

The utilisation of hydro-geophysical methods for soil moisture measurements to optimise irrigation management

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Abstract

Precision agriculture continuously seeks improved methods to enhance productivity whether it is for greater crop yields or economic viability regarding labour inputs and satisfying the demand in a shorter time span. Soil moisture is one important factor that drives the agricultural industry and is therefore of utmost importance to manage it correctly. A shortage of water may result in reductions in yield, while excess irrigation water is a waste of water resources and can also have a negative impact on plant growth.

Electromagnetic induction, Frequency Domain Reflectometry, Neutron Scattering and conventional soil sampling have been utilised to determine the spatial variability of soil moisture within a field. Emphasis has been placed on practicality and accuracy of all the methods. Electromagnetics have proven itself to be the primary method to determine soil moisture within the field by comparing the results of the volumetric soil water content present in the field together with a combination of various soil properties such as clay and silt content, sand fraction, concretions, density and soil depth that contribute towards the accumulation of soil water. Electromagnetic induction has the highest resolution of data collected for a specific time period of all considered methods making it economically the best option for soil moisture management within a variable rate irrigation system. Electromagnetic induction has proven to be successful in delineating a field into management zones consisting of different classes based on observed conductivity values. Higher conductive zones are considered with a small water demand. Lower conductive zones are considered with a greater water demand through a variable rate irrigation system.

Keywords: soil moisture; geophysics; irrigation; soil water management

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List of Abbreviations

API	Antecedent Precipitation Index
CMD	Multi-Depth Conductivity Meter
DSSAT	Decision Support System for Agrotechnology Transfer
EC	Electrical Conductivity
EC _a	Apparent Conductivity
EC _e	Electrical Conductivity
EM	Electromagnetic
EMI	Electromagnetic Induction
ER	Electromagnetic Radiation
ET	Evapotranspiration
FDR	Frequency Domain Reflectometry
GIS	Geographic Information System
GPS	Global Positioning System
PSD	Particle Size Distribution
PVC	Polyvinyl Chloride
Rx	Receiver
TDR	Time Domain Reflectometry
TRMM	Tropical Rainfall Measuring Mission
TMI	Tropical Rainfall Measuring Mission Microwave Imager
Tx	Transmitter
VRI	Variable Rate Irrigation

1. Introduction

One of nature's purest form of chemical compounds, water is an essential component of every living cell (Brady & Weil, 2016). The moisture content of soils plays a significant role in a variety of geohydrological processes; it has an influential effect on almost every aspect of soil behaviour and development. Soil moisture enhances the weathering of minerals and serves as a medium for groundwater contamination. It controls the structure, function and diversity of the vegetation in drylands, the partitioning of precipitation between infiltration and run-off which has a direct effect on streamflow and soil erosion (Robinson *et al.*, 2012). It controls the exchange of water and energy between the atmosphere and land surface (Vereecken *et al.*, 2014).

Conventional hydrogeological techniques for measuring and monitoring water content comprises of destructive soil sampling and oven drying, neutron thermalisation, gravimetric sampling and time-domain reflectometry (Reedy & Scanlon., 2003; Calamita *et al.*, 2015). These techniques yield information on a local scale and are biased to the measuring point. Less accurate results may be obtained due to the disturbance of the soil with these techniques. It is costly and time-consuming especially when monitoring or measuring large areas (Huang *et al.*, 2016).

The utilisation of non-invasive geophysical techniques such as electromagnetic induction (EMI) can provide an extensive spatial and temporal dataset of information in the near subsurface of the earth. EMI measures a depth-weighted average of electrical conductivity (EC), namely apparent electrical conductivity (EC_a). EMI is an effective method for measuring, estimating and monitoring soil water content. Soil electrical conductivity can also vary with clay content, soil salinity, soil texture, cation exchange capacity, organic content, plant available nutrients, pH, bulk density and soil types (Corwin & Lesch, 2013; Gebbers *et al.*, 2009; McNeill, 1980; Sudduth *et al.*, 2001).

Precision farming and soil water management go hand in hand. The most desirable method for optimising crop yields regarding soil water content is through irrigation management. One such management method is variable rate irrigation. The efficiency of precision farming is determined by comparing the input costs of significant zones within crop fields to the crop yield acquired relative to time. The variability in treatment between different zones regarding cost, the response of individual crops regarding yield, and quality of changes in treatments towards crops (Sylvester-Bradley *et al.*, 1999).

1.1 Problem Statement

Food demand increases at a rapid rate with the rise in world population, placing enormous pressure on agricultural practices to deliver higher crop yields in less time. It is therefore essential to introduce a more scientific approach to crop farming, especially regarding agricultural water management. Mismanagement of water through pivot irrigation causes exceptional high electricity usage along with not irrigating the optimal amount of water for the specific crop. Agriculture can be considered as the largest consumer of freshwater with more than 73% in relation to industrial (8%) and domestic (5%) water usage. It is therefore essential in establishing proper soil water management practices for agriculture to cope with water scarcity and misuse.

To satisfy the demand of consumers regarding crop production in a shorter time span a scientific approach such as geophysics can be used to measure, monitor and manage soil water content, rather than time-consuming conventional methods. Monitoring soil moisture attentively by utilising geophysical methods, water application through centre pivot irrigation can more effectively be managed spatially and temporally, saving water in a country below the average rainfall in the global context.

1.2 Research Question

Can soil water content management through pivot irrigation be improved by employing hydro-geophysical techniques and utilising the obtained data to develop an irrigation management scheme through a Variable Rate Irrigation (VRI) system?

1.3 Aim

The primary aim of this study is to determine whether an electromagnetic induction method in conjunction with hydrometric techniques (non-invasive) is useful in determining soil moisture content in various soil profiles both temporally and spatially.

1.4 Objectives

The following objectives were set for the study:

1. Identifying the cause of anomalies in electromagnetic induction (EMI) measurements by acquiring soil samples. Verifying soil moisture with gravimetric analysis, clay content, soil texture and soil density.
2. Verify soil moisture content in the field with hydrometric techniques utilising the Neutron Probe, Diviner 2000 and volumetric soil water content through sampling.
3. Creating a visual representation of hydrogeophysical soil moisture data in a centre pivot field, both spatially and temporally for crop irrigation management and delineating the field into management zones.

4. Determine whether EMI data is sufficient for soil water management in a variable rate irrigation system.

2. Literature Study

2.1 The Relationship between Hydropedology and Precision Agriculture

The term hydropedology can be classified as the study where soil science is interwoven with hydrology. Hydropedology embraces interdisciplinary and multiscale approaches to study the interactivity between pedological and hydrological processes in the Earth's critical zone (Lin, 2003). This interdisciplinary science emphasises the landscape context and in situ soils that have distinct properties of pedological features such as soil structures, horizons, and heterogeneity (Lin, 2006). Hydropedology uses pedological data to improve the performance of process-based hydrologic models and uses hydrologic data to signify the understanding of soil variability, and the interpretations of soil use or limitations (Lin *et al.*, 2006). Landscape water flux can be regarded as a unifying concept for hydropedology. Landscape flux encompasses the source, storage, flux, pathway, residence time, availability and spatiotemporal distribution of water including the transport of chemicals and energy by flowing water into the soils at various spatial and temporal scales. A renewed perspective and a more integrative approach to study landscape-soil-water interaction across scales, and their relationship to climate, ecosystems, land use, and contaminant fate is generated with the synergistic integration of pedology and hydrology into hydropedology (Lin *et al.*, 2006).

Precision agriculture originated in the mid-1980's; it can be regarded as a crop management strategy that seeks to address within-field variability and to optimise the inputs on a point-by-point basis within fields (Pierce and Nowak, 1999). By reducing the over-application and under-application of inputs such as water, fertilisers, herbicides, and pesticides, precision agriculture has the potential to improve profitability for the producer, food security for the consumer and the threat of surface and groundwater contamination from agricultural chemicals (Sudduth *et al.*, 2001). Precision agriculture benefits from the emergence and convergence from a variety of technologies being developed within the agricultural sector such as global positioning systems (GPS), geographic information systems (GIS), remote sensing, miniaturised computer components, automatic control, mobile computing, advanced information processing, and telecommunications (Stafford, 1994). One of the earliest applications of precision agriculture implemented was the on-the-go fertiliser blending and distribution system developed in the United States of America, which used information from aerial photography and grid soil samples to generate a fertiliser application map (Fairchild, 1990). Numerous precision farming studies exist which include Simon *et al.*, (1999) who reported that a net benefit might exist from variably applying nitrogen (N) based on soil type, as opposed to a uniform N application. Sogbedji *et al.* (2001) documented that soil water

content, texture, drainage classes, pH, and soil structure, were relevant in the spatial variability of fertiliser (N,P,K) availability and crop production.

Within-field spatial heterogeneity has long been recognised by researchers and producers, uniform (or traditional) fertiliser and irrigation recommendations for the field or farm scale are still being used (Sawyer, 1994). The likely reason for this is that hydropedological processes are affecting fertiliser and water transportation, transformation, and storage, for example, the soil water movement, soil moisture temporal-spatial variations, and spatial patterns of soil properties have not been adequately recognised. In other words, the underlying processes of the soil-water-landscape dynamics and their implications towards precision agriculture is still not fully understood.

The interaction between landscape, hydrology, and pedology determine various hydropedological processes which include spatial and temporal variations of soil moisture, surface, and subsurface flow and spatial patterns of soil properties. These hydropedological processes are essential controls of soil water and the availability of nutrients and thus crop yield dynamics (Eck, 1984; Johnson *et al.*, 1987; Timlin *et al.*, 1998).

2.2 Soil Moisture

Soil moisture plays a critical role within the land-surface hydrological cycle, due to the unsaturated zone that partitions precipitation into soil moisture or overland flow, depending on the texture of the soil, the saturation levels, and present topography and vegetation. Water captured within the unsaturated zone becomes available in evapotranspiration processes, which is accountable for up to 60% of precipitation over land surfaces being returned into the atmosphere (Seneviratne *et al.*, 2010). Soil moisture also acts as a partitioning regulator of incoming solar energy that comes in contact with the land surfaces; evapotranspiration processes utilise more than half of the incoming solar energy (Trenberth *et al.*, 2009). This evapotranspiration process of soil moisture drives the interaction between soil moisture and the atmosphere, which results in the development of clouds and eventually precipitation and energy fluxes (Pielke, 2001; Findell and Eltahir, 2003; Pal and Eltahir, 2001; Hong and Pan, 2001).

An atmospheric general circulation model to generate a 100-year simulation of soil moisture and their impact on near-surface temperature and precipitation of North America was created by Wang and Kumar (1998). The authors found that atmospheric predictability of surface air temperature and precipitation anomalies during summer months was enhanced utilising soil moisture anomalies. Another study conducted by DeAngelis *et al.* (2010) made use of long-

term precipitation observations of the Ogallala aquifer in the United States to determine whether an increase in irrigation would be a contributor towards increased precipitation downwind. The results have found that the summer month of July has had an increase in average precipitation of 15-30% over the entire 20th century, downwind of the Ogallala aquifer. This increase in precipitation has been fuelled by an increase in irrigation in this area in the 1950s, which resulted in higher soil moisture content and consequently greater evapotranspiration.

Although the processes that influence the partitioning of land surface evaporation into precipitation is still not fully understood, it is well proven that coupling of evapotranspiration rates and precipitation is occurring. The accurate measurements of soil moisture are critical especially at a large spatial scale, as these measurements could strengthen predictive capabilities of climatic models, identifying areas of strong evapotranspiration and precipitation anomalies (Seneviratne *et al.*, 2010). Vegetation can be affected by indirect impacts such as precipitation anomalies derived from soil moisture, especially if a persistent pattern is followed seasonally by soil moisture conditions. Therefore successfully validating the soil moisture active or passive state by NASA, is of crucial importance, as the large-scale coverage of the passive instrument and the rapid revisit period of this mission would improve the understanding of soil moisture conditions globally.

Gravimetric, volumetric and depth of soil moisture with depth are the primary methods that can describe and enhance soil moisture content. A variety of soil moisture content measuring and monitoring instruments exist which one discussed at a later stage of this literature namely: neutron depth probe, tension meters, time domain reflectometry (TDR), frequency domain reflectometry (FDR), electrical resistance, and dielectric probes and sensors. Most of these instruments operate on a principle where it measures the dielectric constant of soil in order to determine the soil moisture content (Muñoz-Carpena *et al.*, 2004). Soil moisture content can be highly variable in both time and space. Soil moisture content can be affected by a wide range of factors including soil texture, topography, crop coverage, climate parameters and irrigation application. The variability of soil moisture is essential to understand the redistribution of soil moisture after a rainfall event or irrigation application results in infiltration, evapotranspiration, and pollutant transport. Numerous sensing approaches have been developed to measure spatial and temporal soil moisture variability, including soil moisture sensing networks, geophysical techniques and methods (Hu *et al.*, 2011) and remote sensing techniques (Moran *et al.*, 2004). Gravalos *et al.*, (2012) conducted the first study on horizontal access tube sensing systems to monitor soil moisture variability on a principle that is based on an electromagnetic sensor. The primary purpose of this specific study was to investigate the effects of uniform rate irrigation and variable rate irrigation on the distribution of soil

moisture and to provide recommendations for improved irrigation scheduling strategies and the design and development of automatic irrigation systems. The soil moisture distribution was based on long-term data sets that were collected during the wet and dry season (permanent wilting point to field capacity), utilising a novel electromagnetic sensor-based platform moving inside subsurface horizontal access tubes with the task of monitoring and measuring soil water content distribution.

