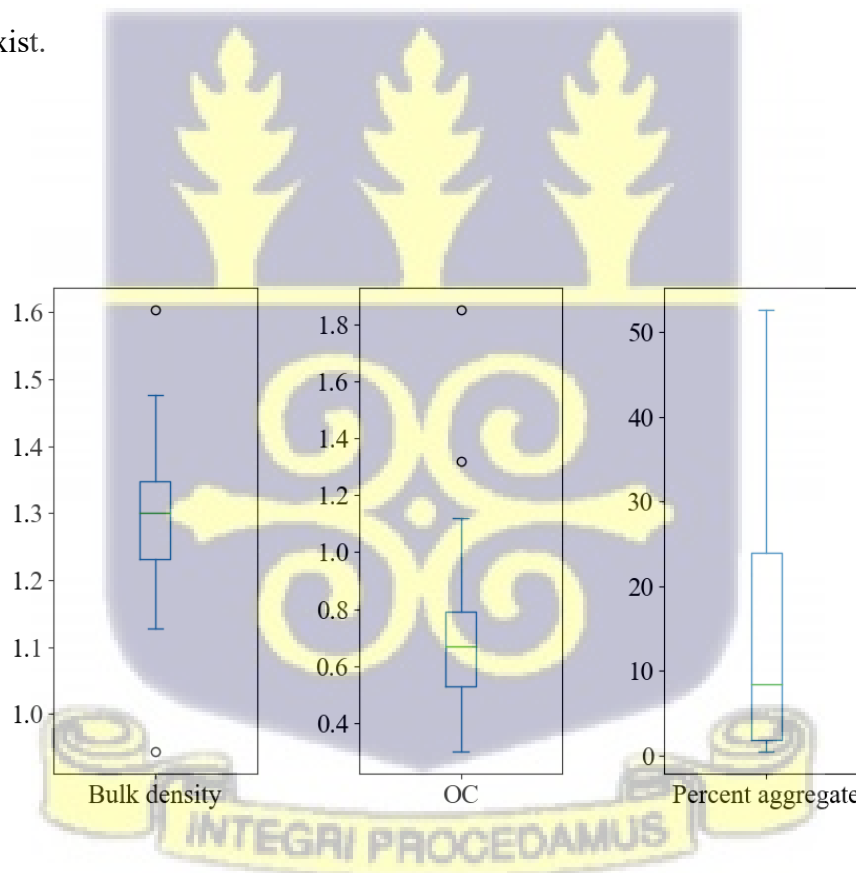


Figure 4. 8 Boxplot of bulk density (g/cm^3), organic carbon (OC) and stone content%(right) for the soils sampled from the interior savannah zone of Ghana.

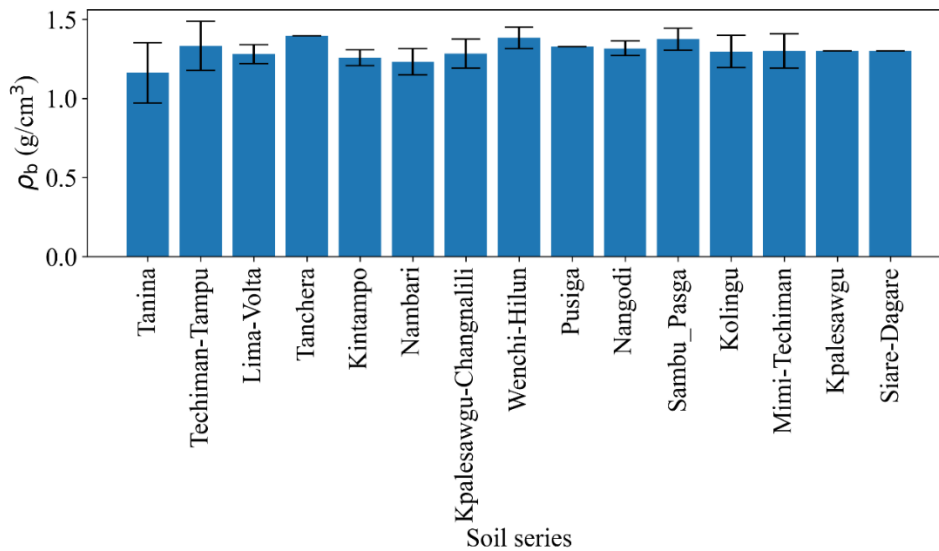


Figure 4. 9 Bar chart of soil bulk density(g/cm³) of the various soil series sampled from the interior savannah zone of Ghana.

4.2.3 Soil organic carbon

Figure 4.8 (middle) displays a box plot of soil organic carbon (OC) content, revealing valuable insights into the distribution of OC values. The mean OC value was 0.70%, while the median value was 0.67%, indicating a relatively consistent central tendency. The minimum and maximum OC values were 0.3% and 1.85%, respectively, showing a notable range of values. The lower and upper quartile OC values were 0.53% and 0.79%, respectively. The coefficient of variability in OC was 41%, and the standard deviation of values from the mean was 0.29, indicating a moderate level of variability. The Sambu-Pasga soil series had the lowest organic carbon content, with a value of 0.30%, while the Lima-Volta series had the highest, with a value of 1.85%. Overall, the average organic carbon content was 0.70% (Figure 10).

4.2.4 Aggregate content

Figure 4.8 (right) presents the results of the measured aggregate content in the analyzed soil samples, revealing a wide range of values. The aggregate content varied from 0.50% to 52.60%, with an average value of 14.45%. The Sambu-Pasga soil series had the lowest aggregate content, while the Siare-Dagare series had the highest (Figure 4.11). The standard deviation and coefficient of variation in aggregate content were 15.3 and 106%, respectively, indicating a high level of variability. The median aggregate content was 8.40%, which is slightly different from the mean, suggesting a skewed distribution. The lower and upper quartile values were 1.89 and 52.60%, respectively, further highlighting the wide range of aggregate content values.

4.2.5 Total porosity

Figure 4.12 (left) presents a summary of the measured soil porosity values of the soil samples, indicating a range of values from 40.0% to 65.0%, with an average porosity value of 51.7%. The Techiman-Tampu soil series had the lowest porosity, whereas the Tanina series had the highest porosity. The coefficient of variation (CV) was 8.04%, indicating a moderate degree of variability in porosity. The standard deviation was 4.16, which represents the average deviation of data points from the mean porosity value. The median porosity was 51.0%, indicating that half of the soils studied had porosity between 45.0% and 51.0%, and the other half had a porosity between 51.0% and 58.0%. This suggests a relatively even distribution of porosity values around the median.

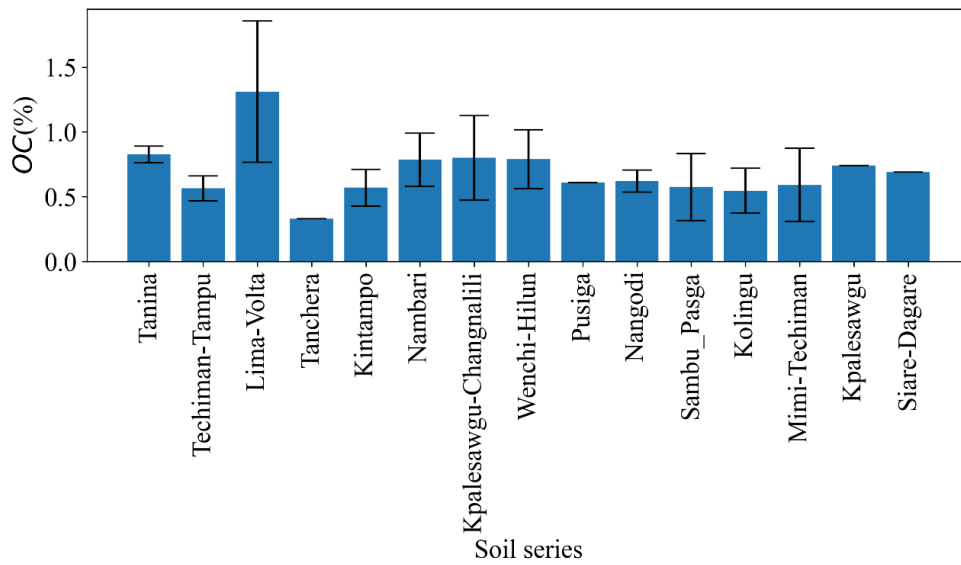


Figure 4. 10 Bar chart of soil organic carbon (%) content of the various soil series sampled from the interior savannah zone of Ghana.

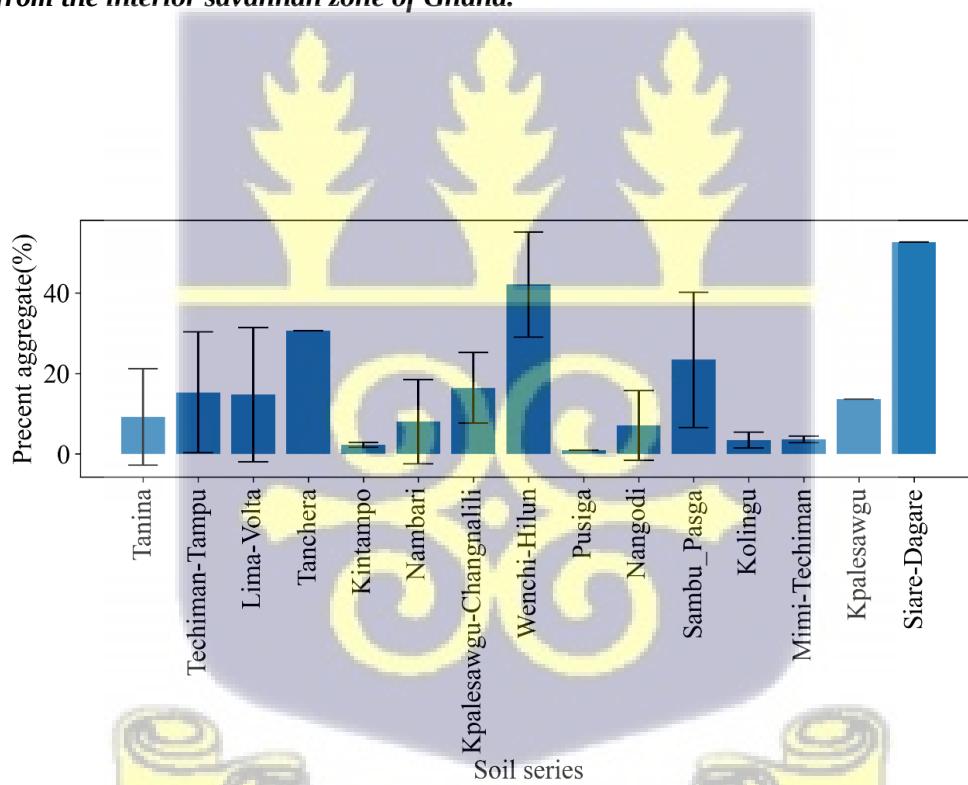


Figure 4. 11 Bar chart of aggregate content of the various soil series sampled from the interior savannah zone of Ghana.

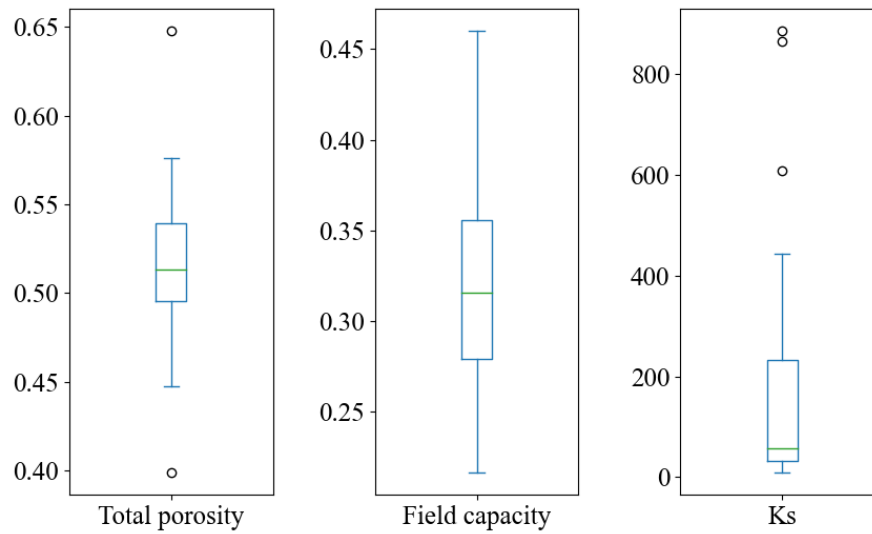


Figure 4. 12 Boxplot of total porosity, field capacity, and saturated hydraulic conductivity (Ks) of the soils sampled from the interior savannah zone of Ghana.

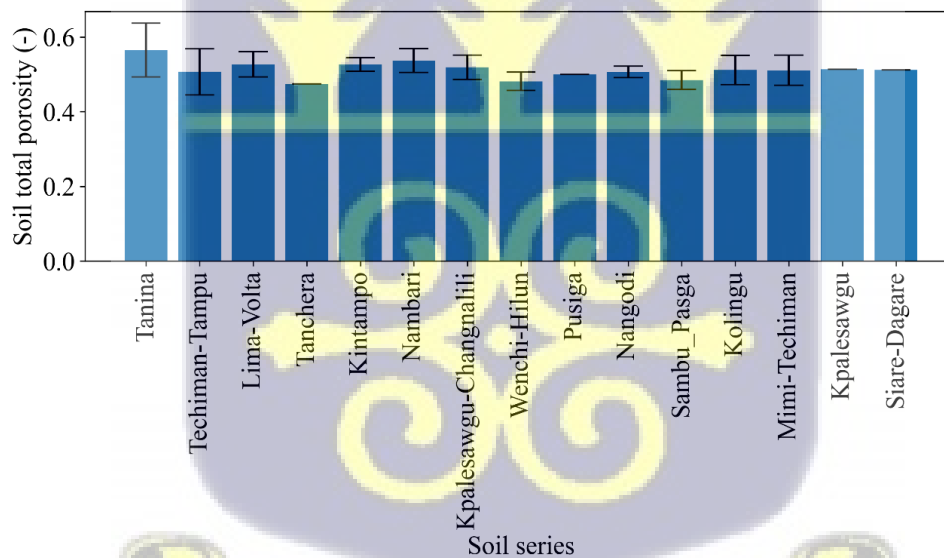


Figure 4. 13 Bar chart of total porosity of the various soil series sampled from the interior savannah zone of Ghana.

The upper quartile of soil series, representing the top 25% of samples, had porosity values ranging from 54.0% to 58.0%, whereas the lower quartile, representing the bottom 25% of samples, had porosity values ranging from 45.0% to 50.0%. The data

exhibited a moderate degree of dispersion among the sampled soils, indicating moderate variability. However, two outliers (i.e., Techiman-Tampu and Tanina soil series) were identified. The porosity of the soil samples showed some variation, with some samples having higher porosity values and others having lower values. However, the data was slightly skewed towards the lower values. The two outliers, Tanina (sample 36) and Techiman-Tampu (sample 29), were likely due to differences in soil texture and land management practices, highlighting the importance of considering these factors in soil analysis. The Techiman-Tampu soil had a high bulk density which may be due to soil compaction. The Tanina soil series had a low bulk density, and this could be due to the presence of organics (as observed during sample drying).

4.2.6 Field capacity

Figure 4.12 (middle) presents the results of the measured field capacity after three days of draining the soil, revealing a range of values from 13.9% to 47.0%, with an average field capacity of 31.6%. The Tanina soil series recorded the lowest field capacity, whereas the Mimi-Techiman soil series recorded the highest value. The coefficient of variation was 21.6%, indicating a relatively low degree of variability in field capacity. The standard deviation was 7.0, representing the average deviation of data points from the mean field capacity value. The median field capacity was 30.9%, indicating that 50% of the soils studied had a field capacity between 21.6% and 30.9%, and the other 50% had field capacity values between 30.9% and 47.0%. The upper quartile had field capacity values ranging from 35.8% to 47.0%, whereas the lower quartile had field capacity values ranging from 21.6% to 27.6%. The data showed a low degree of dispersion among the sampled soils, with little variability between the samples. One outlier was identified, attributed to the Tanina soil series, which had a high sand content

contributing to its low field capacity. The field capacity of the soil samples was relatively uniform, with most samples falling within a narrow range, except for the outlier with low field capacity.

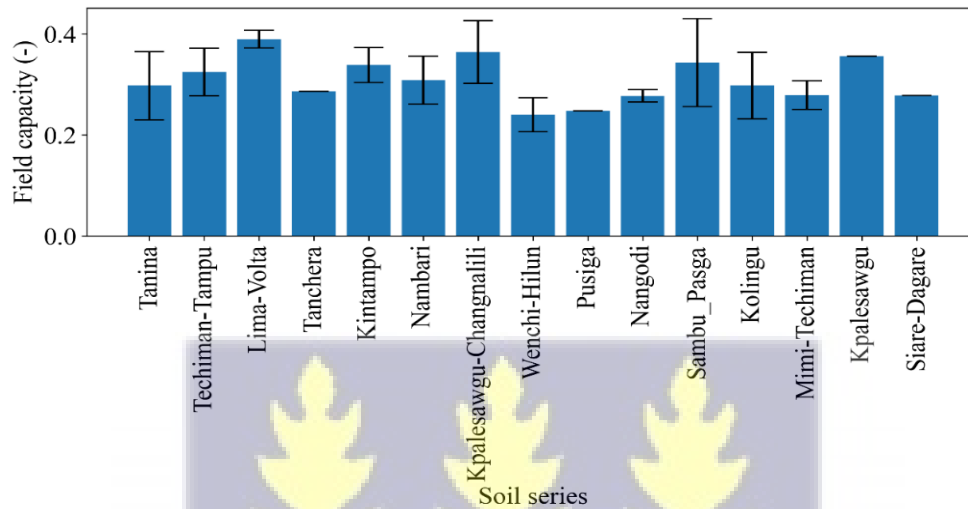


Figure 4. 14 Bar chart of Field capacity of the various soil series sampled from the interior savannah zone of Ghana.

4.2.7 Saturated hydraulic conductivity (K_{sat})

Figure 4.12 (right) presents a summary of the hydraulic conductivity data obtained from the soil samples, revealing a substantial range of values. The Nambari soil series exhibited the lowest but rather variable K_{sat} values. The hydraulic conductivity of the soil samples spanned from 32.2 cm/day to 886.5 cm/day, with a mean value of 169.3 cm/day. The coefficient of variation was 129.3%, indicating a high degree of variability in hydraulic conductivity across the sampled soils.

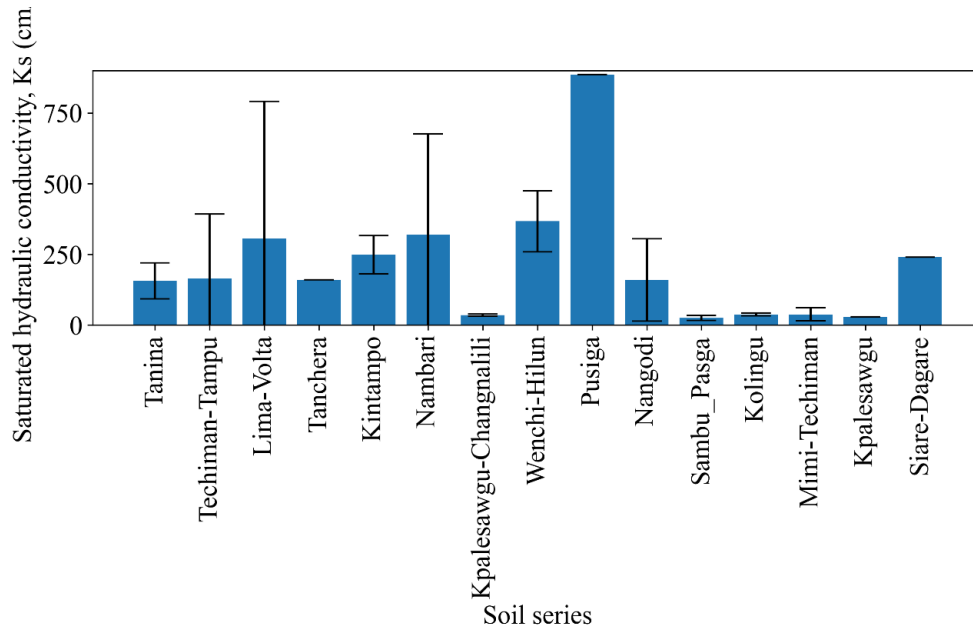


Figure 4. 15 Bar chart of saturated hydraulic conductivity of the various soil series sampled from the interior savannah zone of Ghana.

The standard deviation was 218.7 cm/day, which represents the average deviation of data points from the mean K_{sat} value. The median hydraulic conductivity was 56.9 cm/day, suggesting that half of the soils studied had a hydraulic conductivity between 8.7 cm/day and 56.9 cm/day, and the other half had a hydraulic conductivity between 56.9 cm/day and 886.5 cm/day. The upper quartile, comprising the upper 25% of soil series, had K_{sat} values ranging from 245.6 cm/day to 886.5 cm/day, whereas the lower quartile, representing the lower 25% of soil series, had hydraulic conductivity values ranging from 8.7 cm/day to 56.9 cm/day. The data exhibited a high degree of dispersion amongst the K_{sat} values. Three outliers were identified, attributed to the Nambari, Lima-Volta, and Techiman-Tampu soil series, which displayed hydraulic conductivity values remarkably higher than the average. The K_{sat} of the soil samples varied widely, with some samples exhibiting very high values and others displaying very low values. The data also showed a positive skew, indicating a higher frequency of samples with low

K_{sat} values than samples with high values. The three outliers were likely due to the presence of sand or gravels in the soil, which can significantly influence water flow.

4.3 Daily Evaporation Rate

Figures 4.19 to 4.33 shows the daily soil and open water rate (a), the quotient of soil evaporation rate and open water evaporation rate (b) and the cumulative soil and open water evaporation (c) plotted against time. The observed conditions in the screenhouse during the measurement is shown in Figure 4.33 (a). The relationship between open water evaporation rate and vapour pressured deficits also shows a linear relationship Figure 4.33 (b). The open water evaporation rate sample shows an oscillating pattern, which reflects changing environmental/evaporative demand during the conduct of the experiment.

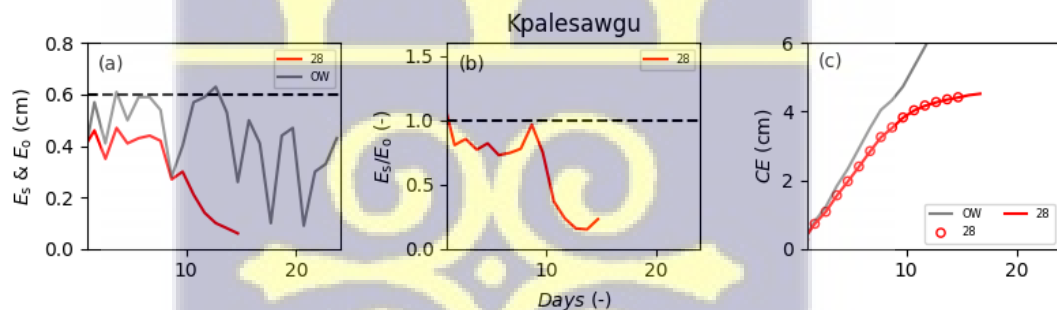


Figure 4. 16 Kpalesawgu soil series: Daily evaporation rates recorded for soil and open water (left), quotient of soil evaporation (middle) and observed (open circles) and modelled (lines; Hydrus-1D) cumulative plotted as a function of days of evaporation.

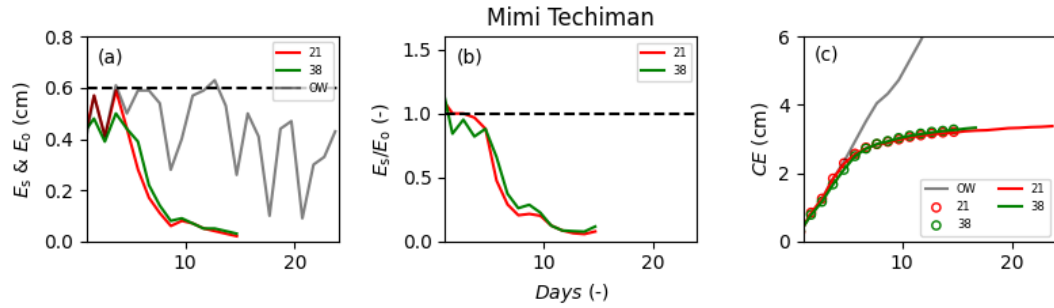


Figure 4. 17 Mimi Techiman soil series: Daily evaporation rates recorded for soil and open water (left), quotient of soil evaporation (middle) and observed (open circles) and modelled (lines; Hydrus-1D) cumulative plotted as a function of days of evaporation.

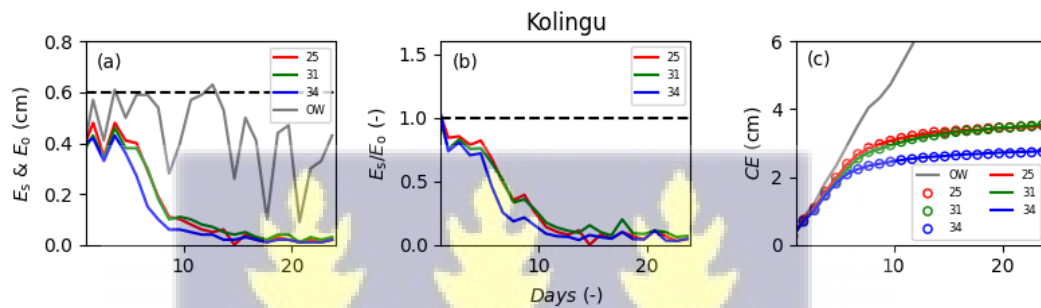


Figure 4. 18 Kolingu soil series: Daily evaporation rates recorded for soil and open water (left), quotient of soil evaporation (middle) and observed (open circles) and modelled (lines; Hydrus-1D) cumulative plotted as a function of days of evaporation.

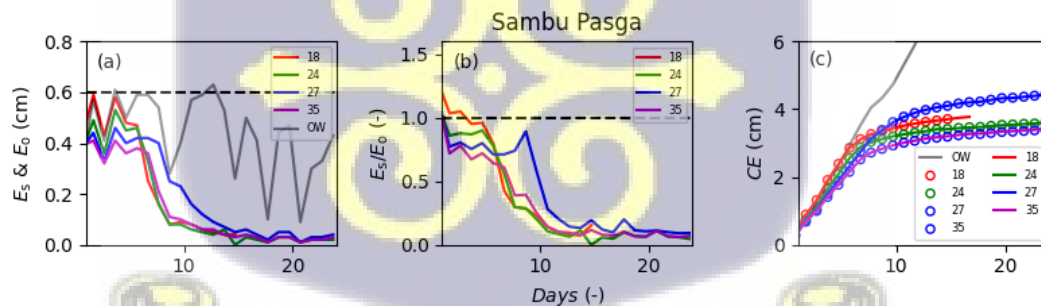


Figure 4. 19 Sambu Pasga soil series: Daily evaporation rates recorded for soil and open water (left), quotient of soil evaporation (middle) and observed (open circles) and modelled (lines; Hydrus-1D) cumulative plotted as a function of days of evaporation.

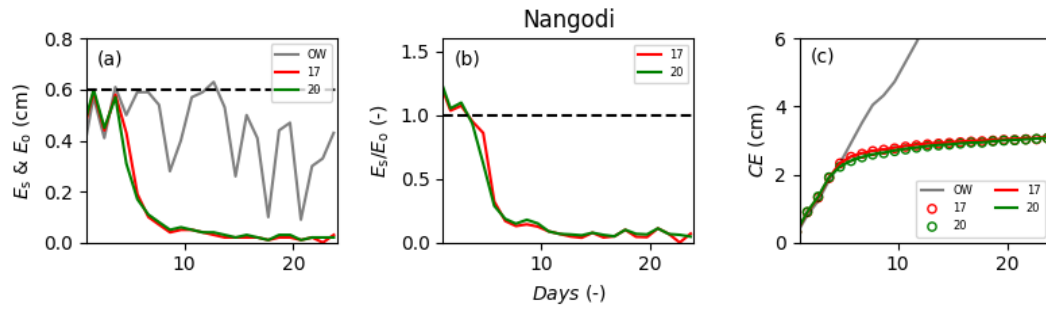


Figure 4.20 Nangodi soil series: Daily evaporation rates recorded for soil and open water (left), quotient of soil evaporation (middle) and observed (open circles) and modelled (lines; Hydrus-1D) cumulative potted as a function of days of evaporation.

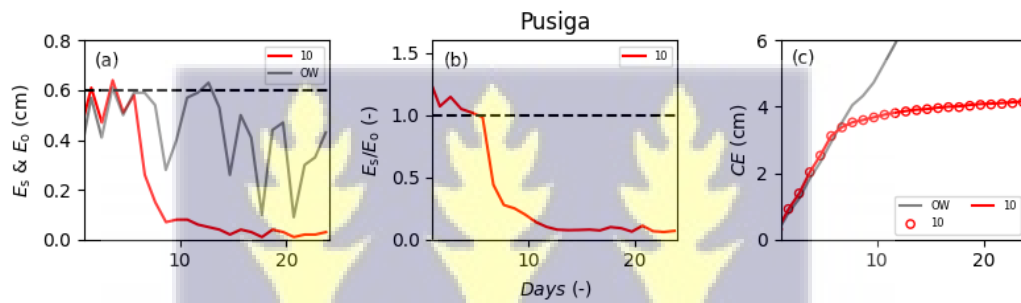


Figure 4.21 Pusiga soil series: Daily evaporation rates recorded for soil and open water (left), quotient of soil evaporation (middle) and observed (open circles) and modelled (lines; Hydrus-1D) cumulative potted as a function of days of evaporation.

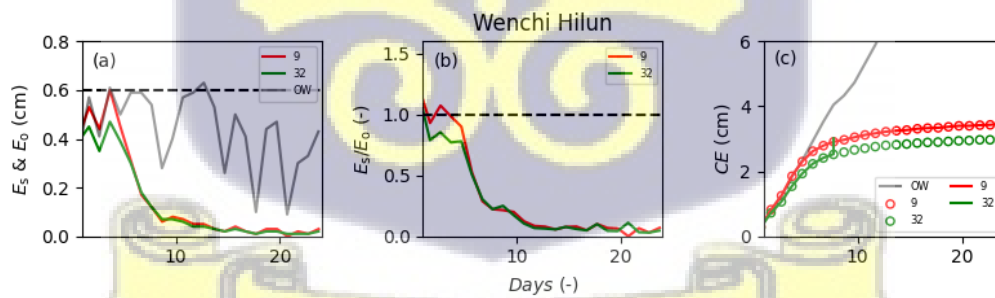


Figure 4.22 Wenchi Hilun soil series: Daily evaporation rates recorded for soil and open water (left), quotient of soil evaporation (middle) and observed (open circles) and modelled (lines; Hydrus-1D) cumulative potted as a function of days of evaporation.

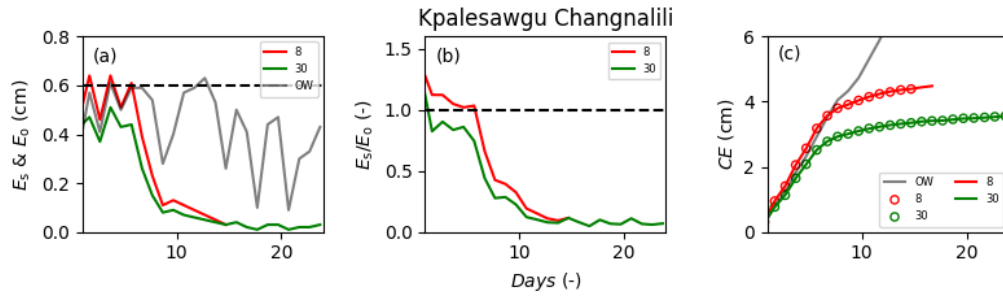


Figure 4. 23 Kpalesawgu Changnalili: Daily evaporation rates recorded for soil and open water (left), quotient of soil evaporation (middle) and observed (open circles) and modelled (lines; Hydrus-1D) cumulative potted as a function of days of evaporation.