Measuring soil water content plays a vital role in various research fields such as soil science, agronomy, civil engineering, hydrology, botany, and meteorology. It is essential to monitor the movement of soil moisture, especially where irrigation is applied on a field within a catchment area where water is insufficient for high-value crops, e.g., wine grapes (Lunt *et al.* 2005).

Variable amounts of water are contained within soil and plants. Plant growth is mainly affected by the amount of water in the soil, along with its energy state. Numerous soils properties rely on moisture content such as mechanical properties including strength and consistency, the respiration process of plant roots which is affected by gas exchange and air content of the soil (Hillel, 2003). Soil wetness can be defined as the per-mass or per-volume fraction of water in the soil. Free energy per unit mass called the potential characterises the physicochemical condition or state of water in the soil. The potential comprises of various components, including matrix potential which defines the work to displace a small volume of soil water from a source of reference water to the soil water (at equal elevation than reference water). Due to the matrix potential representing the energy of a plant to extract water from the soil through its roots, it is directly related to the demand for water by the plants and contributes further evidence that soil water management must be implemented through means of irrigation for optimal crop production.

Soil water can be detected and measured by both direct and indirect methods (Muñoz-Carpena *et al.*, 2008). Direct methods include conventional methods such as removing the moisture content from void spaces through applied heat, called oven-drying or gravimetric method. Converting the gravimetrically determined water content to volumetric water content the bulk density is used as a multiplier (Campbell *et al.*, 1998). The disadvantage of the gravimetric method is that it is time-consuming due to the drying process and the water content cannot be determined in the field.

Indirect methods can be divided into two groups. Measuring the energy status of the soil or energy potential of the soil can be regarded as the first category. The second category is represented by the measuring methods to determine the available water within void spaces of the soil also known as soil water content determination (Tarantino *et al.* 2008).

The agricultural industry can be revolutionised with the accurate measurements of field-scale soil moisture by moving from conventional irrigation and fertilisation techniques to precision agriculture. Determining how close the soil is to field capacity, soil moisture measurements can be taken before irrigation, adjusting their irrigation schedule to maximise infiltration and minimise water loss.

The implementation of precision irrigation would result in a reduction in production costs for the land manager, decreasing overland flow and maximising yield. Fertilisation scheduling is also a form of precision agriculture. The loss of nutrients within the soil can be due to numerous factors such as soil texture, tillage technique, nutrient type, and weather. The reaction of nutrients towards antecedent soil moisture conditions can also vary significantly, e.g., nitrogen's mineralisation is optimised when the soil reaches its near-maximum field capacity, as this process is microbially mediated. With current soil measurements, land managers can adjust scheduling and fertilisation techniques to the soil moisture condition, maximising nutrient uptake and efficiency. A much more economical outcome awaits the landowner, as they would be able to achieve high yields without high fertilisation rates to account for losses. Precise fertilisation would minimise nutrient run-off, which in turn would lead to a reduction in agricultural pollution. Phosphorous is known as a typical agricultural pollutant leading to the eutrophication of numerous water resources (Li *et al.*, 2009). The application of remote sensing towards the agricultural sector is still quite a long way from being realised; although, soil moisture probe measurements at a field scale is becoming more affordable and being implemented much more often.

Floods are regarded as destructive natural phenomena regarding economic loss and damage caused to society. The prediction of floods has drawn much attention, as preparation or evacuation could minimise the damage caused to infrastructure and the loss of life. Soil moisture plays an enormous role in the development of flood events, due to antecedent soil moisture conditions which influence the partitioning of precipitation into either infiltration or run-off. Positive results were found through remotely sensed soil moisture for flood prediction modelling during multiple case studies that were undertaken. Datasets concerning streamflow, precipitation and passively sensed soil moisture, which was then processed through an antecedent precipitation index (API) had been utilised by Crow *et al.* (2005). The passive platform being utilised is the Tropical Rainfall Measuring Mission (TRMM) microwave imager (TMI). Three proxies were calculated for soil moisture by the authors: a TMI soil moisture estimate, an API and an API that was updated with TMI estimations. It was found that when the in situ precipitation measurements were used as a correlation, a Spearman Rank Coefficient existed between pre-storm soil moisture values and run-off ratios. It was found that remotely sensed precipitation estimates by the API proxy was reduced in its ability to forecast

run-off ratios. The above mentioned has illustrated that a need exists to refine the use of remotely sensed data regarding soil moisture management in agriculture or other applications such as flood forecasting.

Forecasting droughts are much more difficult than forecasting floods because droughts do not have a definite start or end. However, studies are conducted to develop prediction models for droughts using soil moisture conditions as a dictating factor. Such studies include these of Aghakouchak (2014) who improved on previous works of Lyon *et al.* (2012) and Quan *et al.* (2006) to develop drought forecasting framework that relied on the persistence of soil moisture. These methods included the calculations of the standardised soil moisture index, which was incorporated into a model and applied to historical data to predict drought conditions in 2012. Results were obtained through the model that correlated with historic drought conditions. This lead to the assumption that there is a significant future in the forecasting models of droughts with soil moisture persistence.

Antecedent soil moisture conditions contribute significantly towards slope instability, due to slope stability decreasing with an increase in soil moisture content. A study conducted by Huang *et al.* (2008) found that when a slope at 31 degrees covered with sandy soil containing 50-70% soil moisture along with interflow between bedrock and soil introduced with simulated precipitation will undergo slope failure. The arrival of a wetting front present at the bedrock soil interface was a clear indicator of slope failure. Utilising remotely sensed soil moisture measurements for mapping potential landslide regions has also been identified; however scaling remains a problem, along with the installation of in situ validation sites (Ray *et al.*, 2010).

A relationship was developed between the soil water potential and soil moisture content by Childs (1940). This relationship is predominantly determined by soil type in particular particle size and influenced by physical conditions, e.g., porosity and connectivity pores. The soil moisture property determines the amount of water available to be consumed by plants for transpiration purposes. Available water is usually termed as either the difference between field capacity and wilting points (Hanks, 1992) or refill point (Cull, 1992). The determination of field capacity is vague because the differing in terminology is accepted. Field capacity relates to the amount of water retained in the soil after complete saturation and drainage due to gravitation forces. Cullen & Everett (1994) and Ahuja & Nielsen (1990) discuss the terminology in greater detail. Wilting point relates to the soil moisture retained in the soil with corresponding potential too high for plants to extract water. Thus the plant's wilt and even after the addition of water will not recover. In production agriculture, the refill point can be regarded as a marked decreased in the daily water use of the plant (assuming similar meteorological conditions) and

corresponds to a loss of production due to moisture stress (Briscoe, 1984). Care needs to be taken when utilising the moisture characteristic as the relationship, as it is influenced by hysteresis. The relationship between the matrix potential and water content relies on the determination of the two constraints that not only relate to particular soil texture and structure, but also to the wetting history of the sample (Campbell, 1988).

2.3 Soil

2.3.1 Hydraulic Properties of Soil

Water movement in the subsurface, especially through soil profiles, is an essential component of agricultural activities. Environmental practices and the understanding of it will contribute towards the thorough understanding to help solve irrigation problems, subsurface drainage to groundwater, saline seeps and water disposal. The proper and efficient management of soil and water is necessary to understand and interpret the properties of water retention and hydraulic conductivity functions of specific areas of concern. Klute & Dirksen (1986) defined these functions as soil hydraulic properties.

2.3.2 Water Infiltration into Soils

The process where water enters the subsurface through the soil surface is called infiltration (Delleur, 2006). Numerous factors regarding forces contribute to the infiltration of water into the soil (Ela *et al.*, 1992). The intensity and amount of rainfall during a storm event play a significant role in the water infiltration process into the soil. Two major forces that dramatically affects infiltration are gravity and capillarity (DeBano, 1971). It is essential to understand the transport of water through the soil for proper application. The rate at which water moves into the soil is known as the infiltration rate (Miller & Gardner, 1962). The rate of water movement through the surface layer is higher at the initial stage of water entry into the soil. Measurement of the rate of infiltration of water into the soil can be done making use of an infiltrometer can be used (Liu *et al.*, 2005). Infiltration reduces due to soil particles swelling and minimising the pore spaces resulting in decreased infiltration over time. When infiltration declines over time and reaches a plateau or constant rate, it is known as the basic infiltration rate (Telis, 2001). Using the Green and Ampt approach cumulative infiltration of water in the soil can be analysed as a function of time (Warrick *et al.*, 2005).

Based on the physical distribution of water within the soil profile during water infiltration, it can be divided into four zones, namely, Saturation Zone, Transmission Zone, Wetting Front and Dry Zone. The saturation zone represents an area where the voids are filled with water and are very close to the soil surface. The transmission zone occupies the region in the next layer to the saturation zone. This zone is where water moves under the force of gravity and the soil are not saturated. The wetting front is a region where there be an increment in the water

content of the soil as water continues to move through the soil surface. It also serves as a linkage between the transmission zone and the wetting front. Finally, the wetting front is the boundary between the wet and dry soil beneath the soil layer (Koorevaar *et al.* 1999; Hillel, 2004; Kahimba, 2008).

The application of irrigation and the efficiency thereof are relying entirely on the infiltration of water into the soil. When soils are in a functional state, which is often expected, infiltration and root zone distribution of applied water would both be expectantly uniform throughout. The result of this can be regarded as relatively high distribution uniformity within the soil as well as on the surface as is expected. However, soil water repellency can have a substantial effect on infiltration and water distribution in the soil resulting in a significant variation in moisture content throughout the root zone (Dekker and Ritsema, 1994; Park *et al.*, 2005). This phenomenon has occurred in a variety of soils, such as sand, loam, clay, and peat (Dekker *et al.*, 2001; Dekker *et al.*, 2005). Hallet *et al.* (2004) have also found this to be a reality even at minor, sub-critical levels of water repellency. When water repellency is present it compromises infiltration within the soil. Root zone distribution uniformity will be lower than irrigation distribution uniformity on the surface, causing reduced irrigation efficiency. In addition to reduced efficiency in water distribution within the root zone, the previously mentioned flow paths will form. This phenomenon occurs due to the repellent parts of the soil, which are not saturated and becomes drier, and the water saturated areas become the channels through which water and solutes are flowing (Dekker *et al.*, 2001). As a result, a significant portion of the water and solutes intended to be present within the root zone will bypass instead (Dekker and Ritsema, 1994; Ritsema *et al.*, 2001). This phenomenon causes an increase in waste, the need for irrigation, and the risk of environmental pollution by solutes reaching groundwater faster than expected.

Since soil surfactants reduce soil water repellency and facilitate wetting, their use in soils with subcritical water repellency can lead to significant improvements in the infiltration process and root zone distribution uniformity.

Park *et al.* (2004), has reported that reduced repellency and improved wettability can be obtained when surfactants are applied with some regularity. Oostindie *et al.* (2005) reported that in water repellent sand, more consistent moisture levels and, correspondingly much lower variation coefficients exists in surfactant-treated soils in comparison with adjacent untreated soil during the same period. Irrigation requirement, preferential flow and associated environmental risks can be reduced by reducing water repellency of soil. Increasing soil wettability of the root zone moisture distribution uniformity can significantly increase the

efficiency of irrigation (Oostindie *et al.*, 2005; Park *et al.*, 2005; Karcher *et al.*, 2006; Aamlid *et al.*, 2007).

Various factors such as soil surface conditions, vegetation cover, physical properties of soil, and temperature can obstruct the movement of water through the soil surface (Hiraoka and Onda, 2010).

2.3.3 Water Retention Characteristics of Soils

Soils differ in its capacity to retain water against gravitational force. Water-binding properties of soils characterise soil water retention. Soil water retention can be regarded as the relationship between the amount of water in the soil and the potential energy with which it is bound to the soil (Jury *et al.*, 1991). The soil water retention relationship is a unique function for each soil, due to variation in soil particle size distribution and structure. Both of these factors affect the soil water retention relationship regarding pore size distribution and the number of given pore size in each size class (Dexter, 2004).

The soil water retention relationship is a valuable soil property which is required for the study of plant available water, infiltration, drainage, hydraulic conductivity, irrigation scheduling, water stress on plants and solute movement (Kern, 1995). In non-swelling soils, the geometry of the pores is reflected and this geometry, in turn, can determine to a large extent the hydraulic conductivity.

Since the pressure difference across an air-water interface is inversely proportional to the equivalent radius of the interface, the soil water retention interface can be manipulated into an equivalent pore size distribution (derivative curve). The water content at any given suction is equal to the porosity contributed by the pores that are smaller than the equivalent diameter corresponding to that suction (Jury *et al.*, 1991). The spatial patterns of water retention characteristics are essential factors for studying the response of vegetation and hydrological systems in climate change (Dolph *et al.*, 1992). The distribution of soil particle size strongly affects the soil water retention relationship at suction heads greater than 100kPa and to a lesser extent, at lower suctions where soil structure is also essential (Hillel, 1998).

2.4 Hydrogeophysics

Hydrogeophysics is regarded as a multi-disciplinary field that connects geophysics with hydrogeological applications. These applications include hydrogeological properties, defining the subsurface features that may affect the movement of water or monitoring groundwater processes (Binley *et al.*, 2010). It is believed that the integration of such techniques to

hydrogeological investigations will contribute towards the improvement of understanding dynamic hydrological processes (Robinson *et al.*, 2008).

Numerous geophysical techniques proved to be practical and viable in estimating soil water content in the shallow subsurface at scales in between those of conventional point measurements and remote sensing data. Groundwater distribution and migration are also accurately determined by electrical methods (Kean *et al.*, 1987; Frolich and Parke, 1989; Daily *et al.*, 1992; Binley *et al.*, 2001; Zhou *et al.*, 2001; Lück and Eisenreich, 2001). Low-frequency electromagnetic techniques have also proven to be successful in determining and mapping groundwater distribution (Sheets and Hendrickx, 1995). However, metal structures tend to interfere when surveys are conducted and lead to inaccurate results, limiting their ability in developed areas. These two techniques can also be time-consuming; it may also require extensive interpretation and calibration, be influenced by factors other than water content, and have much lower resolution than conventional water content measurements. An electromagnetic technique operating on higher frequencies comes in the form of a Time-Domain Reflectometry (TDR). TDR has shown to estimate soil water content accurately in the near-surface soils (Topp *et al.*, 1980; Heimovaara and Bouten, 1990; Herkelrath *et al.*, 1991; Zegelin *et al.*, 1992). TDR does not require calibration at a specific site although it has a minimal sampling area, it can be time-consuming, and it is invasive. It tends to be difficult using the TDR in areas containing compact soils or shallow rocks. Other geophysical methods such as neutron probes and electrical logging also prove to be successful at determining soil moisture content logging (Telford *et al.*, 1990; Faybishenko *et al.*, 2000). These methods can be used with relatively high levels of accuracy in estimating water content, but they are also invasive, they require site-specific calibration, and involve lengthy data collection procedures.

2.4.1 Conventional Hydrometric Techniques

Various methods exist to determine soil water content. It is challenging to determine both frozen and liquid water content simultaneously. Time-Domain Reflectometry can be used to detect and measure unfrozen water content (Kahimba & Ranjan, 2007). The Gravimetric method is time-consuming and is destructive of nature especially on a repeated basis, to determine soil water content (Lubelli *et al.* 2004; Cultrone *et al.* 2007)

Traditional techniques for measuring soil moisture, e.g., gravimetric analysis on collected soil samples, neutron probing and TDR are inadequate and unable to cope with the needs of today's field and watershed scale hydrogeological investigations. These methods provide only point-source information about the subsurface and can be costly and unfeasible to scale up to a degree of spatial coverage required for a more detailed analysis of soil moisture dynamics. Traditional methods are mostly invasive and can result in the inability to perform the repeated

measurements necessary for the temporal monitoring of dynamic processes. Due to larger sampling volumes of these particular techniques in the form of modern geophysical methods are more mobile and non-invasive. Therefore they are ideally suited to provide the information necessary to analyse and monitor hydrological processes. The value of soil moisture content has led to the development of various soil moisture measurement sensors. Frequency Domain Reflectometry is instruments that can be deployed for in situ soil moisture measurements and tracked with a data logger.

2.4.1.1 Gravimetric Method

Gravimetric method is used for calibration purposes of other soil determination techniques or instruments (Gardner, 1986). This method involves water content measurements by weighing the sample, oven-drying to remove the moisture and re-weighing the samples to determine the amount of water being removed. The samples are dried at approximately 110 degrees Celsius for 24 hours. Soil water content can be expressed either with weight or volumetrically if the soil bulk density is known.

- i. Volumetric soil water content is defined as

$$\Theta_v = V_w / V_s \quad (1)$$

where Θ_v is the volumetric water content ($\text{m}^3 \cdot \text{m}^{-3}$), V_w is the volume of water contained in the sample and V_s is the total volume of the sample.

- ii. Gravimetric water content can be defined as:

$$\Theta_g = M_w / M_s \quad (2)$$

where Θ_g is the gravimetric water content ($\text{g} \cdot \text{g}^{-1}$), M_w is the mass of water in the sample and M_s is the total mass of the dry sample.

To convert from volumetric to gravimetric water content the following equation is used:

$$\Theta_g = \Theta_v * (\rho_b / \rho_w) \quad (3)$$

Where ρ_w is the density of water and ρ_b the bulk density of the sample (M_s / V_s)

The equipment required to conduct a gravimetric analysis includes an auger drill, a suitable device to take a sample, a soil container with tight-fitting lids, an oven capable of regulating temperature between 90-150 degrees Celsius, a desiccator with active desiccant, and a balance for weighing the samples. In the field, if soil samples are taken under conditions where

evaporation losses may be significant, special equipment for weighing the samples immediately or covering material must be used to limit evaporative loss.

The main advantage of the gravimetric method according to Reynolds (1970), is that it requires relatively simple equipment. The disadvantage is that it requires a great deal of effort and time. Furthermore, repeated sampling also disturbs the experimental area.

Water status of soil can be determined on a volume basis, θ ($\text{m}^3 \cdot \text{m}^{-3}$), where θ is the volume of the liquid phase per unit bulk volume of soil. The above mentioned are the most popular method of reporting the moisture status of soil for repeated in situ measurement, especially regarding irrigation scheduling. The liquid phase is calculated from wetness if the bulk density of the soil is known.

$$\Theta_G = \Theta_V * (\rho_b / \rho_w) \quad (4)$$

Where ρ_b is the bulk density of the soil, ($\text{Mg} \cdot \text{m}^{-3}$); ρ_w is the density of water (assume the unity of $\text{Mg} \cdot \text{m}^{-3}$), and; w is wetness ($\text{Mg} \cdot \text{Mg}^{-1}$). Most in situ techniques are field calibrated to account for bulk density effects and report moisture on a volume basis. The accuracy of the bulk density and wetness determination dictates the accuracy of the calculated volumetric moisture content as discussed by Gardner (1986).

2.4.1.2 Neutron Depth Probe

The Neutron Depth Probe comprises two main components: a) a probe, which lowered into an access tube located over the drilled hole which is inserted vertically into the soil, and which contains a source of fast neutrons in the form of radioactive material such as Americium-241: Beryllium and Caesium-137, and a detector of slow neutrons: b) a ratemeter (battery powered and portable) to monitor the flux of slow neutrons scattered by soil (Hillel, 1980).

The theory behind this instrument as described by numerous researchers (Long & French, 1967; Visvalingam & Tandy, 1972; Gardner, 1986) is based on the following principle. Hydrogen which has the same size and mass as a neutron has a marked property for scattering and slowing neutrons (thermalising effect). When a fast neutron is placed within the soil, it immediately becomes surrounded by a cloud of thermal neutrons. Using a detector, which is placed in the vicinity of a fast source, thermal neutron density can easily be measured. Then the thermal neutron density can be converted to volumetric water content using the calibration curve which is linear over the range of interest.

Effective irrigation scheduling using the Neutron Probe requires identification of the refill point at which irrigation should occur and periodic soil water content measurements must be taken.

The main advantage of the neutron probe method can be summarised as follows:

- i) It can measure water of any phase;
- ii) A continuous profile of water content measurements can be obtained;
- iii) It can be automated, and
- iv) it has a minimum disturbance of the adjacent soil.

The disadvantages of this method are :

- i) it has inadequate depth resolution;
- ii) Surface soil water content cannot be measured;
- iii) It has a radioactive source potentially a health risk;
- iv) Calibration can be affected by dry bulk density, soil texture, soil temperature, and neutron absorbing elements and;
- v) It is expensive (Visvalingam & Tandy, 1972).

2.4.1.3 Frequency Domain Reflectometry (FDR)

Three sensors operate on the FDR principle namely the Thetaprobe by Delta-T Devices (2001), PR2 profile probe also by Delta-T devices (2001), and Diviner 2000 by Sentek Environmental Technologies (2001). As it is described in the PRI profile probe's user manual (Delta-T Devices, 2001) when power is applied to the sensor, it generates a signal which is applied to pairs of stainless steel rings that emit an electromagnetic current that extends to 100mm horizontally into the soil. If the dielectric properties of the soil differ from that of the probe from the probe some of the signals are reflected. The reflected part of the signal combines with the applied signal to form a standing wave, and this voltage of the standing wave acts as a simple, sensitive measure of the soil water content.

The dielectric permittivity of the soil is a parameter that is representative of the soil moisture content. This provides high-frequency updates on soil moisture status, which are critical for the development and testing of other methods for soil moisture determination, such as soil moisture models and remote sensing.

For irrigation scheduling purposes, periodic soil water content measurements with these sensors give both the ambient soil water content and the rate of water consumed by the crop. This simple method explained by Gear *et al.* (1977), Lukangu *et al.* (1999) and Laboski *et al.* (2001) indicating soil water content versus time allow accurate irrigation scheduling. Making use of sub-hourly soil water content and cumulative irrigation; graphs can be plotted and with the appropriate projection of lines predict the amount and duration of irrigation to be applied as conducted in a study by (Lukangu *et al.* 1999).

The advantage of these sensors is that there are different designs of sensors that are fitted with handheld devices, portable PR2 profile probes that are mechanically similar to the neutron

probe (Roberson *et al.* 1996). Precise measurement of soil water content is provided by the sensors; they have a lower power consumption rate, they are non-distractive, continuous and unattended in situ measurements of soil water content can be taken under field conditions making use of data loggers (Veldkamp and O'Brien, 2000). The disadvantages of the sensors are that readings can be affected by soil texture, soil temperature and air adjacent to the sensor within the soil, and systems operating at a lower frequency are more susceptible to soil salinity (Delta-T Devices, 2001).

2.4.1.4 Time-Domain Reflectometry

The Time Domain Reflectometry (TDR) is an ideal method to avoid soil disturbance unlike other methods of measuring soil water content (Ju *et al.*, 2010). The TDR is capable of measuring soil water content up to a depth of 1 m below the soil surface (Topp and Ferre, 2005). The TDR operates by measuring the time travelled by an electromagnetic wave along the waveguide (Stafford, 1988). The reflection of the electromagnetic pulse at the end of the TDR probe is used to determine the travel time of the electromagnetic step-pulse through the specific soil type in which it is embedded. Once the waveform is determined the propagation velocity of the wave can be obtained (Hashmi *et al.* 2011; Yu *et al.* 2010). This propagation velocity can be regarded as a function of the dielectric constant of the medium in which the TDR probes are embedded (Ledieu *et al.*, 1986). The apparent dielectric constant can be related to the Topp's equation (m^3/m^3) by when calculating the soil water content indirectly.

The discovery of the TDR for measuring soil water content, originated from the development of radio frequencies to determine near surface electrical properties of the moon (Topp *et al.* 2003). The volumetric water content is estimated by the TDR probe using the dielectric constant in a third order polynomial which is based on the relationship between the volumetric water content and the dielectric constant of moist soils (Ledieu *et al.* 1986; Vaz *et al.* 2002; Mailapalli *et al.* 2008).

The TDR can be utilised indirectly to determine soil salinity together with soil water content (Dalton and Van Genuchten, 1986). The Tektronix TDR instrument is an example of an instrument that is capable of obtaining the waveform generated by the electromagnetic step pulse travelling through a waveguide (TDR probe) embedded in the soil to measure soil water content (Dahan *et al.*, 2003).

2.4.1.5 Tensiometers

The instrument consists of a glass tube with a porous ceramic cup at the bottom which is filled with water. The tensiometer gets buried in the below the surface of the soil, where a hand pump is used to create a vacuum. As water is extracted out of the soil by plants the vacuum increases inside the glass tube. As water is added by irrigation the vacuum inside the tube

decreases. The tensiometer is a useful device for determining the matrix-potential of soils (Lungal and Si, 2008). Soil matrix potential can be measured without explicitly calibrating the soil to be used (Munoz-Capena, 2004; Tarantino *et al.*, 2008).