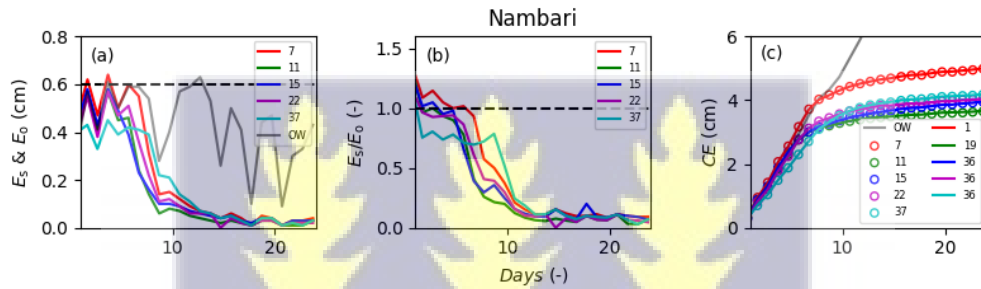


Figure 4. 24 Nambari soil series: Daily evaporation rates recorded for soil and open water (left), quotient of soil evaporation (middle) and observed (open circles) and modelled (lines; Hydrus-1D) cumulative potted as a function of days of evaporation.

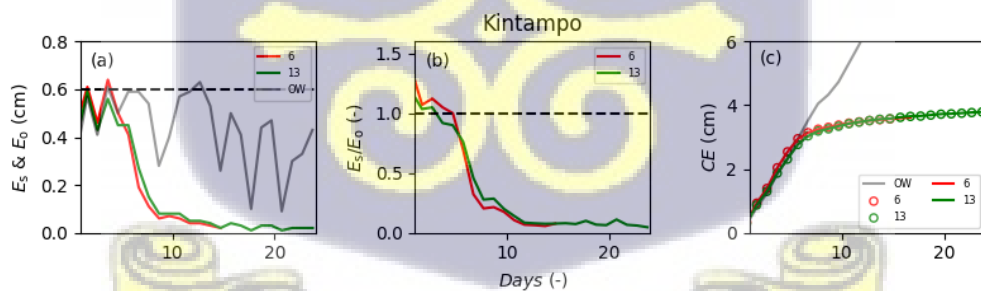


Figure 4. 25 Kintampo soil series: Daily evaporation rates recorded for soil and open water (left), quotient of soil evaporation (middle) and observed (open circles) and modelled (lines; Hydrus-1D) cumulative potted as a function of days of evaporation.

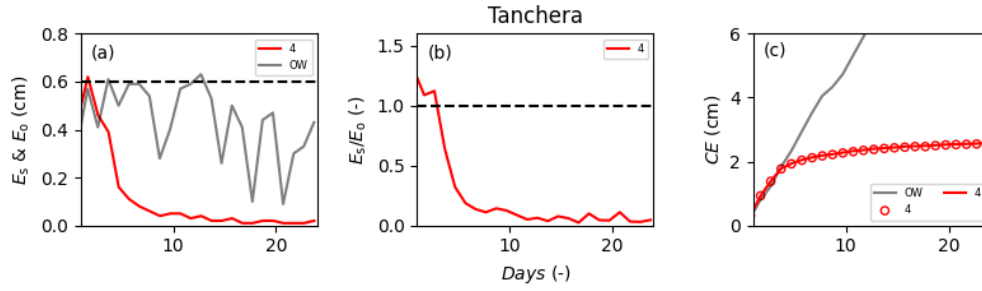


Figure 4. 26 Tanchera soil series: Daily evaporation rates recorded for soil and open water (left), quotient of soil evaporation (middle) and observed (open circles) and modelled (lines; Hydrus-1D) cumulative potted as a function of days of evaporation.

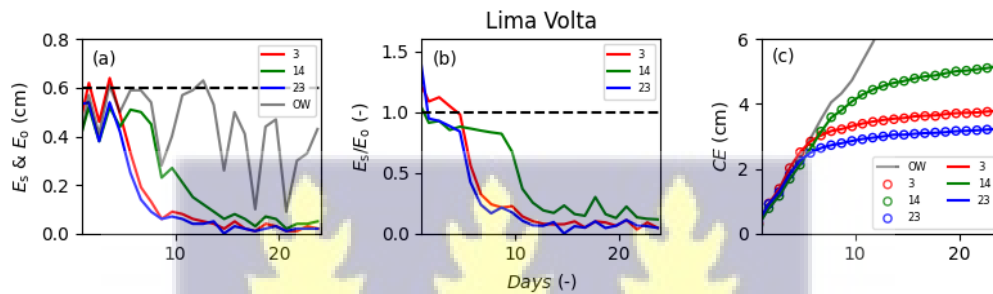


Figure 4. 27 Lima Volta soil series: Daily evaporation rates recorded for soil and open water (left), quotient of soil evaporation (middle) and observed (open circles) and modelled (lines; Hydrus-1D) cumulative potted as a function of days of evaporation.

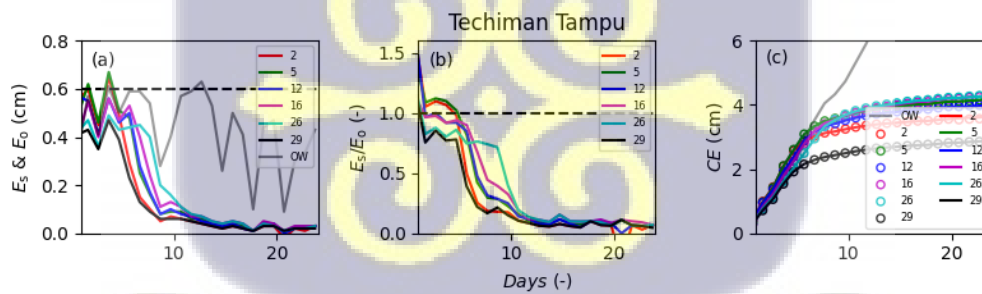


Figure 4. 28 Techiman Tampu: Daily evaporation rates recorded for soil and open water (left), quotient of soil evaporation (middle) and observed (open circles) and modelled (lines; Hydrus-1D) cumulative potted as a function of days of evaporation.

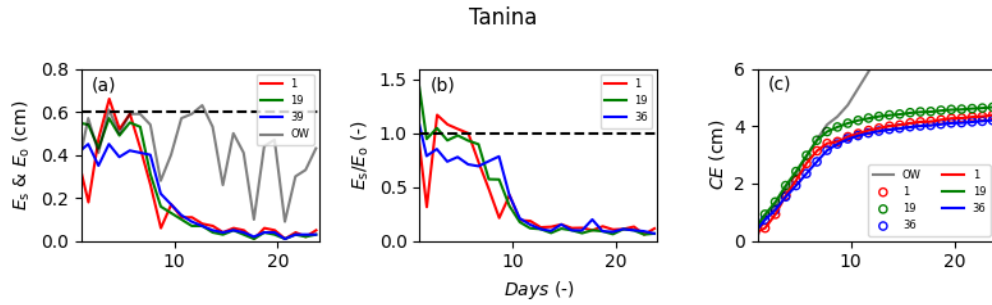


Figure 4. 29 Tanina soil series: Daily evaporation rates recorded for soil and open water (left), quotient of soil evaporation (middle) and observed (open circles) and modelled (lines; Hydrus-1D) cumulative potted as a function of days of evaporation.

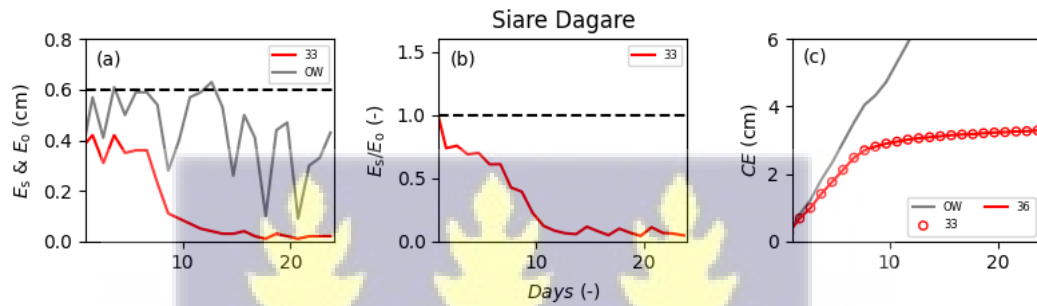


Figure 4. 30 Siare Dagare soil series: Daily evaporation rates recorded for soil and open water (left), quotient of soil evaporation (middle) and observed (open circles) and modelled (lines; Hydrus-1D) cumulative potted as a function of days of evaporation.

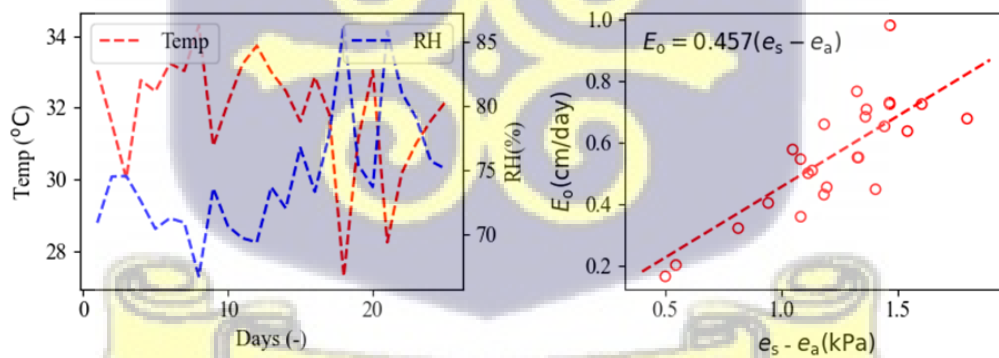


Figure 4. 31 Temperature and relative humidity (a) and correlation between the potential evaporation and vapor pressure deficit (b) in the screenhouse at the Department of Geography & Resource Development at the University of Ghana.

Atmospheric demand was higher at the beginning of the experiment, and this decreased close to the end of the experiment indicated as a downward trend in open water evaporation rate. This trend was also confirmed by the experimental conditions (i.e., temperature and relative humidity) in the screen house (Figure 4.31a). The evaporation process can be partitioned into two periods, stages I and II, given by the departure of soil evaporation rate from open water evaporation rate. Considering the first four to five days of mass loss observation, stage I evaporation ranged from 0.33 to 0.54 cm/day (average value = 0.46 cm/day) whereas stage II evaporation, considering the last 10 days of mass loss observation, ranged from 0.01 to 0.05 cm/day (average value = 0.02 cm/day). The transition time from stage I and II ranged from 2 (Tanchera series) to 9 (Techiman-Tampu) days with an average value of 6 days for the 15 cm column depth. At stage I, evaporation coefficient, ratio of soil evaporation rate to open water evaporation rate, attained close to unity for most cases at stage I and higher or lower than 1 in other cases. Considering the condition of higher atmospheric demand (> 5 mm/day), coarse textured soils with sand content greater than 60% show higher evaporation rate compared to soils with sand content less than 60% (Fig. 4.32). Similar soils also exhibited E_s lower than the situation of low atmospheric demand. If atmospheric demand is high (> 5 mm/day), small grain size promotes a high evaporation rate (as illustrated in Figure 4.32).



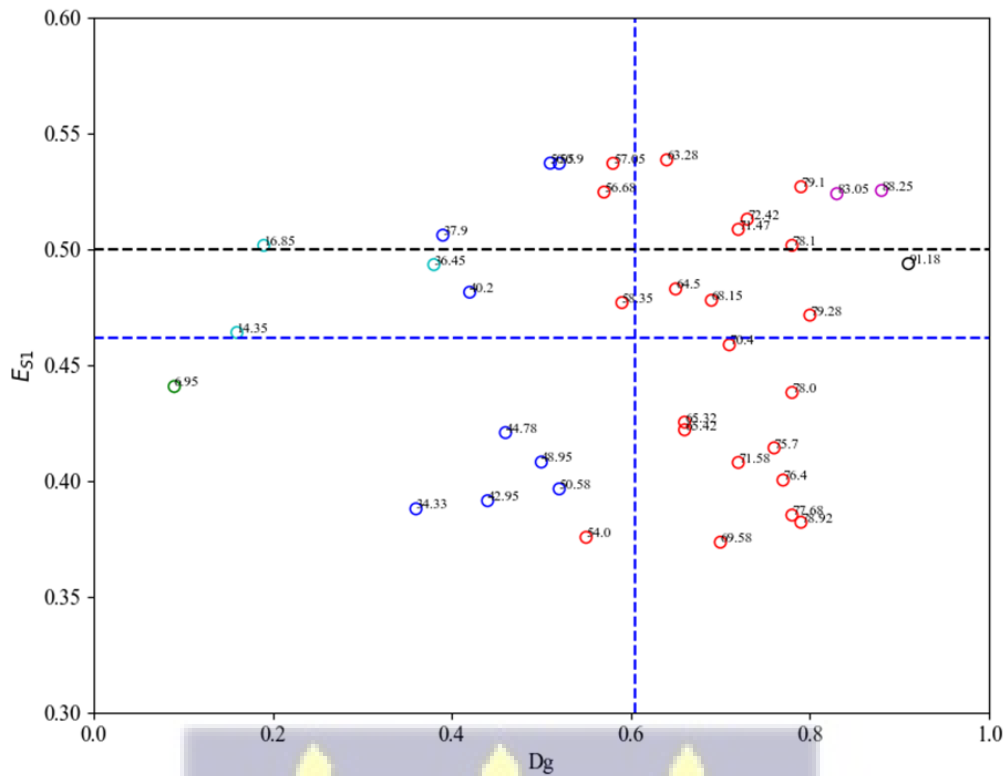


Figure 4. 32 *Evaporation rate at stage II versus mean grain diameter (D_g) of soil (note that the annotation is percent sand content; the black dashed line is atmospheric demand threshold according to Or et al., 2013).*

The evaporation rate at Stage II (E_{S2}) exhibits a distinct inverse relationship with the mean grain diameter (D_g), as shown in Figure 4.33. This indicates that soils with coarser textures, characterized by larger mean grain sizes, tend to have lower E_{S2} values compared to soils with medium to fine textures. Notably, the evaporation rate at Stage II demonstrates a higher sensitivity to grain fraction and texture compared to the evaporation rate at Stage I. This suggests that the texture of the soil plays a more critical role in determining the evaporation rate during Stage II than during Stage I. While soil texture influences both stages of evaporation, its impact is more pronounced during Stage II. In contrast, the dominant factor controlling evaporation rate during Stage I is atmospheric demand.