2.4.2 Electromagnetic Induction

Electromagnetic methods operate on Electromagnetic induction (EMI) phenomena, which are sensitive to any conductive factor in soils. In comparison with the galvanic contact method, the advantage of EMI is that the equipment is lighter in weight, smaller in size, and thus easier to operate. The method uses at least two inductors in the form of coils with fixed spacing and orientation between the coils. High frequency (> 1 kHz) current in the primary coil produces a primary magnetic field. According to Lenz's law, the induced magnetic field generates an eddy current through the soil medium. In turn, this current creates a secondary magnetic field in the receiving coil. The relationship between the primary and secondary currents is related to the conductivity of the soil medium (Lesch, 2005).

Methods commonly used in geophysical prospecting is limited by the following two constraints and is as follows:

- (i) Measurements must be non-invasive, so as not to change the medium, it should be quick (to allow temporal monitoring), it should be achieved with a lightweight instrument, to favour extensive sampling at low cost and minimum labour.
- (ii) The considered geophysical property must be as sensitive as possible to the critical hydraulic parameters or variables: porosity, water content, clay content (Guerin, 2005).

Electrical conductivity is a measurement of ease through which an electric current flows through a substance and the inverse of resistivity. Electromagnetic radiation (ER) is an advancing interaction between electric and magnetic fields which can travel through a substance or voids (Mulders, 1987). In conductors, ER causes electrical current flow which in turn generates secondary ER.

Unconsolidated subsurface earth materials at moderate ambient temperature have EC ranging from 1 to 1000 millisiemens per meter (McNeill, 1980a). In a non-saline environment, loamy soils contain an EC generally in the order of 10 mS/m, higher for clayey soils, and lower for sandy soils. EC of such soils has been found to increase as approximately the square of the moisture content (McNeill, 1980a).

A frequency domain electromagnetic method (FDEM) consists primarily of coils used to generate and measure the magnetic field at a precise location on earth (Boaga, 2017). Several coils are oriented along a different axis in an orthogonal direction, to measure different

components of the earth's magnetic field vector. The total field vector measured at the receiver coil is the sum of the primary field and the secondary magnetic field (Boaga, 2017). FDEM measurements can sense the subsurface response to sinusoidal electromagnetic fields at one or more transmitted frequencies (Boulding, 1993).

The equipment is based on an active method, which is only for shallower hydrological purposes with respect to groundwater velocity and direction (Boaga, 2017). Active methods only consist of one transmitter coil and one receiver coil. These two ends are attached to each end of a non-conductive boom, or they can be separated and attached with a cable (if a wider distance is needed). The further the transmitter is situated from the receiver the deeper the subsurface can be explored, but to maximise accuracy, the two dipoles are usually a fixed distance from each other (Boaga, 2017). For exploring several nominal underground depths, the FDEM can attain several coils with various inter-distances, which can measure several electromagnetic fields simultaneously (Boaga, 2017). The contribution of soils to instrument response depends not only on dipole orientation and the spacing but also on the soil properties regarding magnetic distribution in depth (McNeill, 1980a). This method is also very suitable for determining the salinity of soils (Yoder *et al.*, 2001).

Some stability issues may be present in the reading of EM instruments; instrument drift can be as much as three mS/m per hour, which is significant. Drift per time can be relatively constant within a test but can vary from day to day. A practical approach to compensate for drift is to establish a calibration transect several times during the course a survey of various study areas; another approach could be to re-zero the EM instrument on a frequent basis during a survey (Sudduth *et al.*, 2001).

Advantages of EM include their measurement range regarding depth (McNeill, 1980a), comprehensive feedback for precision agricultural management practices (Lesch *et al.*, 2005; Corwin & Lesch, 2003). It is non-radioactive, easy to use and quick in obtaining data of some significant areas, comprising of cropped- or fallow fields (Huth & Poulton, 2007).

One of the significant advantages above other geophysical methods is that it is a straightforward and cost-effective method for exploring the subsurface, rather than the auger drilling of a high number of holes for exploration purposes, which would cause labour and costs to rise (de Lima *et al.*, 1995).

2.4.2.1 Multi-depth Conductivity Meter (CMD-Mini-Explorer)

Low-Frequency EM instruments operate at <300 kHz, more specifically 30 kHz. There is no predetermined fixed frequency applicable to all EM instruments as the subsurface conductive material depends on the physical properties such as coil geometry, and sensor height and the physical attributes of the soil or geology. The fixed distance on an EM instrument between the

Transmitter (Tx) and Receiver (Rx) coils have a more pronounced influence on the depth of penetration than that of change of frequency. The new generation of EM instruments contains multiple Rx coils separated from the Tx coils by differing distances, allowing for an assessment of various depth levels. The known frequency, coil geometry, and sensor height allow for the approximate calculation of depths for each Tx/Rx pairing. The CMD is used in conjunction with a handheld control unit, fitted with Bluetooth that operates within the GHz band which does not influence the KHz range of the EMI sensor. The Bluetooth connection allows for either pedestrian handheld survey or GPS- enabled sledge/cart mounted survey. Internal temperature compensation automatically provides an absolute calibration of apparent conductivity data before each profile of data is collected, which limits drift across the data set. The operational temperature of the instrument is -10 °C to +50 °C. Two examples of the new multi-receiver/depth type EM instrument is the CMD-mini Explorer by GF-instruments and the Dualem-21S by Dualem Inc.

The CMD Mini-Explorer has a total length of 1.275 m, 0.05m in diameter and has a total weight of 1.8kg. The manufacturer (GF-Instruments) confirms that the Mini-Explorer has a sufficient depth range of 0.25m, 0.5m, and 0.9m for the vertical co-planar (VCP) in the horizontal coil dipole orientation; this depth is extended when making use of horizontal co-planar in the vertical coil dipole orientation to 0.5m, 1.0m, and 1.8m respectively. This depth range is extended when the Tx/Rx orientation is rotated 90° between the HCP and VCP. By conducting surveys using both dipoles, data at six different depth levels can be obtained ranging from 0.25m to 1.8m. Responses from 0.5m can be expected from both the VCP and HCP data; each coil orientation measures a different volume of earth, and these should not be expected to produce identical data at this specific depth level. The CMD-Mini-Explorer's depth as determined by the Manufacturers (GF-Instruments), is indicative only and it is suggested that it is equal for both in phase responses and quadrature; however (Tabbagh, 1986; Scollar *et al.*, 1990) indicated that this is not the case for most EM-instruments investigating soils.

2.4.2.2 CMD-Explorer

The CMD-Explorer operates on the same principles as the CMD-Mini Explorer but due to the difference in coil spacing being further apart greater depths of up to 6.7m are reached with the CMD-Explorer.

2.4.2.3 EM-38

The Geonics Limited Inc. (Mississauga, Ontario, Canada) manufactured EM-38 sensor is an example of a well-established instrument based on the EMI method, one of the most commonly utilised commercial sensors for soil surveying. As with other EMI sensors, the EM-38 sensor provides the ability to make measurements in both the horizontal and vertical modes

of operation (McNeil, 1980b). The instrument requires calibration over a relatively homogeneous area before it is ready for operation in the field. The EM-38 MK-2 is capable of conducting simultaneous ground conductivity measurements in the quadrature phase and magnetic susceptibility which is in-phase with two transmitter and receiver coil separations of 1.0 m and 0.5 m, for two effective depth ranges of 1.5m and 0.75m in vertical dipole mode. The horizontal dipole consists of measuring depths at 0.75m and 0.38 m respectively (EM-38 MK-2 Operating Manual).

The EMI depth sensitivity depends on the coil orientation but generally decreases with depth such that the region in closest proximity or just below the ground surface has the most influence on the observed value of EC_a (McNeil, 1980b). The EM-38 in horizontal dipole orientation provides a shallower depth of investigation, however, it is much more sensitive to the upper region of the subsurface as a higher percentage of cumulative response is obtained from 0.75m. The vertical mode, on the other hand, penetrates deeper and is representative of a higher volume of earth regarding the depth of investigation. The maximum sensitivity is achieved at a normalised depth of 0.4 times the coil separation (McNeil, 1980b).

The normalised depth can be defined as the depth measured in the units of distance between the two coils (Deidda *et al.* 2003).

2.4.3 Apparent Conductivity (EC_a) Mapping

Among various other soil attributes that contribute towards conductivity and that can be mapped with high-density measurements is soil EC_a . It is one of the most common properties that relate to that ability of soil to conduct an electrical charge. Unlike the standard laboratory tests for electrical conductivity performed on soil solutions, measurements of EC_a are performed on the soil in its natural state (Corwin & Lesch, 2003). In general, soil EC_a measurements are influenced by a range of factors including both chemical and physical properties such as salinity, water content, texture, depth to claypans, cation exchange capacity (CEC) and exchangeable Ca and Mg (Sudduth *et al.*, 2005; Allred *et al.*, 2008; Carter *et al.*, 1993; Corwin and Lesch, 2005).

The measurements of soil EC_a promises to provide many applications for precision agriculture (Corwin and Lesch, 2003, 2005; Allred *et al.*, 2008). The application of soil EC_a measurements to reveal the level of soil salinity has been well documented (Corwin and Lesch, 2005; Corey and Logsdon, 2005). Additionally, mapping of soil EC_a helps the crop producer to interpret the spatial variability of yield maps. Soil EC_a maps can also be used in various combinations with other soil properties to delineate management zones. A management zone strategy is an approach to define locations with potentially different soil types. Such zones can be further utilised for direct sampling and zone-based management of agricultural inputs. In many

practices, soil EC_a maps help classify soil texture, especially with claypan soils that hold more moisture (Williams and Hoey, 1987; Brus *et al.*, 1992; Inman *et al.*, 2001; Triantafilis *et al.*, 2001).

Soil EC_a mapping techniques are currently based on electrical and electromagnetic concepts. Proximal soil sensing technology is currently based on electrical conductivity or resistivity that has been accomplished through the use of galvanic contact and capacitive coupling resistivity techniques (Allred *et al.*, 2008) as well as electromagnetic conduction (Daniels *et al.*, 2008). In each case, the data and the spatial resolution vary depending on the specific method applied. As a further investigation, several different methods have been used to estimate how soil characteristics change with depth.

2.4.3.1 Factors affecting EC_a of Soil

Electrical Properties of Soils

Friedman (2005) presented several studies concerning soil properties that affect geoelectrical properties. A summary of these properties is discussed in this section. Geoelectrical methods respond to the electrical resistivity or electrical conductivity of the subsurface. Electrical resistivity is the quantification of how well a material opposes the flow of an electrical current. Mathematically, the reciprocal of electrical resistivity(ρ) is electrical conductivity (σ).

i) Soil water content

Several researchers have proven that an excellent correlation exists between soil moisture content and EC_a (Rhoades *et al.*, 1976; Hendrickx *et al.*, 1992). A report by Brevik *et al.* (2006) stated that soil water content was linearly related to EC_a. A variation of more than 80% in soil water storage was recorded by Kachanoski *et al.* (1990) in a calcareous soil with a moderately-fine texture. The sensitivity of the EM-38 was investigated by Padhi & Misra (2011) to determine soil water distribution of a wheat field being irrigated; results indicated both linear and non-linear functions explaining 70% to 81% of water content.

Various investigations have confirmed that soil water content is indeed the most crucial factor of all other factors to influence EC_a since the main dependency of current flow is water content within the soil (Brevik & Fenton, 2002; Huth & Poulton, 2007). Due to the displacement of charge from water molecules, water flowing through or down soils creates a path for electric current flow (Williams & Hoey, 1987; Sudduth & Kitchen, 1993; Doolittle *et al.*, 1994). Soil properties are significantly affected as water moves through the soil. Water movement can remove or translocate soluble chemical components as well as colloids in suspension through a recharge process, under circumstances provided by the discharge process (Richardson *et al.*, 1992). During the same process, salt can dissolve increasing heat conductivity and

causing soil temperature to increase. Utilising an electromagnetic device (CMD, EM-38) under these conditions can result in variations within EC_a datasets along with other contributions from various soil properties.

In arid soil conditions, it can be expected that EC_a would be significantly affected because soil chemical reactions and current flow would cease under such conditions. Due to a weak correlation found by Johnson *et al.* (2001) between EC_a of soils and other soil properties within a dry land. Rainfall events also affect the EC_a data of soil during or within a short time-frame of an electromagnetic survey (Brevik *et al.*, 2006). An abundance of rainfall events resulting in an excessive amount of soil water content can cause the possibility that one would not be able to distinguish between low-level variations within EC_a data values (Clay, 2005).

ii) Soil salinity

Soil salinity is a direct result of the accumulation of salts. The salt content can be quantified under laboratory conditions as EC_e (electrical conductivity) is measured using saturated paste extraction methods or 1:1, 1:2 and 1:5 soil to water ratio methods which can be expressed in mS/m. These extracted soil paste samples through suction contain several electrolytes, and under wet soil conditions, these electrolytes enhance the ability of soil to conduct electrical current efficiently. The higher the presence and concentration of soluble salts within the soil the higher the electrical conductivity and vice versa. The paste extraction method is a very efficient and accurate method of measuring soil salinity despite stressful conditions that might occur (McNeil, 1992). Results obtained with the paste extract method with respect to EC_e is the field equivalent of EC_a measured using an electromagnetic device such as the CMD (Nadler & Frenkel, 1980). The EM device only requires a calibration function to complete the conversion between EC_e and EC_a (Vlotman, 2000). In the presence of low conductive soils, the relationship between these two variables is significantly reduced. Some relationships exist between EC_a and EC_e for a variety of soils according to Rhoades (1989), he illustrated that EC_a values increase in proportion to the percentage clay present within each soil type. On high conductive soil, salinity could influence EC_a values. When excessive salt dissolves within a soil, this phenomenon can affect the soil-water balance; it can cause the water table to rise through capillarity, exposing salts making it readily detectable with the EM device, more than the soil actually of interest (Rhoades & Corwin, 1981).

2.5 Soil Water Management

Optimising soil water management can lead to increased profitability as well as conserving water and energy. Implementing such management strategies results in environmentally friendly and sustainable agricultural practices. Across various agricultural fields, water has been managed through irrigation practices in a low-rainfall-, water-scarce area, with drainage

when the amount of rainfall is excessive and water table management if the water supply changes from excessive to deficient during the growing season. One approach that can contribute significantly towards precision irrigation includes characterising spatial and temporal variations of soil properties to delineate management zones within an agricultural field (Sadler *et al.*, 2005).

Removing excess water from the rooting zone can be conducted by implementing surface drainage to provide favourable conditions for plant seeding and emergence. Shao *et al.* (2012) conducted a study concerning water-logging and soil salinity in the coastal areas of China where the effects of subsurface drainage were examined. Studies indicated, under the prevailing soils and agro-climatic conditions subsurface drainage is an effective method to implement and correct waterlogged soils and to remediate saline soils. Water tables levels can also be significantly dropped instantly after a rainfall event implementing subsurface drainage.

In order to support water table management, in addition to their traditional use for water drainage and flood control, the design management strategy, and operation of land drainage systems need to improve. Recent studies explored the benefits of spatially targeted water level management to reduce salinity (Simpson *et al.*, 2011; Holman *et al.*, 2013). Holman *et al.* (2013) conducted a study where the impact of water level management was considered for implementation within a drained lowland coastal aquifer. The study promoted the development of a computational model, linking the peat and drainage data to drain coefficients, to reproduce patterns present in drain salinity. It is confirmed that acceptable solutions need to balance the costs and benefits on a correct scale, taking into account the impact of the intervention in the areas immediately adjacent to the drained area.

Another model was developed for quantifying the performance of multi-component drainage, and related water management systems on a continuous basis. For example, DRAIMOD which is a field-scale, process-based, and distributed simulation model that was initially developed in the 1970's (Skaggs, 1977, 1978). The model and algorithms were recently described by Skaggs *et al.* (2012) that were used to quantify different hydrologic components. The model consisted of inputs for soil properties, site parameters, weather data, and crop characteristics. This study also demonstrated methods for determining the useful field values of critical inputs to the model through a case study approach. Further model development of DRAIMOD-DSSAT, which integrated the crop growth modules of the Decision Support System for Agrotechnology Transfer (DSSAT) and DRAIMOND, resulted in a whole system model for crop production on drained lands.

Controlled drainage systems have beneficial water quality characteristics that can be maximised only by proper design and management (Thomas *et al.*, 1992). Unfortunately maintaining an adequate level of water for usage by crops in every part of the field is complicated when conducting water table management.

The correlation between crop yield variation and the application of water causing variations in water content has been thoroughly investigated (Allen *et al.*, 1998; Forbes & Watson, 1992; Hanks, 1974). Through these studies, it has repeatedly been proven that soil water management is a possible solution for the higher demand in crop production, in the form of variable rate irrigation systems (VRIS) or centre pivot irrigation systems (CPIS). VRIS can alter water application rates spatially. This system maximises water use efficiency by maintaining the desired amount of water within the soil for the plants to transpire at its optimum rate, and to withhold irrigation when the soil is at its maximum desirable water content or field capacity (Hedley and Yule, 2009a). However, Lu (2005) concluded in his investigation that VRIS are uneconomic since the profit from conserved water and increased yield cannot balance the high costs involved. However, with the increase in given attention to conserving fresh water for irrigation during drought, to domestic and industrial demands, and by keeping environmental needs and recreational activities in mind, the conclusions regarding desirability and profitability of VRIS may change (Sadler *et al.*, 2005).

Various technologies exist to improve agricultural irrigation operations, through better management and efficient use of irrigation water. Ranging from soil moisture detection and monitoring tubes to sophisticated canal automation and telemetry.

The best irrigation practices strive to maintain soil water content between field capacity, where the soil reaches a saturated state unable to absorb more water, and allowable management depletion where soil water content is halfway between field capacity and permanent wilting point (Peters *et al.*, 2013). When these limits are exceeded, under or over irrigation of water occurs. The outcome of both scenarios may result in stress that can reduce crop yield (Martin *et al.*, 2014). The permanent wilting point is the soil water content level at which the plant cannot extract water and thus is subject to permanent damage. While the consequences of under watering are well recognised, the consequences of overwatering may sometimes be underestimated. Overwatering can lead to the leaching of mobile nutrients in soils, drainage issues, waterlogging, and salination of patches caused by evaporation of water that leaves its salt content on the soil surface (Martin *et al.*, 2014). An increase in algae and aquatic plants can also be generated by fertilisers that wash into the groundwater or surface water, known as eutrophication (Smith *et al.*, 1999). This phenomenon can degrade the quality of freshwater- and alter ecosystem structure and function worldwide (Dodds *et al.*, 2008). The

scientific community understands the consequences of under- and overwatering, but the way to maintain soil water content at the optimal level at every location of the field still requires further investigations.

Available water-holding capacity is the maximum amount of water accessible to crops within the root zone, held between field capacity and the permanent wilting point (Schmitz and Sourell, 2000). The field capacity and permanent wilting point change with soil properties. Hence a delineation of field areas possessing homogenous characteristics for site-specific management zones (Fleming *et al.*, 2000), which is important for precise irrigation management (Hedley *et al.*, 2009). Differences in available water-holding capacity require different irrigation frequencies, thus emphasising the need for detailed soil maps, characterising the variability in soil water content to more efficiently manage irrigation. There is enormous potential for improvement in water management, and more knowledge and techniques are to be obtained and implemented.

Site-specific management zones are described as similar regions within fields that have similar edaphic properties limiting crop yield. In the case of site-specific management zones for precision irrigation, these are the soil hydraulic properties that define the optimal soil water parameters for each region (Hedley *et al.*, 2009a). The adoption of site-specific management zones for irrigation has demonstrated to be an active practice to increase irrigation efficiency, defined as the amount of water used by the plant by the total amount of water applied (Evans and Sadler, 2008).

Research has indicated a significant improvement in the water use per unit of dry matter produced for potatoes, maize, and pasture with the application of site-specific management zones (Hedley and Yule, 2009b). Sadler *et al.* (2002) explained the spatial response of maize to irrigation rates in fields that present different soil types.

Precision irrigation or variable rate irrigation systems provide the possibility of varying the amount of water across the field (Yule *et al.*, 2008). Thereby, precision irrigation presents an opportunity to improve the water-use efficiency by targeting optimal water rates needed within each site-specific management zone. Precision irrigation has the potential to reduce contamination of groundwater through a decrease in chemical leaching, increasing the harvestable area by limiting water-logging, and decrease the incidence of crop diseases (Sadler *et al.*, 2005). Hedley *et al.* (2009) demonstrated the potential of variable rate irrigation to address the soil hydraulic spatial variability and reported water savings of up to 26.3% on a 53ha maize field with little variability (161-164mm) in available water-holding capacity. Sadler *et al.* (2005) reported savings of up to 50 % with precision irrigation techniques. Variable rate irrigation strategies are currently extensively based on apparent soil electrical conductivity

surveys (Hedley and Yule, 2009; Martin *et al.*, 2014). Measuring apparent soil electrical conductivity is a quick, non-invasive, and reliable technique that is commonly employed to characterise the spatiotemporal variability of a variety of edaphic properties (Corwin and Lesch, 2005a). Previous studies directly divided fields into high, medium and low EC_a zones to assess the soil water content variability (Fleming *et al.*, 2000; Hedley *et al.*, 2009). Commercial agricultural retailers use this approach broadly. Peralta *et al.* (2013) suggested that using more than three zones does not increase the available information on various soils. However, the determination of the optimal number and boundaries for the classification is not straightforward. There are complex interactions between soil factors that may affect soil hydraulic properties. Thus the number of zones definition should be tailor-made for each field.

2.5.1 Centre Pivot Irrigation

Centre-pivot irrigation, sometimes called circle irrigation or waterwheel, is a method of crop irrigation in which equipment rotates around a central pivot point and crops are watered using sprinklers (Omary *et al.*, 1997). The majority of centre-pivot irrigation systems apply water at a uniform rate to entire fields. However, most fields exhibit spatial heterogeneity for several soil characteristics that influence soil water content, such as soil type and topography (Yule *et al.*, 2008). Common agricultural practice is to adjust the irrigation rate for the driest part of the field ensuring that no part of the field is under irrigated (Peters *et al.*, 2013). The result is the sub-optimal utilisation of water on the other parts of the field, thereby wasting water.

2.5.2 Variable Rate Irrigation

The principle of variable rate irrigation technology is the management of irrigation water for individual sub-areas within a field to match the water requirements of that zone. The science developed around these technologies is also applicable to better inform uniform irrigation application. The benefits of variable rate irrigation management technology are demonstrated by King *et al.* (1995). Several centre pivot manufacturers also have a variety of variable rate irrigation options (Kranz *et al.*, 2012; Evans *et al.*, 2013), the adoption of this technology has been relatively slow (Evans *et al.*, 2013). Evans *et al.* (2013) linked this in part, with a need to quantify economic and other benefits of variable rate irrigation technology. Evans and King (2012) and Evans *et al.* (2013) discussed the need to produce technologies to inform VRI water management schemes. A number of the recent variable rate irrigation prescription or schemes has focused on tailoring irrigation to soil spatial variability (Hedley *et al.*, 2009). Hedley and Yule (2009a, 2009b) and Hedley *et al.* (2009) related soil electrical conductivity to available water-holding capacity. Available water-holding capacity management zones based on apparent electrical conductivity maps were generated by the above-mentioned authors. They were then able to simulate a water balance separately for each zone assuming uniform precipitation and evapotranspiration. One advantage of this approach was an increased ability

to obtain the maximum benefit from rainfall as compared with irrigating an entire field based on soil with relatively low available water-holding capacity. (Lo *et al.*, 2016).

Earlier models were improved by Hedley *et al.* (2013) combining apparent electrical conductivity and terrain maps coupled with soil moisture data at specific locations to develop VRI prescriptions. They planned to validate the procedure in future years. A more complex approach by coupling a crop development model with the soil water balance to optimise variable rate irrigation management based on various objects was utilised by McCarthy *et al.* (2014b). It was found that the irrigation management model, when coupled with a predictive crop model, performed better than when informed via soil and crop status sensors (McCarthy *et al.*, 2014a). Hillyer and Higgins (2014) made use of a deficit irrigation optimisation model to develop prescription maps for deficit irrigation with variable rate irrigation. The grouping of soils generated management zones by field capacity and available water-holding capacity. The assumption that soils with similar field capacity and available water-holding capacity would have similar soil water depletion. The preliminary results suggested water and energy savings after applying four consecutive prescriptions on a study field near the end of the growing season in 2013. Infrared thermometers were used by O'Shaughnessy *et al.* (2015) to inform a variable rate irrigation prescription algorithm of crop water status in cotton. The algorithm generated a dynamic variable rate irrigation prescription. The methodology compared well with a treatment that required manual oversight for all but their lowest water application treatment. This specific research demonstrates the need for sensing and modelling for variable rate irrigation prescription development.

Today, precision agriculture involves the variable-rate application of all critical agricultural inputs, including water. In the irrigation industry, this means a precise amount of water is applied at the correct time and at the correct rate in every part of the field, instead of uniform rates across the field with a fixed time interval (Sadler *et al.*, 2000). In this paper, it was demonstrated that to achieve variable-rate irrigation, an otherwise conventional irrigation system would need variable-rate sprinklers, position determination, variable-rate water supply, and possibly, the capacity for the variable-rate application of other agricultural inputs, such as nutrients and pesticides. In contrast to the conventional, uniform rate irrigation, this irrigation application aims to provide a water supply based on the site-specific local needs and finally, leads to the conservation of water and energy while achieving higher crop productivity. These practices were found to be more advantageous when implemented in agricultural fields with relatively high levels of spatial variability of soil hydrological characteristics.