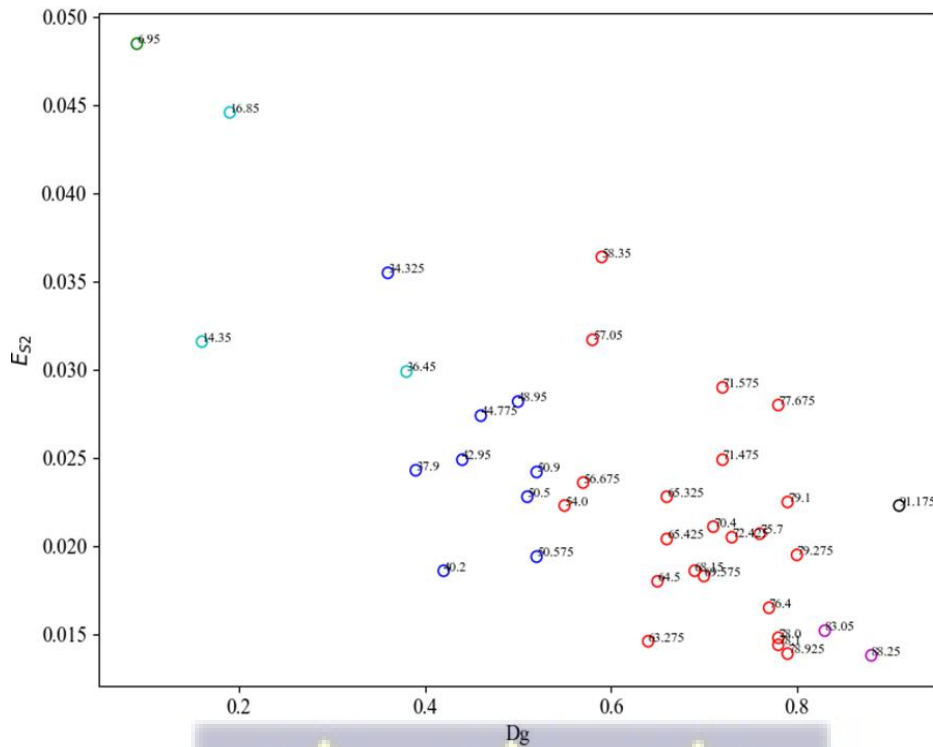


Figure 4. 33 Evaporation rate at stage II versus mean grain diameter (D_g) of soil (note that the annotation is critical moisture content $\theta_{1/2}$).

4.7 Hydrus -1D simulation and soil hydraulic functions

Figures 4.16(c) to 4.30(c) showed plotted cumulative evaporation obtained from experiment and modelled (Hydrus-1D) results as a function of time (days). Overall, Richards' equation in Hydrus 1-D was able to predict cumulative evaporation ($r^2 > 0.98$ in all cases). The derived moisture characteristics and conductivity functions are plotted in Figures 4.34 to 4.48. Though this study did not determine the soil moisture characteristic, nor the entire hydraulic conductivity functions directly, the input of the observed evaporation data into HYDRUS 1-D enables these functions to be derived. The soil moisture characteristics, Figures 4.34(a) to 4.48(a), and conductivity function, Figures 4.34(b) to 4.48(b), differ for the various soils. For example, Tanina series had a high saturated water content of more than $0.55 \text{ cm}^3/\text{cm}^3$, whereas that of Siare-Dagare was only $0.4 \text{ cm}^3/\text{cm}^3$.

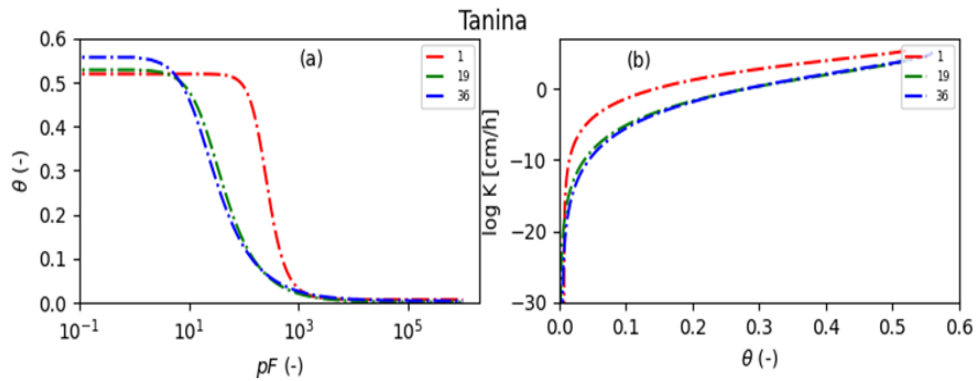


Figure 4. 34 Tanina Soil series: Moisture characteristics (left) and hydraulic conductivity function (right) derived from evaporation measurement.

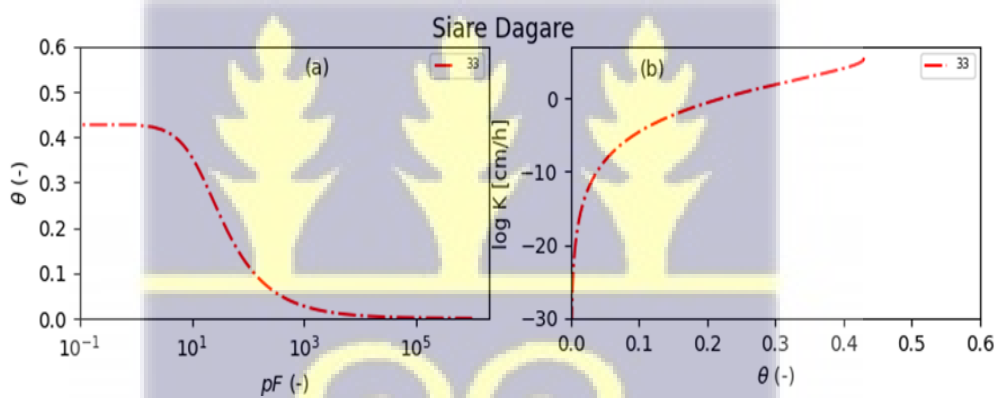


Figure 4. 35 Siare Dagare soil series: Moisture characteristics (left) and hydraulic conductivity function (right) derived from evaporation measurement.

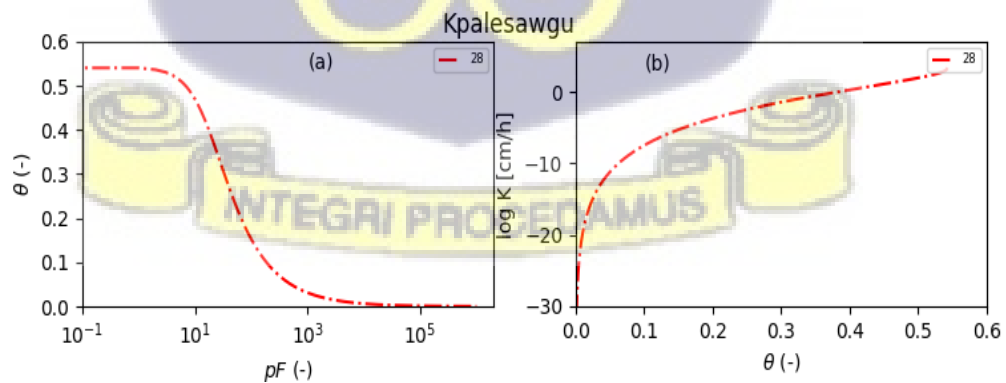


Figure 4. 36 Kpelesawgu soil series: Moisture characteristics (left) and hydraulic conductivity function (right) derived from evaporation measurement.

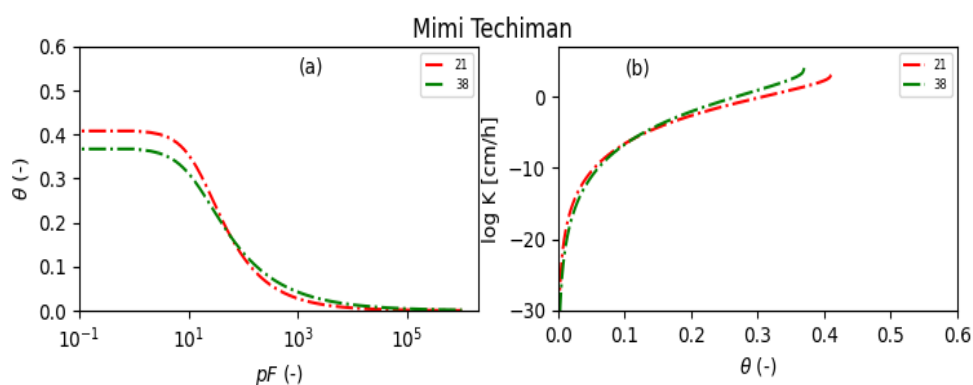


Figure 4.37 Mimi Techiman soil series: Moisture characteristics (left) and hydraulic conductivity function (right) derived from evaporation measurement.

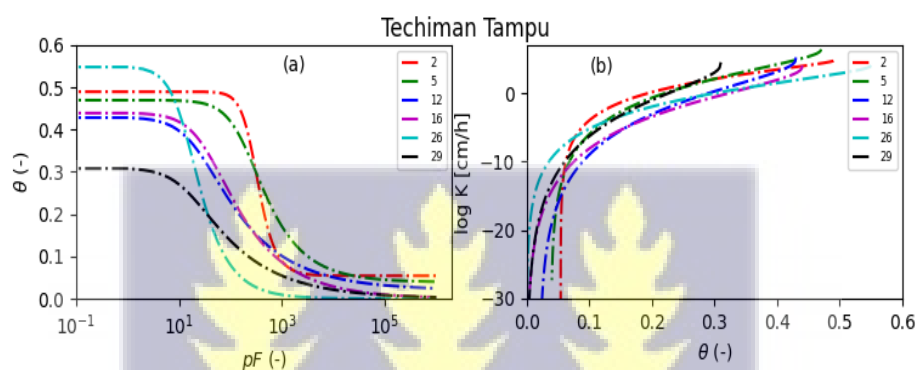


Figure 4.38 Techiman Tampu soil series: Moisture characteristics (left) and hydraulic conductivity function (right) derived from evaporation measurement.

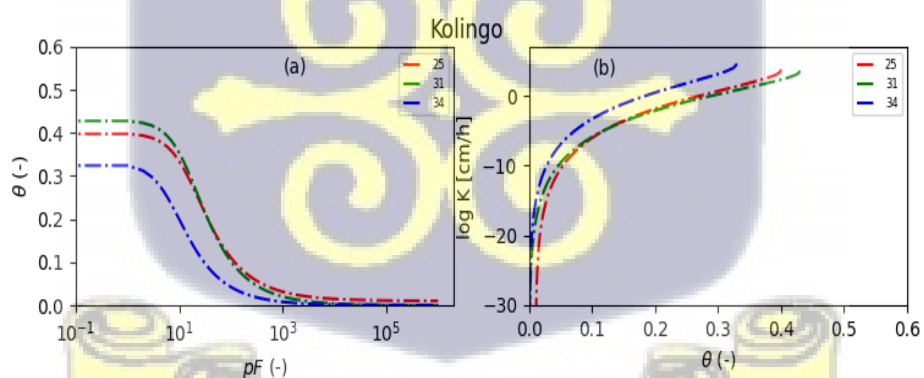


Figure 4.39 Kolingu soil series: Moisture characteristics (left) and hydraulic conductivity function (right) derived from evaporation measurement.

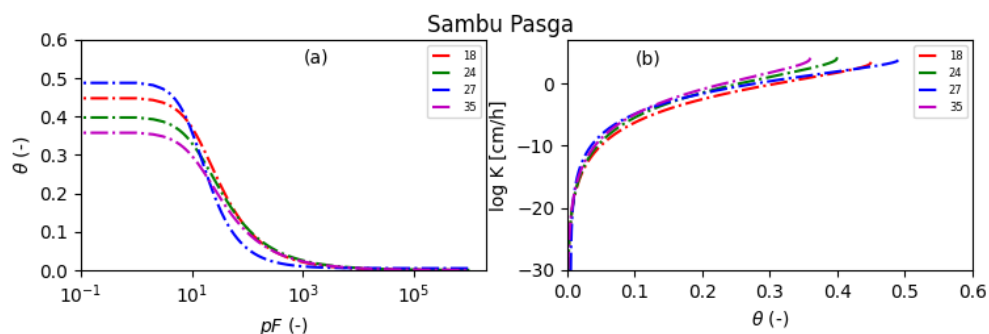


Figure 4.40 Sambu Pasga soil series: Moisture characteristics (left) and hydraulic conductivity function (right) derived from evaporation measurement.

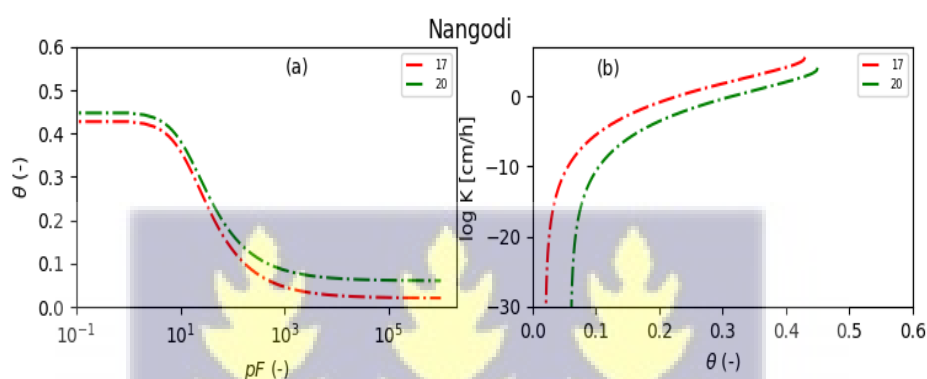


Figure 4.41 Nangodi soil series: Moisture characteristics (left) and hydraulic conductivity function (right) derived from evaporation measurement.

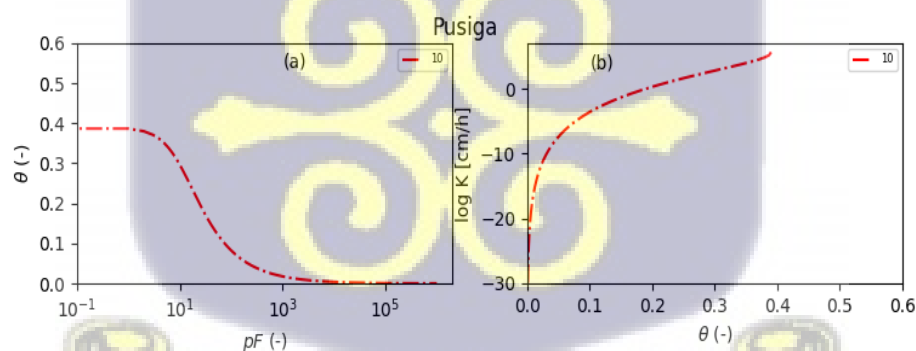


Figure 4.42 Pusiga soil series: Moisture characteristics (left) and hydraulic conductivity function (right) derived from evaporation measurement.

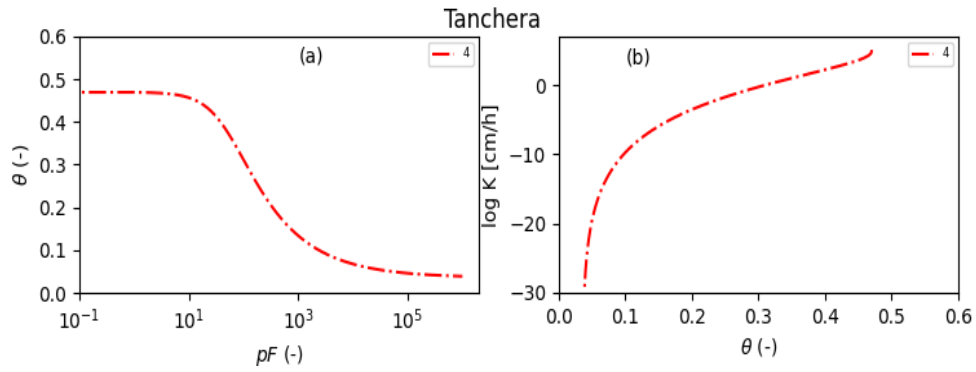


Figure 4.43 Tanchera soil series: Moisture characteristics (left) and hydraulic conductivity function (right) derived from evaporation measurement.