Results from the case studies of Sadler *et al.* (2005) provided estimates of the possibility of nearly 50% water conservation using precision irrigation in single years, and an average from

8 – 20 %, depending on the previous irrigation management strategy. However, this study has not received favourable economic analyses based on the grain price to conserved water cost ratio; the relatively high cost of modifying the commercial machines needed to achieve precision irrigation capability that did not result in a profitable outcome.

A more recent study conducted by Hedley *et al.* (2009) compared VRI and uniform-rate irrigation (URI). The direct value of water saved using VRI was determined to be NZD \$149/ha in their study. Though the benefits of VRI are apparent, capable systems are slightly more expensive. However, as more producers adopt VRI systems, the cost of this technology will likely be reduced.

2.5.3 Scheduling for irrigation

Numerous strategies have been implemented for irrigation scheduling such as fixed timing and different depth of application, fixed depth and various timing, fixed depth, and fixed timing methods to obtain scheduling that includes using a soil-water balance, sensors, crop growth models, and crop water stress indices. Soil water content is an essential component of soil water balance and has been measured using multiple instruments which include neutron probes, TDR, and gravimetric methods (Camp 1998).

Three irrigation scheduling applications for corn were studied from 1979 to 1981 by Camp *et al.* (1988). These three applications consisted of tensiometers, screen-covered evaporation pan, and a computer-based water balance. The scheduling treatments for soybeans included tensiometers and screen-covered evaporation pan, that was replaced by a computer-generated water balance in the third year of study. It was found that mean yields over the three-year span were not statistically different among different treatments for both corn grain yields and soybean seed yields.

A study conducted by Caldwell *et al.* (1994) comprised of drip irrigation for corn using several irrigation frequencies replenishing the cumulative soil-water depletion every one, three, five and seven days. Irrigation initiation at cumulative soil water depletion of 12.7, 25.4, 38.1, and 50.8mm was evaluated. It was found that yields did not differ statistically for any of the eight treatments. Treatments with more extended periods of irrigation events had higher irrigation water use efficiencies and lower amounts of drainage.

Subsurface drip irrigation in corn under varying dripline spacing and irrigation cycling was evaluated by Stone *et al.* (2008). A 1-meter and 2-meter dripline spacing were used to apply 1, 2, or 3 pulses per irrigation. The two pulse treatment applied equal amounts of irrigation 12 hours apart, and the three pulse treatment applied equal amounts 8 hours apart. Irrigation was scheduled weekly using estimated crop water requirements. Irrigation was applied twice weekly; each application presented half of the crop water requirement for that specific week.

If rainfall occurred before the irrigation application, then the irrigation depth was calculated by subtracting the amount of rainfall from the total weekly crop water requirements. No statistical difference in yield could be determined in the first year between any of the spacing and pulse treatment combinations. In the second year, the one and two pulse treatments with dripline spacing of one meter resulted in statistically higher yields than the one and two pulse treatments for the lateral spacing of two meters.

Irrigation treatments of 0%, 25%, 50%, 75%, and 100% of crop evapotranspiration (ET) for soybeans were applied where each percentage of the irrigation treatments is a factor of the ET taking place. Crop ET was measured with a neutron probe. It was found that irrigating to 100% of ET had a statistically higher yield than the other treatments. Irrigated water use efficiency was not statistically different for any of the irrigated treatments.

2.5.4 Water Conservation through Irrigation

Efficient irrigation is near impossible without a thorough operative design and installation of an irrigation system, especially if it is not well maintained. Nonetheless, it is also true that how water move in the soil is key to overall irrigation efficiency, crop performance, and water conservation. When the movement of water becomes unmanageable within the soil, most well designed and managed irrigation will be unable to reach the expected outcomes. Therefore, irrigation is applied much more often due to plants that exhibit stress, which increases the consumption and decreases the efficiency of the irrigation schedule. Through the utilisation of well designed and operated irrigation systems, water usage can be optimised regarding irrigation through the efficient application of water delivery to the soil through the correct management practices that ensure the desirable soil hydrological behaviour. The application of soil surfactants will ensure that soils are still wettable to apply water at appropriate rates regarding irrigation and rainfall, which will move uniformly and quickly into the soil. The result of in-depth research has led to the conclusion that more efficient delivery at the root zone, especially where soil water repellency is a factor, can cause dramatic reductions in water use or requirements. In turfgrass management, reductions of at least 20% are achieved (Kostka *et al.*, 2005; Oostindie *et al.*, 2005). In various cases more than 50% of reductions have been reported (Park *et al.*, 2005; Karcher *et al.*, 2006). The utilisation of soil surfactants will enhance the conservation of water and the efficiency of irrigation.

2.5.5 Causes of Irrigation Mismanagement

A significant amount of irrigated water and rainfall is lost through run-off. This run-off can also cause a rise in the risk of pollution and erosion, and it increases the application of irrigation required. The run-off is amplified when water is applied at excessive rates or when infiltration is reduced through consolidation or compaction. While compaction has long been responsible

for the cause of reduced infiltration, this role has been exchanged for soil water repellency which is another cause of reduced infiltration and increased run-off. This has been confirmed in numerous studies conducted by Dekker *et al.* (2005). While this consequence has been responsible for a significant period in the case of severe water repellency, it has more recently been identified to occur with low levels of repellence as well (Hallet *et al.*, 2001).

3. Study Area

3.1 Location

The study was performed on the farm Cyferfontein in the Free State (Figure 1). The farm borders the Vaal River to the north within the C24B quaternary catchment drainage region near the towns of Viljoenskroon (Free State) and Orkney (North-West), South Africa (-26.974; 26.833). Geology of the area consists mainly of siliciclastic rocks especially in the vicinity of field C4 that give rise to the very sandy soil that is encountered. The farm consists of approximately twenty-two fields under pivot irrigation namely C1 to C22. The study was conducted on field C4 in the southeastern corner of the farm. The size of field C4 is 55.5 ha.

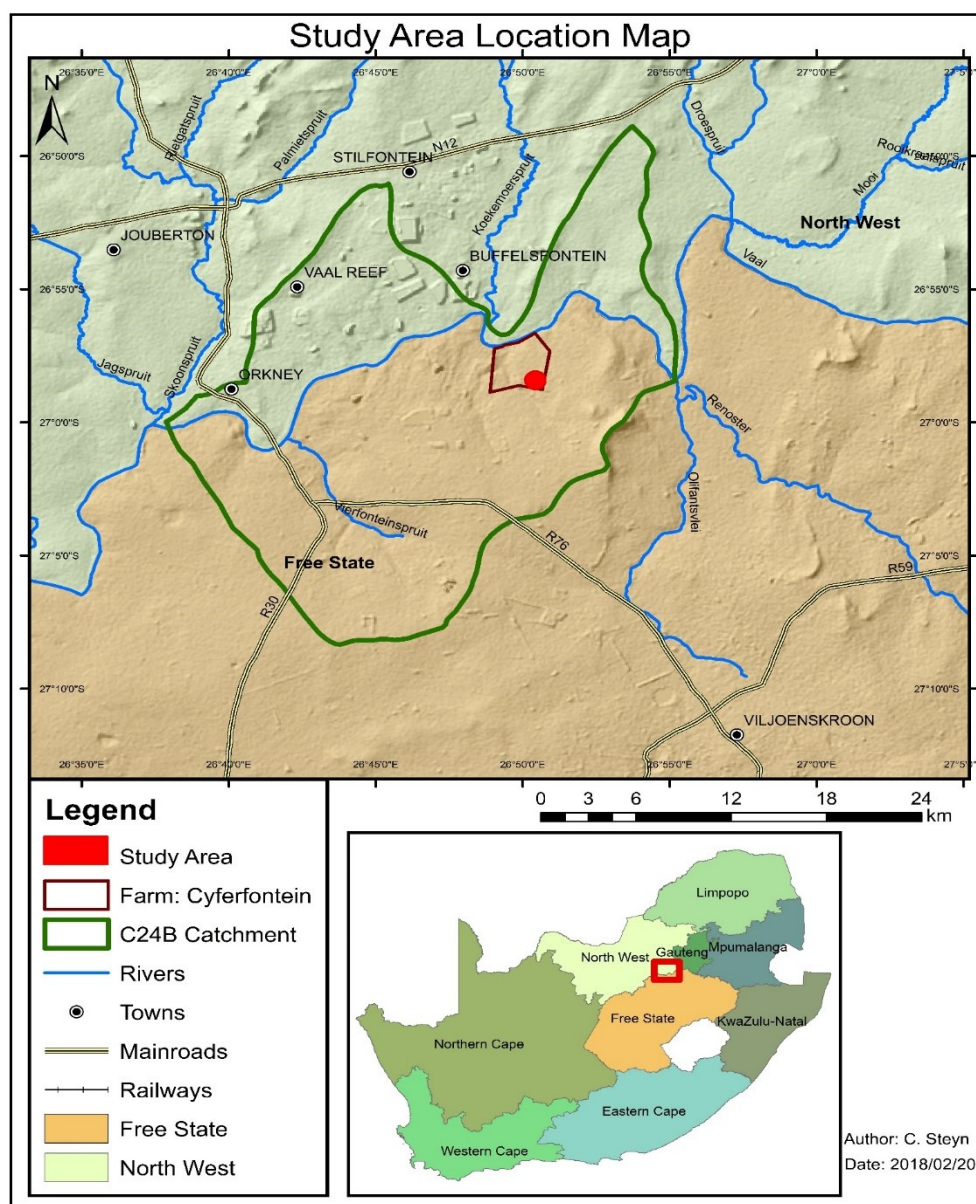


Figure 1: Location Map of Study Area

3.2 Topography

The elevation of the field is situated at approx. 1321 m above mean sea level. Sloping downwards towards the Vaal River in a north-westerly direction. The flow direction arrow in close proximity to the study area gives an indication of the run-off direction as seen in Figure 2.

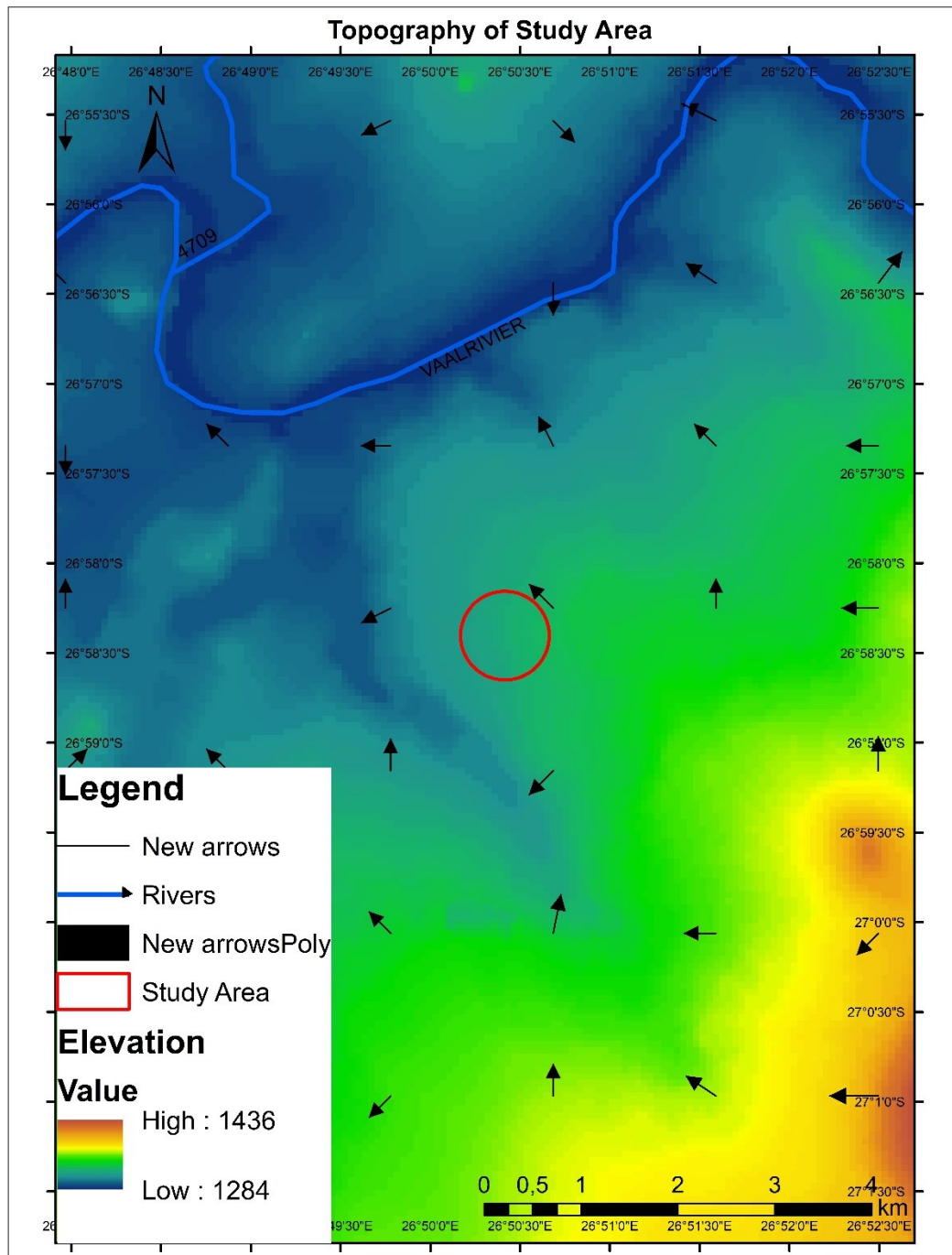


Figure 2: Topography map of the study area.