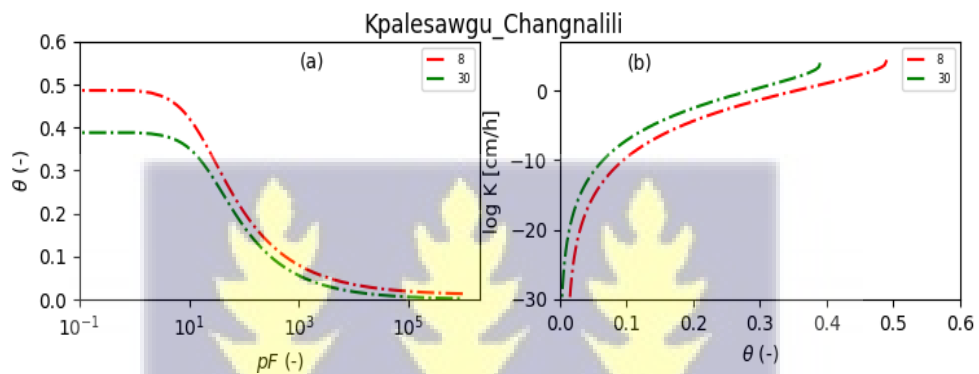


Figure 4.44 Kpalesawgu Changnalili soil series: Moisture characteristics (left) and hydraulic conductivity function (right) derived from evaporation measurement

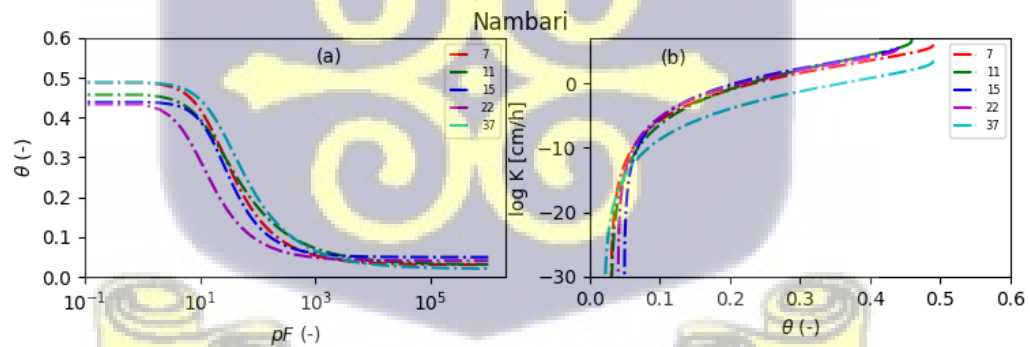


Figure 4.45 Nambari soil series: Moisture characteristics (left) and hydraulic conductivity function (right) derived from evaporation measurement.

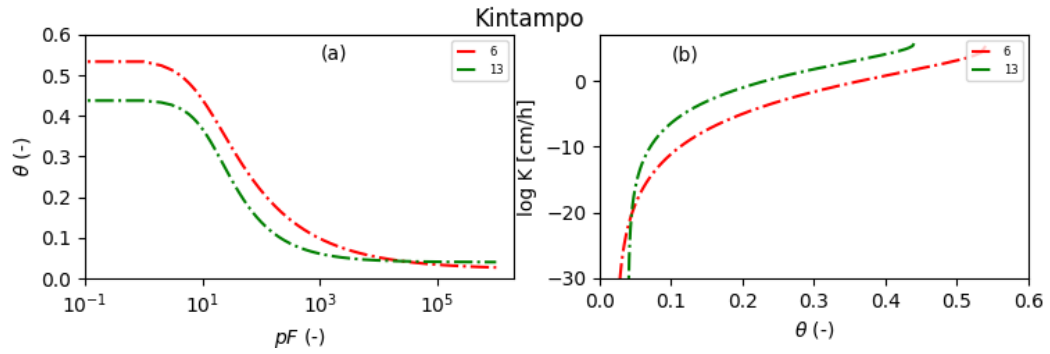


Figure 4.46 Kintampo soil series: Moisture characteristics (left) and hydraulic conductivity function (right) derived from evaporation measurement.

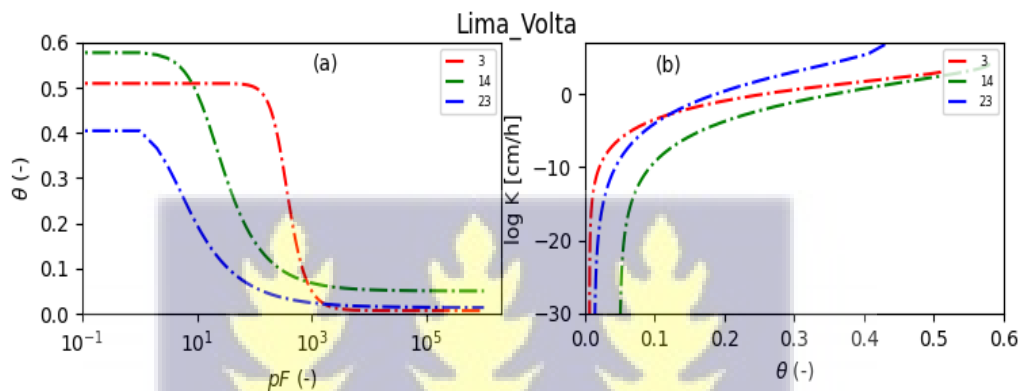


Figure 4.47 Lima Volta soil series: Moisture characteristics (left) and hydraulic conductivity function (right) derived from evaporation measurement.

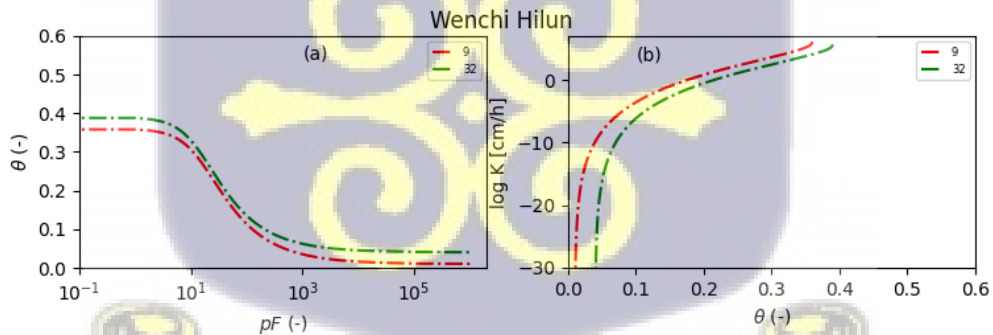
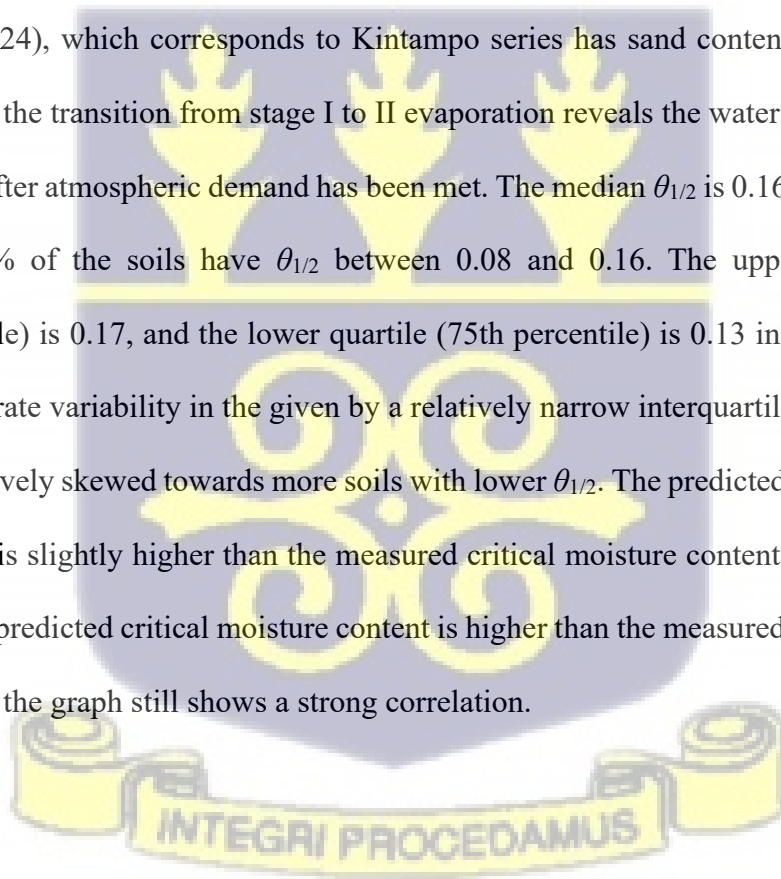


Figure 4.48 Wechi Hilun soil series: Moisture characteristics (left) and hydraulic conductivity function (right) derived from evaporation measurement.

4.8 Critical moisture content ($\theta_{1/2}$)

The critical moisture content ($\theta_{1/2}$) at the transition from stage I to II evaporation is summarised in Figures 4.47. In Figure 4.46(right), the measured $\theta_{1/2}$ is compared with predicted $\theta_{1/2}$ using the pedotransfer function of Merlin et al. (2016). The measured $\theta_{1/2}$ values ranged from 0.08 to 0.24 with an average and a standard deviation of 0.15 and 22.1 respectively. There is substantial variability in among the $\theta_{1/2}$ values and this reflects soil heterogeneity. Generally, coarse grained soils with mean grain diameter greater than 0.6 mm have $\theta_{1/2}$ value less than 0.16 whereas samples with grain diameter less than 0.6 have $\theta_{1/2}$ values greater than 0.16. The lowest $\theta_{1/2}$ (=0.08), which corresponds to Techiman-Tampu soil has sand content of 88.25% whereas the highest $\theta_{1/2}$ (=0.24), which corresponds to Kintampo series has sand content of 6.95 %. The slope of the transition from stage I to II evaporation reveals the water holding capacity of soil after atmospheric demand has been met. The median $\theta_{1/2}$ is 0.16, which indicates that 50% of the soils have $\theta_{1/2}$ between 0.08 and 0.16. The upper quartile (25th percentile) is 0.17, and the lower quartile (75th percentile) is 0.13 indicates that there is moderate variability in the given by a relatively narrow interquartile range. The data is negatively skewed towards more soils with lower $\theta_{1/2}$. The predicted critical moisture content is slightly higher than the measured critical moisture content. Despite the fact that the predicted critical moisture content is higher than the measured critical moisture content, the graph still shows a strong correlation.



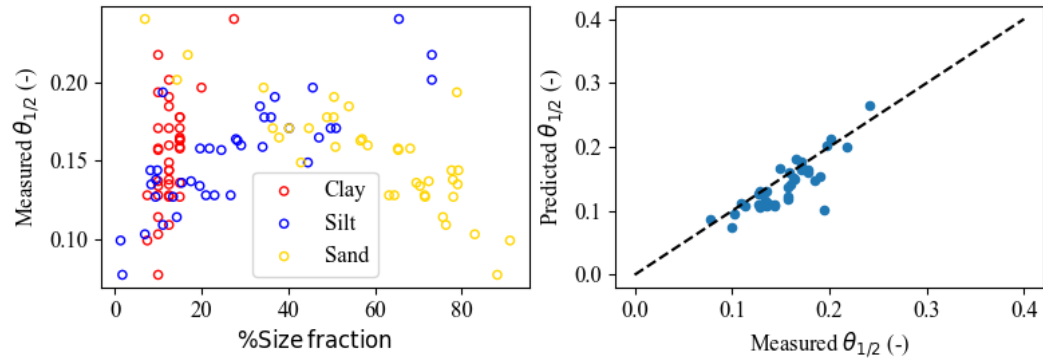


Figure 4.46 Measured $\theta_{1/2}$ versus grain size fraction (%sand, %silt and %clay), versus measured $\theta_{1/2}$ versus predicted $\theta_{1/2}$ (predicted CMC from pedo-transfer function and observed from evaporation curves).

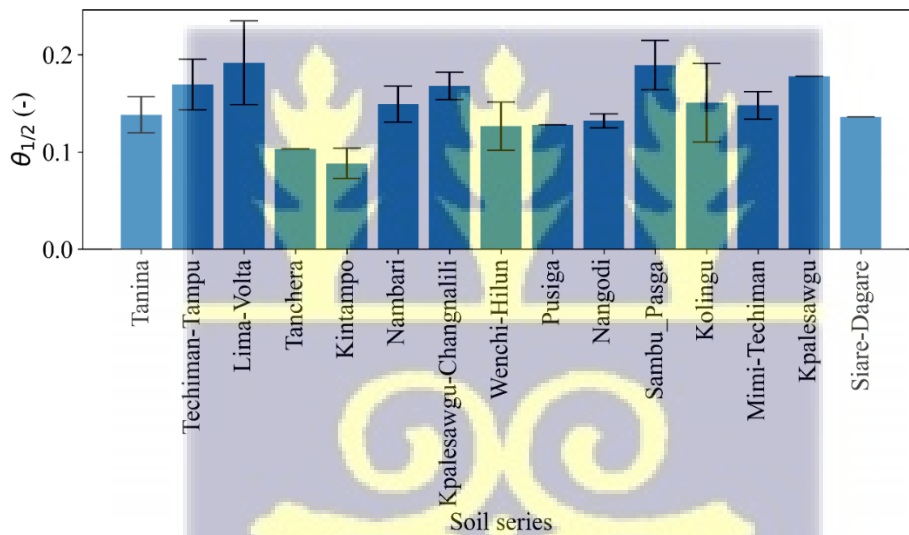


Figure 4.47 Bar chart of critical moisture content of the various soil series of the soil series sampled from the interior savannah zone of Ghana.

4.9 Semi-distributed landscape model

Figures 4.48 to 4.53 present the spatial distributions of key soil physical and hydrological properties that are of particular interest to this study. A closer examination of Figure 4.48 reveals that the bulk density values exhibited a notable spatial variation, with

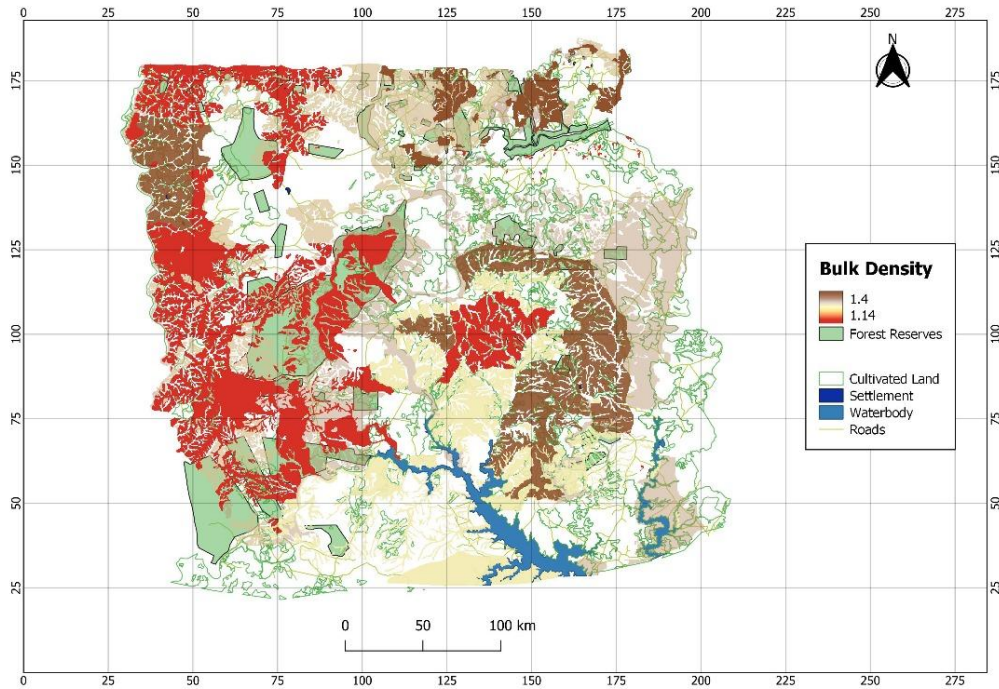


Figure 4.48 A semi distributed landscape model of bulk density of the soil series sampled from the interior savannah zone of Ghana.

significantly higher values observed in the eastern locations compared to western locations. This disparity in bulk density values can be attributed to key landscape processes. Notably, the eastern location is characterized by highlands, whereas the western location is comprised of lowlands. This topographic contrast has significant implications for soil formation and development. Weathering, transportation, and deposition processes occur westward resulting in the deposition of finer materials in the western regions as reflected in the sand (Figure 4.50) and clay (Figure 4.49) content. Consequently, this leads to lower bulk density values in the eastern areas and intermediate to high values in the western regions surrounding the Volta Basin (Figure 4.51). This spatial distribution of bulk density values has important implications for understanding soil physical and hydrological properties, as well as their impact on environmental processes and ecosystem functioning. In Figure 4.52, the spatial distribution of sand and clay content, used as a predictor of $\theta_{1/2}$ is shown.

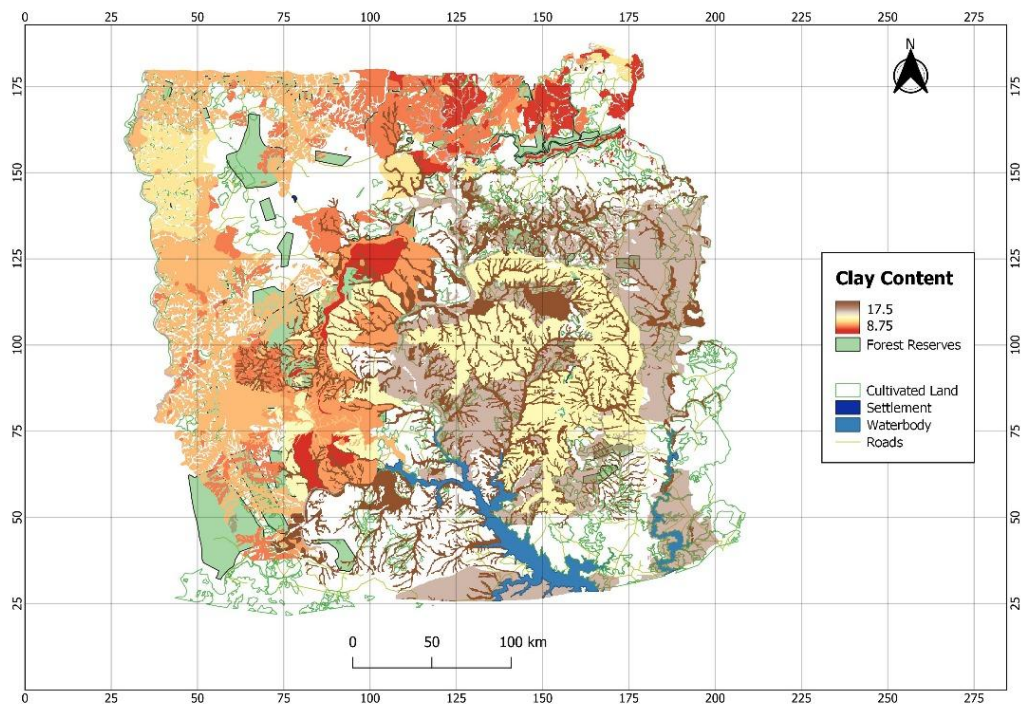


Figure 4. 49 A semi distributed landscape model of clay content of the soil series sampled from the interior savannah zone of Ghana.

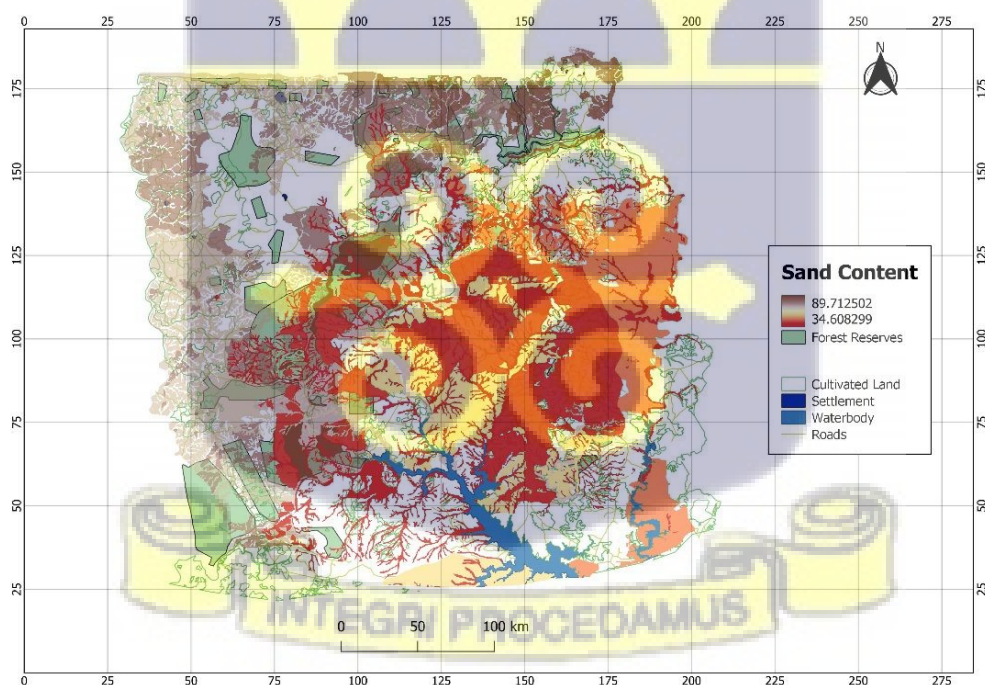


Figure 4. 50 A semi distributed landscape model of sand content of the soil series sampled from the interior savannah zone of Ghana.

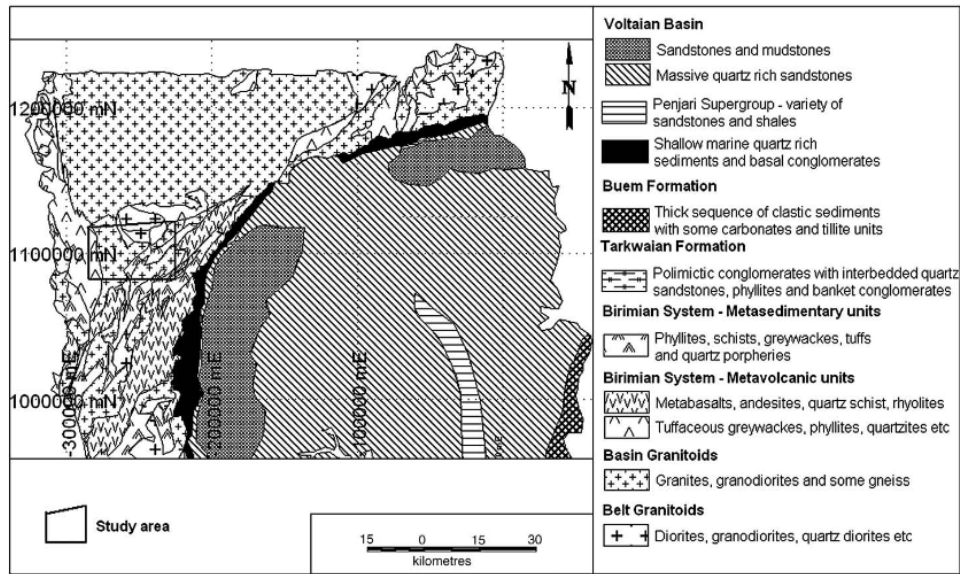


Figure 4. 51 Geological map showing the Northern strip of Ghana (after Nude and Arhin, 2009).

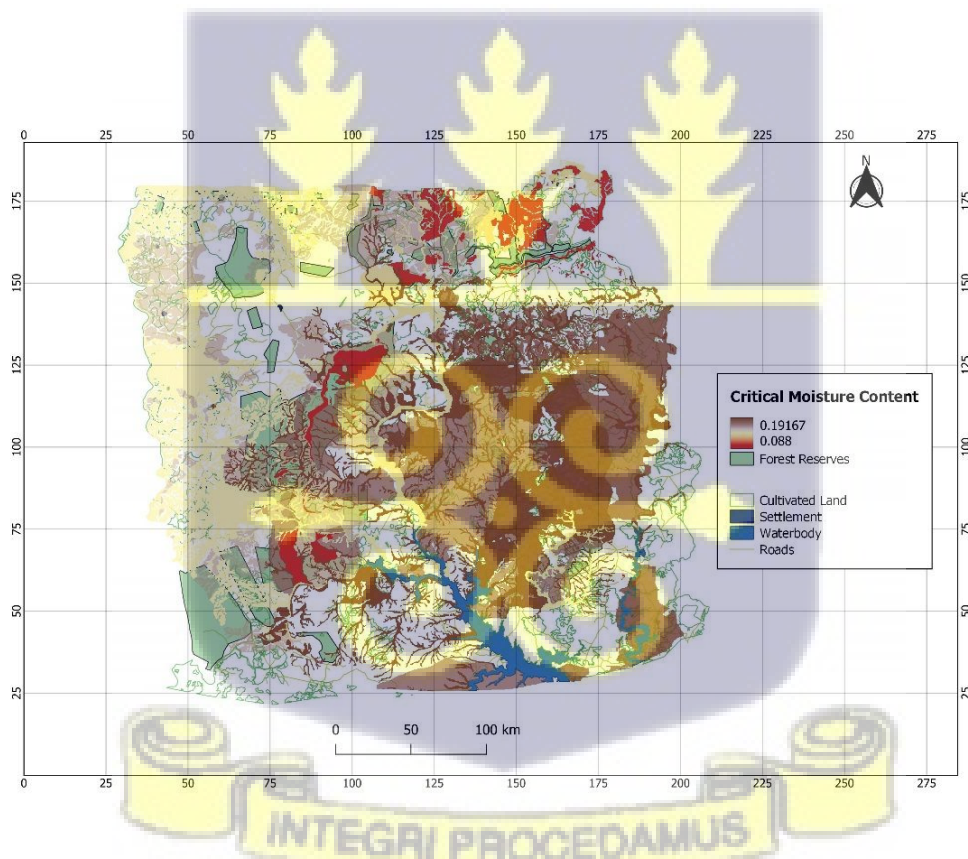


Figure 4. 52 A semi distributed landscape model of the critical moisture content of the soil series sampled from the interior savannah zone of Ghana.

The map shows the critical moisture content of the soil series that were studied in this research. The selected soil series in the northeast region had a lower critical moisture

content than the other regions. This means that those soils will require less volume of water to reach full saturation.

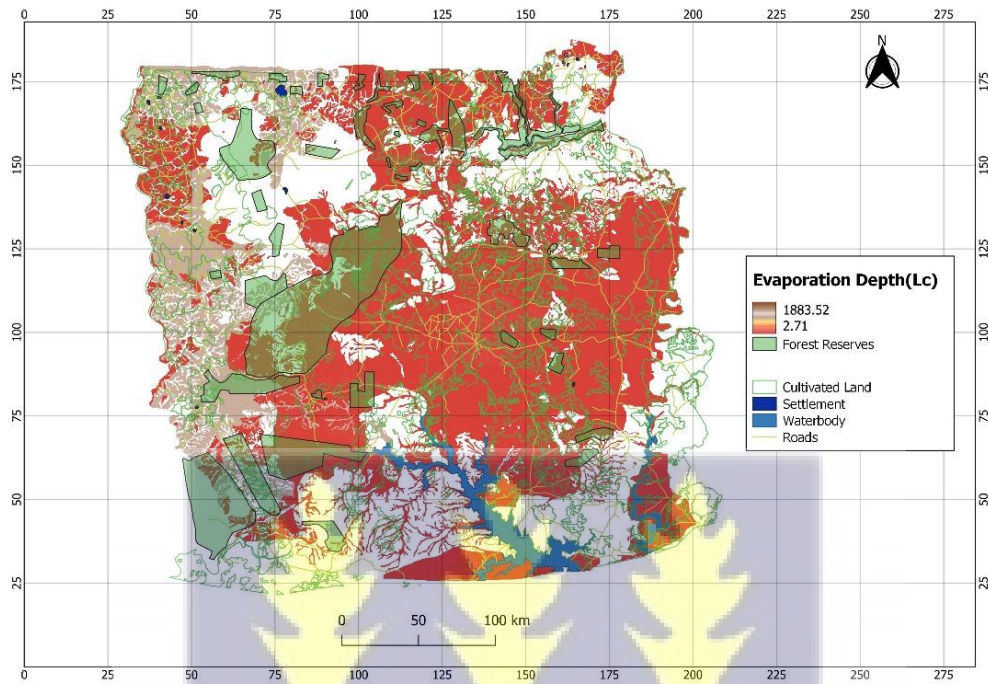


Figure 4. 53 A semi distributed landscape model of the Evaporation Depth of the soil series sampled from the interior savannah zone of Ghana.

CHAPTER FIVE

5.0 DISCUSSIONS

5.1 Weather variability and change

Within the agriculture, climate change and food security nexus, the trends in monthly rainfall distribution, temperature, relative humidity and ET_o (calculated based on the Penman-Monteith equation) have some implications. Firstly, variability in these parameters across the interior savannah zone of Ghana, invoke uncertainties with regards to farmer practices (e.g., choice of planting date), crop production (Baffour-Ata et al., 2021) and livelihood (Asante et al., 2021). The expected soil moisture deficits during certain months of the year (October to May/June) does not support year-round crop produce to meet increasing food demand emphasizing the need for expanding the use of irrigation and water management practices (Faurès et al., 2002; Gondim et al., 2012; Schaldach et al., 2012; Kresovica et al., 2014; Batchelor and Schnetzer, 2018; Awazi, 2022). The overlap in cropping windows and rainfall- ET_o surplus windows suggests that farmers can optimize crop selection, for instance early maturing varieties (Liang et al., 2024), and planting times to coincide with favourable weather conditions for crop production. Meanwhile, changing climate is in terms of increasing air temperature (Klutse et al., 2020) and number of rainy days per year (MacCarthy et al., 2020), an imminent short-duration drought within cropping window highlights the need to develop and extend irrigation facility in the Northern strip of Ghana.

5.2 Soil of the Northern Strip of Ghana

According to Anani et al. (2019), the base geologic of the northern strip (northern interior (Guinea) savannah zone) of Ghana are the Neoproterozoic and early Paleozoic sequences and Archean and Paleoproterozoic (Eburnean) crystalline basement and the Dahomeyide belt. The thirty-eight (38) samples belonging to fifteen (15) soil series (Table), resulting from the weathering of a variety of systems. The diversity of soils underscores the importance of understanding soil characteristics to optimize agricultural practices, improve soil fertility, and promote sustainable land use.

5.3 Soil Properties

5.3.1 Soil Texture

Soil texture influences soil processes including infiltration (Ma et al., 2016), runoff (Jourgholami and Labelle, 2020), and soil water dynamics and storage (Li et al., 2022). Information on soil texture is useful for optimizing agriculture practices, water and nutrient management in soils, and overall soil protection. Soil texture determines crop selection and affects soil productivity (Amsili et al., 2021) and plant growth (Nasir et al., 2024). The soils of the northern strip (northern interior (Guinea) savannah zone), generally sandy loam soils are suitable for various crops, but may require irrigation management due to moderate water-holding capacity (e.g., Fang and Su, 2019). However, some soils within the region are sands and loamy sands which may require more frequent irrigation due to high infiltration rates and low water-holding capacity (Huang and Hartemink, 2021) and loams and silty loams can retain more water, reducing irrigation needs (Burke et al., 1999). Soil texture affects nutrient availability, retention, and leaching (Gaines and Gaines, 1994). Sandy soils may require more frequent fertilization due to high nutrient leaching potential (Chilundo et al., 2018).

Loams and silty loams can retain more nutrients, reducing fertilization needs (Zhou et al., 2017). However, (Gaines and Gaines, 1994) noted that soils with more silt, clay, and organic matter retained more $\text{NO}_3\text{-N}$ than the straight sand. Soil texture affects erodibility and susceptibility to degradation (Wu et al., 2017). Sands and loamy sands are more prone to erosion due to their loose soil. Loams and silty loams are more resistant to erosion but require conservation measures to cushion them against degradation (Zhou et al., 2019). Knowledge of soil texture in general can inform soil-specific agricultural practices in terms of tailored irrigation, soil conservation measures and the application of appropriate soil amendments and fertilization strategies.