3.3 Climate

The study area falls within a summer rainfall area with the majority of precipitation between the months of November and February, gradually decreasing towards the winter months as displayed by Figure 3. The data collection were conducted in January, March and June. January represented the wet season, March was to capture the transition from summer to winter and June was to obtain data for the dry season

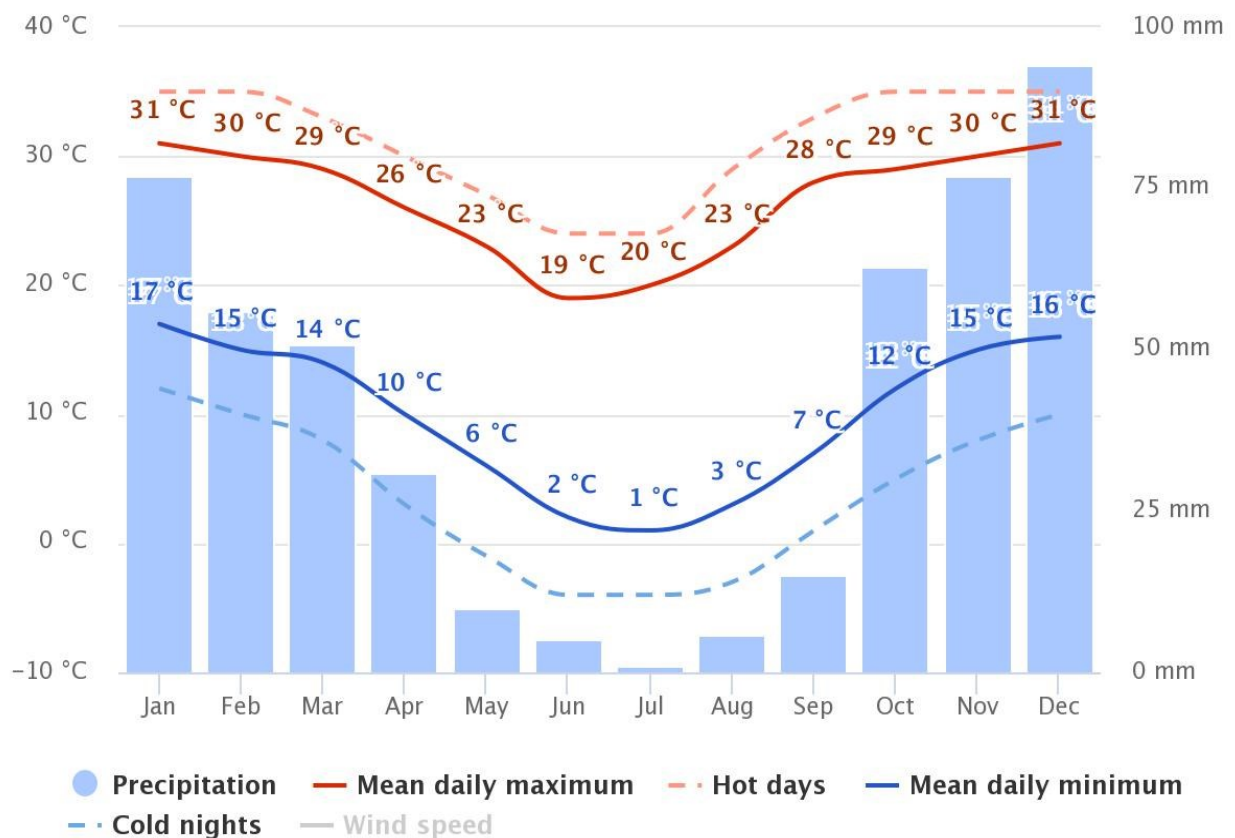


Figure 3: Average rainfall and temperatures for the study area (Meteoblue, 2018).

3.4 Soils

Five different soil forms were encountered as shown in Figure 4 namely, Avalon, Constantia, Longlands, Wasbank and Westleigh. The Wasbank soil form gives a good indication of shallow depth when compared with absolute depth, as well as with the concretions. The deeper soils consisted mostly of Avalon, Constantia and Westleigh.

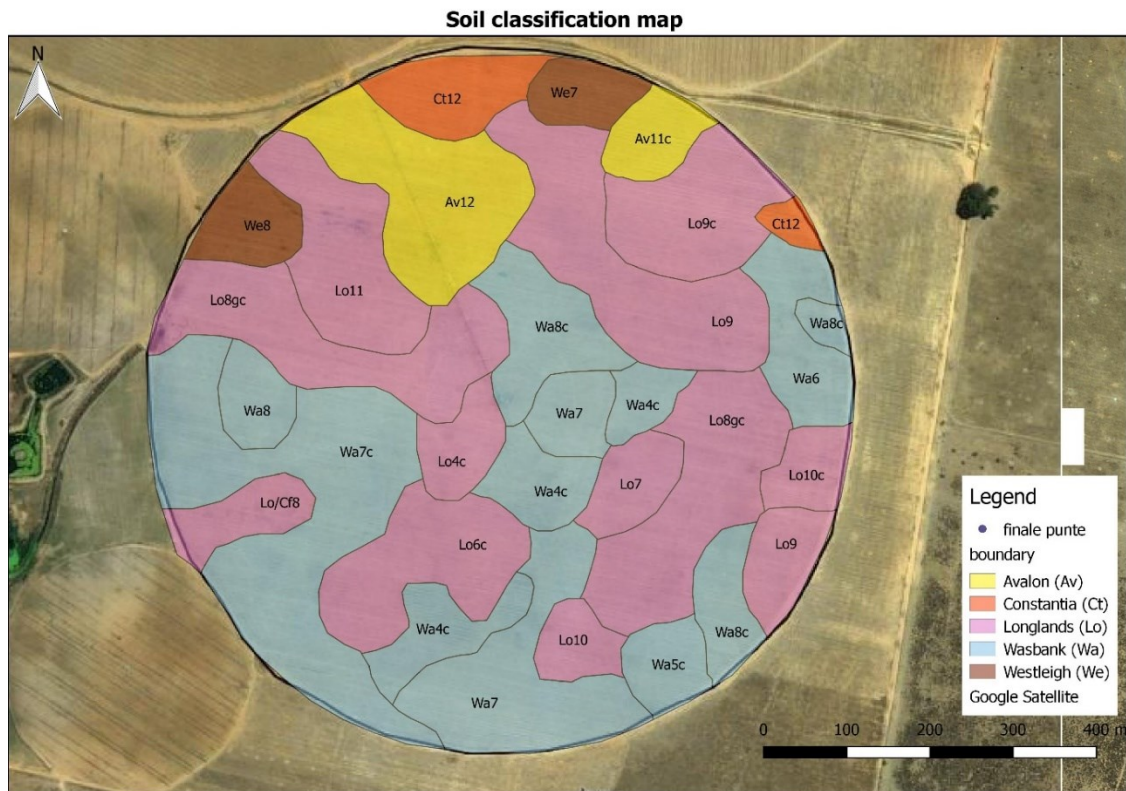


Figure 4: Soil classification map of study area.

4. Materials and Methodology

4.1 Soil Sampling

The pivot field was divided into a 100m x 100m grid indicated by Figure 5. Soil samples were taken at the centre of each grid cell by making use of an auger drill. Holes were drilled up to a maximum depth of 2.1m or up to the bedrock or present pebble or concretion layer.

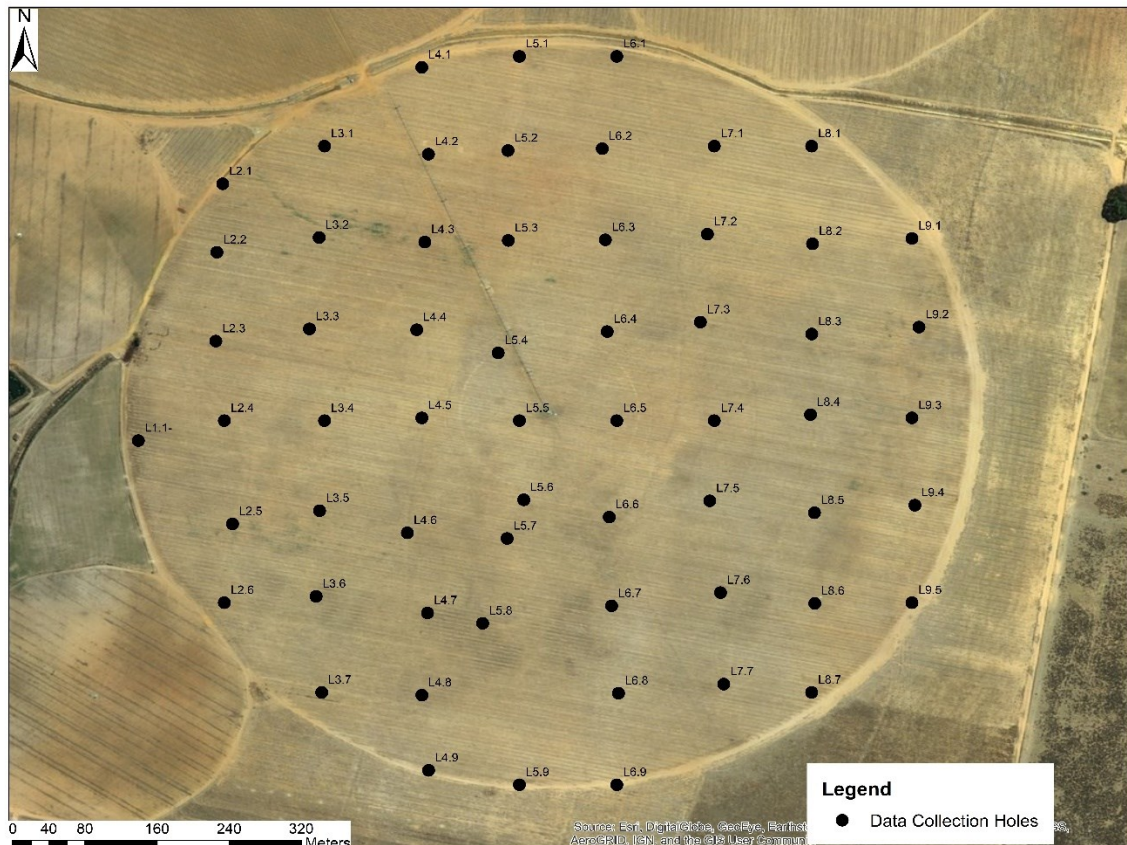


Figure 5: Data collection hole locations.

Numerous quantitative ways to express soil moisture exists. The sampling shown in Figure 6 and the drying method displayed in Figure 7 is the conventional way of measuring mass soil wetness. In this method, the wet and dry weights (after oven drying at 110°C for 24 hours) of the ratio of the weight loss in drying to the dry weight of the sample and be expressed as a percentage water content (Hillel, 2003). This method can be regarded as highly accurate; however; the sampling procedure is an invasive and destructive exercise, which may result in sufficiently disturbing an observational or an experimental plot to distort the results. Additionally, with this method, it is not practical to make high-resolution soil moisture measurements, as well as the sampling, can be limited with depth due to the inability to drill deeper due to pebble or concretion layers. The gravimetrically calculated soil moisture values were used for the calculation of volumetric water content. The soil samples were collected one

day after each CMD survey, to assess the soil properties that may contribute towards ECa measured at each point. If the soil between the points were homogenous, then any substantial deviation in measurement could be contributed to interference from the treatments at the centre of each transect. Using the Auger drill, samples were collected at ten different depth levels (0 to 0.3m; 0.3 to 0.6m; 0.6 to 0.9m; 0.9 to 1.2m; 1.2 to 1.5m; 1.5 to 1.8m, 1,8 to 2.1m) if permitted by the soil profiles at the 60 measuring holes, resulting in a total of 374 samples for the experiment for a specific data collection period. These samples were collected in plastic bags and weighed immediately before oven-drying. After the drying period samples were measured again in order to determine the amount of water that was released in the drying process, resulting in the final gravimetric water content.