5.3.2 Bulk Density

Soil bulk density reflects the degree of soil compaction (e.g., Campbell, 1994) as well as provide information of key landscape processes including weathering, sediment transport and deposition pattern (Willgoose, 2018). In the interior savannah zone of Ghana, the eastward locations are highlands, and the westward locations are lowland. Sediment transports and the expected sedimentary differentiation would therefore follow the topographic gradient were finer materials, with tendency of having higher bulk density, would be deposited westward in the Voltain basin (Figure 4.51). Understanding bulk density variations can inform soil management practices, such as tillage. Soil bulk density affects soil aeration (Khan et al., 2000), water infiltration (Gumbs and Warkentin, 1972), and nutrient availability (Topa et al., 2021), influencing soil fertility and plant growth (Lipiec and Hatano, 2003). Soils with higher bulk densities may be more susceptible to erosion due to increased compaction. Estimation of bulk density at the field scale would greatly improve carbon stock estimates for tropical soils (e.g., Taalab et al., 2013)

5.3.3 Organic Carbon

Soil organic carbon (OC) is a vital component of soil, playing a crucial role in maintaining soil fertility, structure, and overall health, which in turn impacts crop growth and productivity (Rani, 2022). As a key indicator of soil health and resilience, soil OC content influences the soil's ability to resist erosion, compaction, and other forms of degradation. Moreover, soil OC affects water infiltration, retention, and availability, thereby impacting soil water management and irrigation strategies (Karami et al., 2012). Soils with higher OC content tend to have improved water-holding capacity, reducing the need for frequent irrigation, and exhibit enhanced nutrient cycling, availability, and retention, leading to improved soil fertility and plant growth (Karami et al., 2012). The range of OC values (0.3 to 1.85%) underscores the need for tailored conservation and management strategies to restore and protect soil OC. Notably, the low OC status of soil in the Northern strip of Ghana suggests widespread soil degradation (Yiran et al., 2012).

5.3.4 Soil Aggregation

Soil aggregate content is a vital determinant of soil health, structure, and fertility, with significant implications for crop productivity and soil resilience to external factors. Soils with high aggregate content exhibit improved water-holding capacity, aeration, and nutrient retention, fostering plant growth while minimizing erosion and degradation risks (Graber et al., 2006). However, the substantial variability in aggregate content across different soil series underscores the need for tailored conservation and management strategies to preserve and enhance aggregate content. Practices such as conservation tillage, cover cropping, and organic amendments can improve aggregate

content in soils from the Northern strip (northern interior (Guinea) savannah zone) of Ghana.

5.3.5 Porosity

Soil porosity significantly impacts water management decision, irrigation strategies, and soil fertility, affecting plant growth and root development (Gavrilescu, 2021). Soils with higher porosity (e.g., Tanina series) absorb and retain water better, reducing runoff and erosion, while those with lower porosity (e.g., Techiman-Tampu series) may need more frequent irrigation and fertilization due to reduced water-holding capacity and nutrient availability. The moderate variability in porosity (8.04% CV) emphasizes the need for soil-specific management practices to optimize water and nutrient management, with most soils having moderate porosity but some requiring special attention to manage resources effectively.

5.3.6 Saturated Hydraulic Conductivity

The saturated hydraulic conductivity (K_{sat}) values have significant implications for water management and soil hydrology, affecting water infiltration, percolation, runoff, irrigation scheduling, and water conservation (Gupta et al., 2020). Soils with high K_{sat} (e.g., Lima-Volta and Techiman-Tampu series) are expected to have rapid water infiltration, reducing runoff and erosion, whereas soils with low K_{sat} (e.g., Nambari series) are expected to exhibit slower water infiltration, increasing runoff and erosion risk. The K_{sat} value influences soil water storage, groundwater recharge, and soil moisture availability, impacting plant growth and ecosystem functioning. The high variability in K_{sat} (129.3% CV) highlights the need for soil-specific management

practices to optimize water use and reduce environmental impacts. Understanding K_{sat} is crucial for irrigation scheduling, soil conservation, groundwater management, and crop selection.

5.4 Evaporation Studies

The open water evaporation rate changes due to its dependence on the temperature difference between air and water. When air temperature exceeds water temperature (high evaporative demand), evaporation rate increases, and when air temperature is lower, evaporation rate decreases (Finch & Hall, 2001; Penman, 1948). Coarse soils exhibit lower evaporation rates due to their lower surface area-to-volume ratio, resulting in less water exposure to air (Novák, 2012). Conversely, fine soils have higher evaporation rates due to increased capillary conduction and a higher surface area-to-volume ratio, leading to greater water exposure to air (Novák, 2012). When atmospheric demand exceeds 5 mm/day, fine to medium-textured soils experience high evaporation rates (Figure 4.34). This is due to rapid water vapor transport through smaller pores and the strong driving force of high atmospheric demand. Additionally, evaporation rate at Stage II (E_{s2}) is inversely related to mean grain diameter, indicating that coarser soils with larger mean grain diameters have lower E_{s2} than medium to fine-textured soils. This means that as mean grain diameter increases, evaporation rate at Stage II decreases during the contribution of film flow to the overall evaporation process. Notably, evaporation at stage II is more sensitive to grain fraction and texture than at stage I, highlighting the critical role of soil texture in determining evaporation rate during stage II. While soil texture influences both stages, its impact is more pronounced during stage II, whereas atmospheric demand dominates during stage I. This underscores the complex interplay between soil properties and atmospheric conditions in determining

evaporation rates, with different factors assuming greater importance at different stages.

Soil evaporation rates vary greatly depending on atmospheric demand and soil texture

5.5 Model Results

The Hydrus-1D model demonstrates its capability to accurately predict cumulative evaporation and derive soil moisture characteristics and hydraulic conductivity functions through the results presented in Figures 4.16(c) to 4.30(c) and 4.34 to 4.48. This has significant implications for water management and soil protection, enabling informed irrigation scheduling and water conservation strategies. The derived soil moisture characteristics and hydraulic conductivity functions can inform soil-specific water management practices, highlighting the importance of soil-specific management due to variability within and between soil series. Understanding these functions can also inform strategies to reduce soil erosion and waterlogging, and derived van Genuchten parameters can calculate drying front depth, informing soil conservation practices. The Hydrus-1D model is a valuable tool for predicting cumulative evaporation and deriving soil moisture characteristics and hydraulic conductivity functions, which can be used to develop soil-specific management practices to reduce soil degradation and promote soil health.

5.6 Critical water content, evaporation length and distributed landscape model

The critical moisture content ($\theta_{1/2}$) is a key factor in water management and soil protection, marking the transition from stage I to II evaporation (Merlin et al., 2016; Lehman et al., 2018) and indicating soil water-holding capacity. Soils with high sand content tend to have lower $\theta_{1/2}$ values, requiring more frequent irrigation due to reduced

water retention. Soil heterogeneity is reflected in varying $\theta_{1/2}$ emphasizing the need for soil-specific moisture management. Soils with higher $\theta_{1/2}$ values have better water-holding capacity, reducing erosion and waterlogging risks. Measured and predicted $\theta_{1/2}$ values show a strong correlation, despite some variability. Moderate variability in $\theta_{1/2}$ values among soils highlights the need for soil-specific management. By understanding $\theta_{1/2}$ values, farmers and agricultural managers can develop targeted strategies to optimize water use, reduce soil evaporation, and promote soil protection. Figures 4.51-4.56 show the spatial distribution of key soil physical and hydrological properties. Figure 4.51 reveals significant spatial variation in bulk density, with higher values in eastern highland areas and lower values in western lowland areas. This disparity is attributed to landscape features, weathering, transportation, and deposition processes, which have shaped the region's soil formation and development. The eastern highlands have coarser soils with higher bulk density, while the western lowlands have finer soils with lower bulk density due to the deposition of finer materials. This spatial distribution has important implications for understanding soil properties and their impact on the environment and ecosystem functioning. Soil texture plays a crucial role in determining bulk density, with coarser soils having higher bulk density due to larger particle size and lower porosity, and finer soils having lower bulk density due to smaller particle size and higher porosity. The relationship between soil texture and bulk density is essential for understanding soil physical and hydrological properties and their impact on the environment.

The study area's soils are predominantly sandy loam in texture, which significantly influences bulk density. Coarser soils, like sandy soils, typically have higher bulk density values due to their larger particle size and lower porosity. In contrast, finer soils

like clayey soils have lower bulk density values due to their smaller particle size and higher porosity. The spatial distribution of texture (% sand and % clay) values in the region correlates with bulk density. Highland eastern locations have coarser soils and higher bulk density values, while lowland western locations receive finer materials through weathering, transportation, and deposition, resulting in lower bulk density values. The predicted critical water content (based on texture) and predicted evaporation depth (based on van Genuchten n and α values, evaporation rate at stage I, and K_{sat}) show a notable relationship. Figure 4.56 illustrates that the evaporation depth is low in the northeast regions, while the western locations, particularly in the Volta Basin, have shallow evaporation depths due to finer materials. In contrast, the eastern location, characterized by coarser materials, exhibits deeper evaporation depths. This evaporation depth pattern is attributed to several factors such as lower air entry value in coarse materials compared to fine materials, rapid displacement of drying front in coarse materials than fine materials, higher capillary conduction in fine materials compared to coarse materials and lower conductivity of fine materials compared to coarse materials especially in the dryer region of the moisture release function. The soil evaporative depth is also influenced by factors such as soil texture, mineralogy, bulk density, and water content conditions (An et al., 2018). The high sand content by soils in the interior savannah of Ghana, especially with soils in the northeastern part, can be a reason for the low evaporation depth. Soil texture is a major factor that influences the evaporative depth of soil. Soil with finer texture has a lower evaporative depth than soil with coarser texture (Yost & Hartemink, 2019). The evaporative depth determines the extent of the hydraulically connected region between the receding drying front and evaporating surface (Lehman et al., 2018). Understanding soil evaporation depth and characteristic length is essential for effective water management and soil protection.

Knowledge of evaporation depth helps in designing efficient irrigation schedules, ensuring water is applied when and where it is needed most. Also, farmers can predict when the soil will transition from Stage I to Stage II evaporation, allowing for better moisture management. Proper management of soil moisture and evaporation can reduce the risk of erosion and waterlogging, promoting healthier soil and better crop yields.



CHAPTER SIX

6.0 CONCLUSION AND RECOMMENDATION

Measuring bare soil evaporation offers numerous benefits for agricultural productivity and water efficiency. Accurate measurements of soil evaporation rates provide farmers with valuable insights into their field's water balance, facilitating informed decisions on irrigation scheduling, crop management, and resource allocation. By quantifying atmospheric water loss, farmers can adjust their irrigation plans to minimize waste and maximize yields. Additionally, identifying areas with high water loss enables targeted interventions, such as supplementary irrigation or tailored management practices, to optimize crop growth and reduce water consumption.

Regarding objective 1 of this study which seeks to investigate the effect of different soil types on the evaporation of bare soils obtained from the northern strip (northern interior (Guinea) savannah zone) of Ghana. This study revealed substantial variability in soil properties across cultivated fields in Ghana's interior Savannah zone, shedding light on the complex interplay of factors influencing soil evaporation. The research revealed that both exogenous factors, such as atmospheric conditions, and endogenous properties of the soil itself, significantly impact the evaporation process. Notably, two key endogenous parameters emerged as critical controllers of evaporation: soil texture and bulk density. Soil texture plays a pivotal role in regulating evaporation behavior, primarily through its influence on critical moisture content. This critical threshold governs the transition from Stage I to Stage II evaporation, where the rate of evaporation shifts from being energy-limited to vapor diffusion-limited. Specifically, soils with varying textures exhibit distinct critical moisture contents, affecting the onset

and progression of evaporation. Bulk density, another essential endogenous factor, affects evaporation by influencing total porosity and, subsequently, the overall cumulative evaporated water. Soils with higher bulk densities tend to have reduced porosity, limiting water movement and evaporation. Conversely, soils with lower bulk densities exhibit increased porosity, facilitating water transport and elevating evaporation rates. The relationships between soil texture, bulk density, and evaporation underscore the importance of considering these endogenous properties in agricultural management and irrigation strategies, particularly in regions with diverse soil characteristics like Ghana's interior Savannah zone.

Regarding objective 2 of this study which seeks to derive the cumulative water characteristics (CWCs) and critical water content (θ_{crit}) as basis of assessing the texture effect on soil evaporation. Based on cumulative water characteristic of soils investigated, and linear piecewise fitting, Merlin et al. (2016) based on soil texture proved to be a robust descriptor of θ_{crit} which is the transition from stage I to stage II evaporation.

Regarding objective 3 of this study which seeks to validate the Hydrus 1-D model for simulating the evaporation of the bare soils. Richards' equation implemented in Hydrus-1D model demonstrated its capability to accurately predict cumulative evaporation and derive soil moisture characteristics and hydraulic conductivity function. However, measured hydraulic properties of these soils are required for validation.

Regarding objective four (4) of this study which seeks to develop a bare soil evaporation map for the northern strip (northern interior (Guinea) savannah zone) of Ghana. GIS techniques can be used to generate a landscape model, which will aid land users make informed water management decisions in cultivated soils in the interior savannah zone of Ghana. This has been demonstrated for key soil properties and state variable such as evaporation depth.

To optimize water use and promote soil protection, it's crucial to develop soil-specific management practices that cater to the unique properties of each soil type. This approach will help reduce soil evaporation, mitigate soil erosion, and promote sustainable water management practices. This study recommends a century old practice “mulching” for water conservation and organic fertilization to boost the organic carbon levels of the soils that are low in soil organic carbon. These simple yet effective strategies can significantly enhance soil health and resilience against short duration droughts that soil on the northern strip (northern interior (Guinea) savannah zone) are faced with. Further to this study, the following are recommended: (1) expanding soil sampling to refine the resolution of the soil property and evaporation maps, (2) characterization of the hydraulic properties of these soils which are lacking as a basis for a more detailed modelling study.



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APPENDICES

Appendix A: Selected soil properties analysis

Appendix 1: Measured bulk density, organic carbon, moisture content and aggregate content.

Administrative ID	Soil Series	Organic Carbon(g/kg)	Bulk Density(g/cm ³)
1	Tanina	0.79	1.29
19	Tanina	0.79	1.25
36	Tanina	0.90	0.94
2	Techiman - Tampu	0.67	1.36
5	Techiman - Tampu	0.43	1.32
12	Techiman - Tampu	0.51	1.28
16	Techiman - Tampu	0.52	1.30
26	Techiman - Tampu	0.59	1.13
29	Techiman - Tampu	0.67	1.60
3	Lima-Volta	1.85	1.30
14	Lima-Volta	1.32	1.21
23	Lima-Volta	0.76	1.33
4	Tanchera	0.33	1.40

6	Kintampo	0.67	1.22
13	Kintampo	0.47	1.29
7	Nambari	1.12	1.15
11	Nambari	0.61	1.33
15	Nambari	0.64	1.32
22	Nambari	0.73	1.18
37	Nambari	0.82	1.19
8	Kpelesaw gu- Changnali li	1.03	1.22
30	Kpelesaw gu- Changnali li	0.57	1.35
9	Wenchi- Hilun	0.95	1.34
32	Wenchi- Hilun	0.63	1.43
10	Pusiga	0.52	1.29
17	Nangodi	0.68	1.28
20	Nangodi	0.56	1.35
18	Sambu- Pasga	0.49	1.32
24	Sambu- Pasga	0.30	1.35
27	Sambu- Pasga	0.92	1.35
35	Sambu- Pasga	0.59	1.48
25	Kolingu	0.67	1.23

31	Kolingu	0.62	1.25
34	Kolingu	0.35	1.41
21	Mimi-Techiman	0.79	1.22
38	Mimi-Techiman	0.39	1.38
28	Kpelesawgu	0.74	1.30
33	Siare-Dagare	0.69	1.30



Appendix 2: Measured soil moisture content and aggregate content

Administrative ID	Soil Series	Moisture Content (%)	Aggregate Content (%)
1	Tanina	1.21	1.60
19	Tanina	0.48	2.92
36	Tanina	1.03	23.02
2	Techiman - Tampu	0.66	17.78
5	Techiman - Tampu	0.38	1.58
12	Techiman - Tampu	1.00	24.26
16	Techiman - Tampu	11.48	1.44
26	Techiman - Tampu	0.40	7.00
29	Techiman - Tampu	1.05	39.68
3	Lima-Volta	1.17	9.98
14	Lima-Volta	6.33	0.98
23	Lima-Volta	0.75	33.22
4	Tanchera	0.37	30.60
6	Kintampo	0.37	2.68
13	Kintampo	0.37	1.82
7	Nambari	0.49	25.48
11	Nambari	0.77	0.96
15	Nambari	0.59	9.80
22	Nambari	0.57	1.40
37	Nambari	0.58	2.30

8	Kpelesawgu- Changnalili	0.65	10.22
30	Kpelesawgu- Changnalili	1.33	22.58
9	Wenchi- Hilun	0.73	51.30
32	Wenchi- Hilun	1.03	32.80
10	Pusiga	0.47	2.10
17	Nangodi	0.47	0.98
20	Nangodi	1.30	13.18
18	Sambu- Pasga	0.35	0.50
24	Sambu- Pasga	1.02	32.78
27	Sambu- Pasga	1.21	21.74
35	Sambu- Pasga	1.13	38.54
25	Kolingu	0.31	1.40
31	Kolingu	0.29	3.62
34	Kolingu	0.23	5.40
21	Mimi- Techiman	0.41	4.20
38	Mimi- Techiman	0.66	3.00
28	Kpelesawgu	1.02	13.62
33	Siare-Dagare	0.60	52.60

Appendix 3: Particle size distribution

Administrative ID	Soil Series	Porosity(%)	Field Capacity (%)
1	Tanina	52.00	16.26
19	Tanina	53.00	15.52
36	Tanina	65.00	19.26
2	Techiman - Tampu	49.00	17.14
5	Techiman - Tampu	50.00	17.08
12	Techiman - Tampu	52.00	13.99
16	Techiman - Tampu	55.00	18.05
26	Techiman - Tampu	58.00	17.03
29	Techiman - Tampu	40.00	14.45
3	Lima-Volta	51.00	18.77
14	Lima-Volta	57.00	20.70
23	Lima-Volta	50.00	14.95
4	Tanchera	47.00	12.69
6	Kintampo	54.00	16.70
13	Kintampo	51.00	15.65
7	Nambari	57.00	18.47
11	Nambari	50.00	14.04
15	Nambari	50.00	15.40
22	Nambari	56.00	18.44
37	Nambari	56.00	16.04
8	Kpelesawgu - Changnalili	54.00	20.22

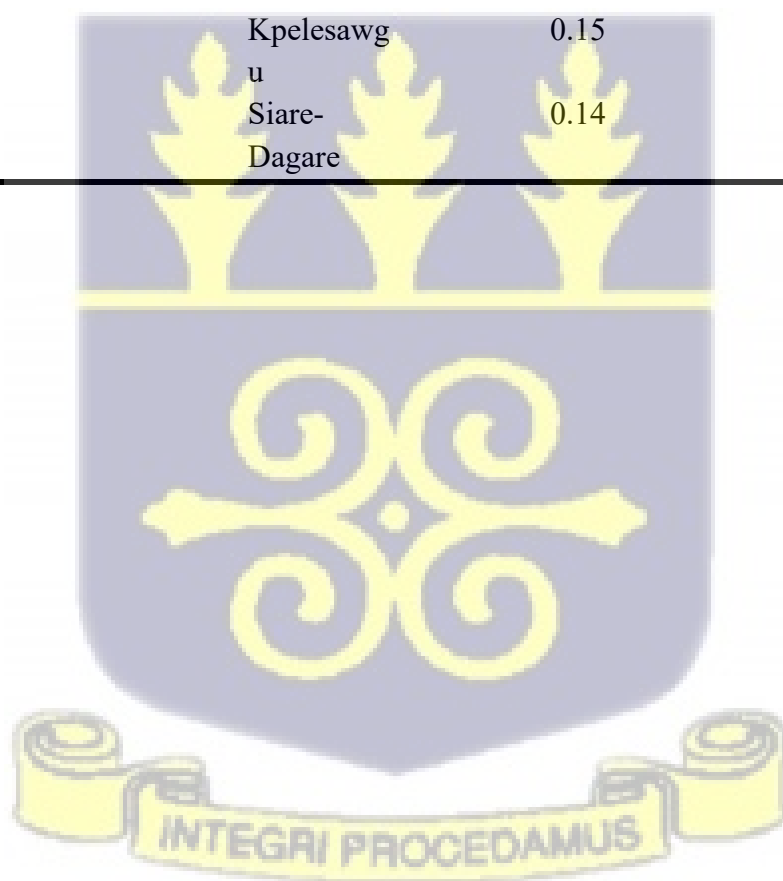
30	Kpelesawgu	50.00	17.33
	-		
	Changnalili		
9	Wenchi-	50.00	12.55
	Hilun		
32	Wenchi-	46.00	13.68
	Hilun		
10	Pusiga	52.00	13.82
17	Nangodi	52.00	14.16
20	Nangodi	50.00	17.96
18	Sambu-	50.00	16.97
	Pasga		
24	Sambu-	50.00	16.46
	Pasga		
27	Sambu-	49.00	22.71
	Pasga		
35	Sambu-	45.00	16.66
	Pasga		
25	Kolingu	54.00	16.52
31	Kolingu	53.00	16.27
34	Kolingu	53.00	11.91
21	Mimi-	54.00	17.28
	Techiman		
38	Mimi-	48.00	16.04
	Techiman		
28	Kpelesawgu	51.00	18.95
33	Siare-	51.00	14.24
	Dagare		



Appendix 3: Measured critical content and evaporation depth.

Administrative ID	Soil Series	Critical Moisture Content	Evaporation Depth
1	Tanina	0.16	1.95
19	Tanina	0.13	0.03
36	Tanina	0.16	0.11
2	Techiman - Tampu	0.10	0.61
5	Techiman - Tampu	0.16	4.36
12	Techiman - Tampu	0.08	0.13
16	Techiman - Tampu	0.16	0.53
26	Techiman - Tampu	0.18	0.61
29	Techiman - Tampu	0.14	0.61
3	Lima-Volta	0.14	0.02
14	Lima-Volta	0.13	0.51
23	Lima-Volta	0.17	0.61
4	Tanchera	0.10	18.03
6	Kintampo	0.24	0.00
13	Kintampo	0.17	0.01
7	Nambari	0.20	0.68
11	Nambari	0.13	0.09
15	Nambari	0.22	0.46
22	Nambari	0.13	0.61
37	Nambari	0.14	0.04
8	Kpelesawg u- Changnalili	0.16	0.42
30	Kpelesawg u- Changnalili	0.13	0.25
9	Wenchi- Hilun	0.17	1.94
32	Wenchi- Hilun	0.16	0.04
10	Pusiga	0.11	0.60

17	Nangodi	0.17	0.37
20	Nangodi	0.20	0.01
18	Sambu- Pasga	0.18	0.93
24	Sambu- Pasga	0.19	0.61
27	Sambu- Pasga	0.16	0.61
35	Sambu- Pasga	0.14	2.33
25	Kolingu	0.11	0.61
31	Kolingu	0.14	0.19
34	Kolingu	0.19	1.75
21	Mimi- Techiman	0.19	0.61
38	Mimi- Techiman	0.13	0.41
28	Kpelesawg u	0.15	0.61
33	Siare- Dagare	0.14	0.46

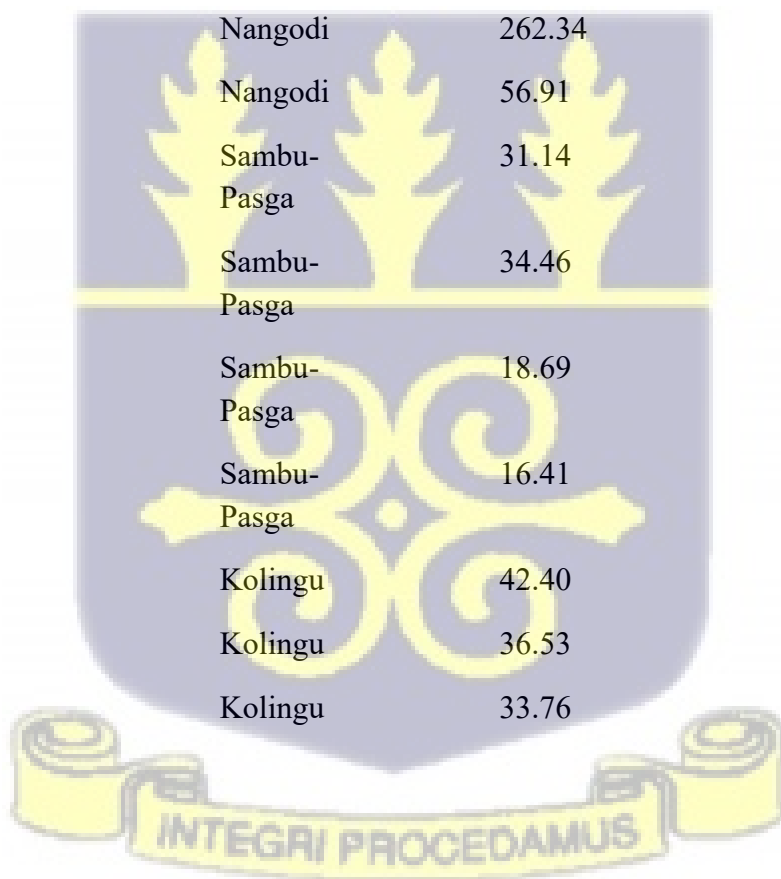


Administrative ID	Soil Series	Silt(%)	Sand(%)	Clay(%)	Critical Moisture Content	Evaporation Depth
1	Tanina	29.15	58.35	12.50	0.16	1.95
19	Tanina	21.03	71.48	7.50	0.13	0.03
36	Tanina	13.43	71.58	15.00	0.16	0.11
2	Techiman - Tampu	26.73	63.28	10.00	0.10	0.61
5	Techiman - Tampu	34.10	50.90	15.00	0.16	4.36
12	Techiman - Tampu	47.10	37.90	15.00	0.08	0.13
16	Techiman - Tampu	73.15	14.35	12.50	0.16	0.53
26	Techiman - Tampu	40.23	44.78	15.00	0.18	0.61
29	Techiman - Tampu	36.93	50.58	12.50	0.14	0.61
3	Lima-Volta	28.33	56.68	15.00	0.14	0.02
14	Lima-Volta	65.55	6.95	27.50	0.13	0.51
23	Lima-Volta	49.80	40.20	10.00	0.17	0.61
4	Tanchera	6.95	83.05	10.00	0.10	18.03
6	Kintampo	1.75	88.25	10.00	0.24	0.00
13	Kintampo	1.33	91.18	7.50	0.17	0.01
7	Nambari	27.95	57.05	15.00	0.20	0.68
11	Nambari	23.00	64.50	12.50	0.13	0.09
15	Nambari	51.05	36.45	12.50	0.22	0.46
22	Nambari	19.60	70.40	10.00	0.13	0.61
37	Nambari	44.55	42.95	12.50	0.14	0.04
8	Kpelesawgu-Changnalili	34.50	50.50	15.00	0.16	0.42
30	Kpelesawgu-Changnalili	19.68	65.33	15.00	0.13	0.25
9	Wenchi-Hilun	8.22	79.28	12.50	0.17	1.94
32	Wenchi-Hilun	11.10	76.40	12.50	0.16	0.04
10	Pusiga	8.40	79.10	12.50	0.11	0.60
17	Nangodi	9.40	78.10	12.50	0.17	0.37
20	Nangodi	17.58	72.43	10.00	0.20	0.01
18	Sambu- Pasga	73.15	16.85	10.00	0.18	0.93
24	Sambu- Pasga	24.58	65.43	10.00	0.19	0.61
27	Sambu- Pasga	45.68	34.33	20.00	0.16	0.61
35	Sambu- Pasga	33.50	54.00	12.50	0.14	2.33
25	Kolingu	14.30	75.70	10.00	0.11	0.61
31	Kolingu	9.82	77.68	12.50	0.14	0.19
34	Kolingu	11.08	78.93	10.00	0.19	1.75
21	Mimi- Techiman	21.85	68.15	10.00	0.19	0.61
38	Mimi- Techiman	9.50	78.00	12.50	0.13	0.41
28	Kpelesawgu	36.05	48.95	15.00	0.15	0.61
33	Siare-Dagare	15.43	69.58	15.00	0.14	0.46

Appendix 4: Measured Hydraulic conductivity and Silt content

Administrative ID	Soil Series	Hydraulic Conductivity(cm/day)	Silt(%)
1	Tanina	209.84	29.15
19	Tanina	86.10	21.03
36	Tanina	172.25	13.43
2	Techiman - Tampu	113.91	26.73
5	Techiman - Tampu	608.60	34.10
12	Techiman - Tampu	183.07	47.10
16	Techiman - Tampu	15.25	73.15
26	Techiman - Tampu	56.89	40.23
29	Techiman - Tampu	14.20	36.93
3	Lima-Volta	44.41	28.33
14	Lima-Volta	32.60	65.55
23	Lima-Volta	866.55	49.80
4	Tanchera	158.66	6.95
6	Kintampo	200.53	1.75
13	Kintampo	296.30	1.33
7	Nambari	398.53	27.95
11	Nambari	886.51	23.00
15	Nambari	269.84	51.05
22	Nambari	8.73	19.60

37	Nambari	33.44	44.55
8	Kpelesaw gu- Changnali li	38.14	34.50
30	Kpelesaw gu- Changnali li	31.00	19.68
9	Wenchi- Hilun	443.57	8.22
32	Wenchi- Hilun	290.40	11.10
10	Pusiga	96.59	8.40
17	Nangodi	262.34	9.40
20	Nangodi	56.91	17.58
18	Sambu- Pasga	31.14	73.15
24	Sambu- Pasga	34.46	24.58
27	Sambu- Pasga	18.69	45.68
35	Sambu- Pasga	16.41	33.50
25	Kolingu	42.40	14.30
31	Kolingu	36.53	9.82
34	Kolingu	33.76	11.08
21	Mimi- Techiman	21.45	21.85
38	Mimi- Techiman	54.51	9.50



28	Kpelesaw gu	28.63	36.05
33	Siare- Dagare	240.01	15.43



Appendix: Measured Sand and clay content.

Administrative ID	Soil Series	Sand(%)	Clay(%)
1	Tanina	58.35	12.50
19	Tanina	71.48	7.50
36	Tanina	71.58	15.00
2	Techiman - Tampu	63.28	10.00
5	Techiman - Tampu	50.90	15.00
12	Techiman - Tampu	37.90	15.00
16	Techiman - Tampu	14.35	12.50
26	Techiman - Tampu	44.78	15.00
29	Techiman - Tampu	50.58	12.50
3	Lima-Volta	56.68	15.00
14	Lima-Volta	6.95	27.50
23	Lima-Volta	40.20	10.00
4	Tanchera	83.05	10.00
6	Kintampo	88.25	10.00
13	Kintampo	91.18	7.50
7	Nambari	57.05	15.00
11	Nambari	64.50	12.50
15	Nambari	36.45	12.50
22	Nambari	70.40	10.00
37	Nambari	42.95	12.50
8	Kpelesawgu- Changnalili	50.50	15.00

30	Kpelesawgu- Changnalili	65.33	15.00
9	Wenchi- Hilun	79.28	12.50
32	Wenchi- Hilun	76.40	12.50
10	Pusiga	79.10	12.50
17	Nangodi	78.10	12.50
20	Nangodi	72.43	10.00
18	Sambu- Pasga	16.85	10.00
24	Sambu- Pasga	65.43	10.00
27	Sambu- Pasga	34.33	20.00
35	Sambu- Pasga	54.00	12.50
25	Kolingu	75.70	10.00
31	Kolingu	77.68	12.50
34	Kolingu	78.93	10.00
21	Mimi- Techiman	68.15	10.00
38	Mimi- Techiman	78.00	12.50
28	Kpelesawgu	48.95	15.00
33	Siare-Dagare	69.58	15.00