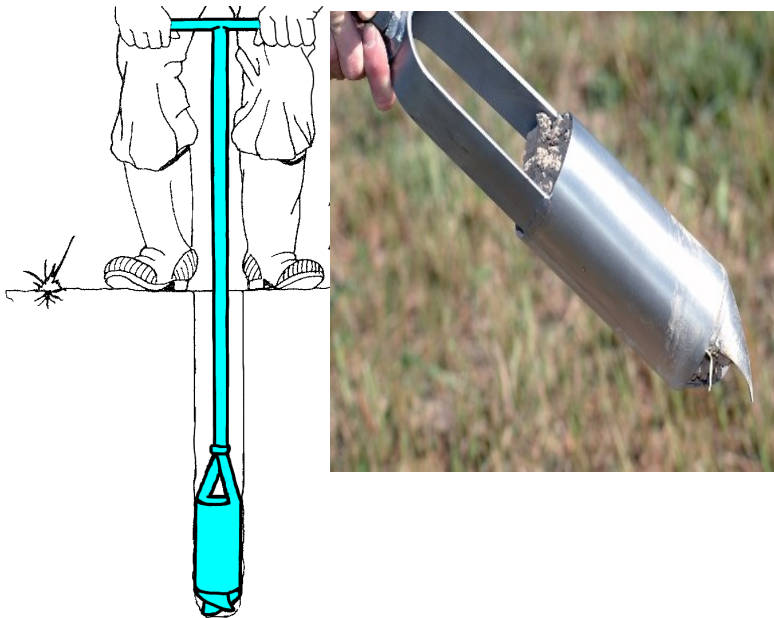


Figure 6: Soil sampling (AMS Samplers, 2018)



Figure 7: Laboratory setup for sample weighing and drying.

4.2 Neutron Probe

Neutron scattering is accepted as an efficient and reliable technique for measuring soil wetness in situ (Hillel, 2003). It has the advantage of providing less laborious, more rapid, non-destructive (after the initial installation of an access tube) measurements, which are not influenced by temperature and pressure. This method also allows for the measurements to be repeated periodically in the same location and at identical depths. The Neutron Probe results are all expressed in moisture count units. These units are acquired by the receiver determining the number of neutrons colliding with hydrogen atoms within the subsurface induced by the radioactive material. Unfortunately, access tubes could not reach the preferred depth of 1.6 m across the entire extent of the field due to the limiting factor of the available soil depth; this phenomenon makes it challenging to interpolate data with an increase in depth due to the

reduction in data. This reduction in data is due to the inability of the auger drill to extend to the preferred depth due to pebble layers that were encountered. This allows for a low degree of spatial resolution; it is difficult to measure soil moisture near the surface, and the neutron and gamma radiation involved may be hazardous to the health of the operator if the correct safety protocol is not followed.

Soil water content data were collected utilising the Neutron Depth Probe displayed in Figure 8. A total of 59 neutron probe PVC (Polyvinyl Chloride) access tubes as seen in Figure 9 were installed in field C4 within the data collection holes, distributed in a systematic grid, indicated by Figure 5. Soil water data were collected at 0.1m intervals to the full extent of the access tube if permitted by the soil depth; the maximum depth was 2.1m. The neutron probe readings were taken after each CMD survey and soil sampling session. The survey with the neutron probe was conducted for January 2018, March 2018 and June 2018. Moisture counts from the probe were used to determine the amount of soil moisture relative to other parts of the field. Neutron probe was calibrated against measured gravimetric soil water and bulk density measurements as obtained from the study area.

The Neutron Probe was also used to take density measurements by utilising the density measurement in the dry state function of the instrument. These density measurements were taken at 20 cm intervals, similar to the moisture measurements, throughout the total depth of each access tube. The Neutron probe was calibrated by taking readings from a total of three different experimental pre-determined densities. These three densities consisted of loose gravel, compacted gravel and water. By obtaining the absolute density of each of the materials, density calibration coefficients were calculated. Neutron density counts were plotted against the calibrated density values in order to obtain the bulk density of each measured sample.



Figure 8: Neutron Probe in operation.



Figure 9: Polyvinyl access tubes.

4.3 Diviner 2000

The frequency domain reflectometry instrument, the Diviner 2000 comprises a display unit and a 1.6m portable probe displayed in Figure 10. The probe can measure soil water content at 10cm intervals up to a depth of 1.6m into the soil profile. The probe consists of an aluminium rod with a probe cap containing the sensor at the bottom. A connection cable connects the probe with the display unit transferring data. The display unit is also used as a storage unit and conversion tool. Each measurement can be regarded as a snapshot of the present water content within the soil profile at a specific insertion hole shown in Figure 9. The diviner 2000

operates on the following principle: an electromagnetic field which is generated within a soil profile where the soil acts as a dielectric media of the circuit thus measuring the soil water content. This sensor relies on the fact that water has a much higher dielectric constant than air or dry soil. Taking into consideration that changes in soil water content are reflected by the changes in the dielectric constant of the subsurface (Sentek Environmental Technologies, 2001).

The more frequent measurements are taken, the more complete the change in water content becomes over a specific period. As described by the Diviner 2000 manual:

- (i) The sensor is very accurate with the measurements and consistent.
- (ii) The sensor is fast responding when taking measurements of the whole profile and can be completed in less than 10 seconds.
- (iii) The sensor is waterproof and signals an alarm when in contact with water inside an access tube.
- (iv) The results output can be numerical or graphics and can be assessed in the field to make instant decisions.

For this study, a default calibration equation was used. This equation was given by the manufacturers manual (Sentek Environmental Technologies, 2001), they recommended that relative changes in volumetric soil moisture content based on the default calibration can show the most critical soil water trends across a specific field.

Diviner 2000 measurements were taken along the same auger-drilled holes as shown in Figure 5. The diviner readings were taken up to a depth of 160 cm for each centimetre within the PVC access tubes. Before each fieldwork survey, the probe was calibrated for air and water by taking readings within an access tube above ground level for the air count and within a 1 m tall bucket filled with water for the water count. This is a standardised calibration for the Diviner 2000 to determine the upper and lower limits regarding moisture measurement readings for when actual water is encountered within an access tube or when the probe has not entered the soil for measurements. As was the case with the Neutron probe a reduction in data were encountered with the increase in depth that made the interpolation of data with an increase in depth difficult and less accurate.

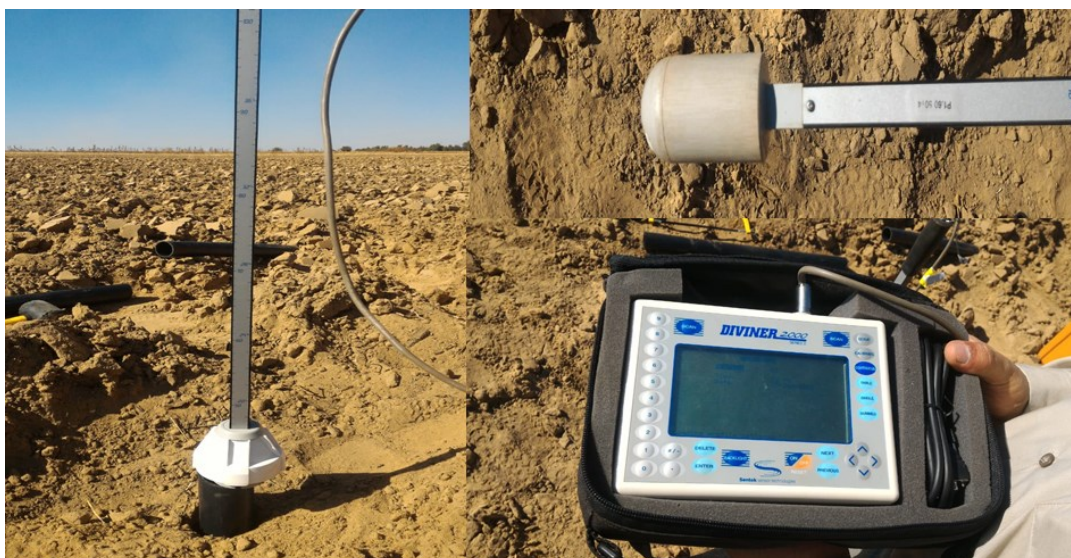


Figure 10: Diviner 2000 in operation.

4.4 Electromagnetic Induction

A predetermined grid, different from the soil sampling grid was surveyed where electrical conductivity measurements were collected with both CMD Mini-Explorer and CMD Explorer by GF-instruments displayed in Figure 11. A Bluetooth enabled GPS that communicates with the CMD was used to provide georeferenced apparent conductivity measurements, and flags were used to mark the survey lines to ensure that transects were repeated accurately for each survey. These surveys were designed to capture the temporal variation of soil EC_a at different times of a year. The CMD Explorer data were not utilised due to the depth of data acquisition being deeper than the depth of interest. The CMD Mini-Explorer data can be seen in Appendix B for both the wet- and dry season. By utilising various coil separations and instrument dipole orientations, the variations in average apparent conductivities could be inferred. The average apparent conductivity in mS/m was qualitatively compared with volumetric water content, neutron probe counts, frequency domain reflectometry values. CMD Explorer data although not incorporated in this study, can be viewed in Appendix B.

4.4.1 CMD Mini-Explorer

A different grid was followed with the CMD Mini-explorer. The CMD Mini-Explorer survey was conducted by dragging the CMD-Mini explorer behind an all-terrain vehicle (ATV) on top of a conveyor-belt sledge which consisted of no metal parts whatsoever to keep noise to a minimum shown in Figure 12. The field's survey grid was roughly divided into quarters, due to the difficulty in keeping a constant line direction caused by uneven terrain within the field. The line spacing of each quarter was approximately 10m. Readings were taken at half-second intervals while driving the ATV at an average speed of 17 km/h resulting in a reading being

taken every 2.35 meters. The CMD Mini-Explorer can operate on two different dipole orientations, firstly in the horizontal dipole to reach measurement depths of 0.25 m; 0.5 m and 0.9 m, secondly the vertical dipole that reaches depths of 0.5 m; 1.0 m and 1.8 m indicated in Figure 13. For this study, the vertical dipole was employed due to the measurement depths that covers the effective depth range rather than the horizontal dipole with shallow measurements. This device was also pre-calibrated by the manufacturer, and no in-field calibration was conducted. Each survey was completed over a period of 2 days from January 2018 to July 2018. The CMD-Mini Explorer enjoyed priority in this study due to the maximum depth of measurement being within the effective depth range which is more applicable than the much deeper measurements of the CMD-Explorer. The CMD Mini-Explorer measurements are also more comparative with the other hydrometric techniques than the CMD-Explorer. Due to the CMD Mini-Explorer being tugged behind the ATV, the armrest unit and telescopic handle were dismounted. The CMD Mini Explorer consists of one transmitter that induces a primary magnetic field into the soil, the secondary magnetic field is obtained by three different receivers at certain coil spacings from the transmitter to obtain the data at the respective depths, explained in Figure 13 and Figure 14.



Figure 11: CMD Mini-Explorer measurement grid.



Figure 12: CMD Mini-Explorer in operation (Freeland et al., 2002).

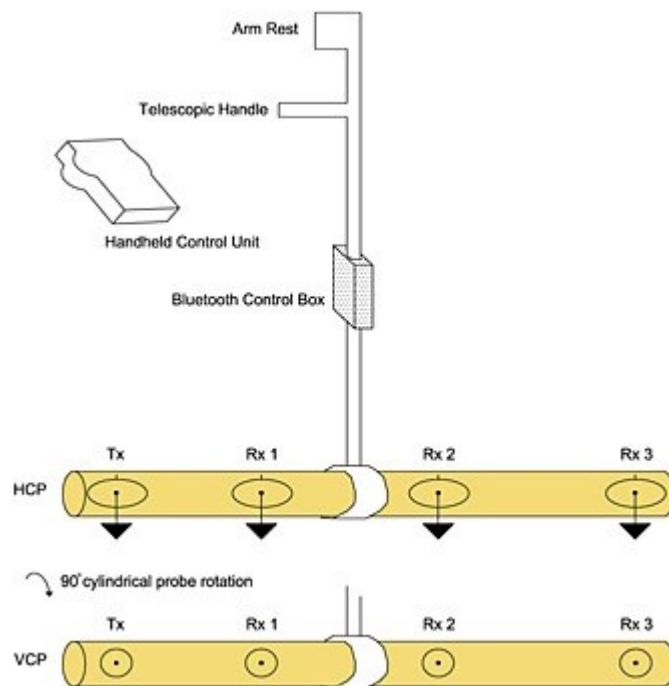


Figure 13: Layout of the CMD Mini-Explorer and the positions of the transmitter and receiver coils (Bonsall et al., 2018).

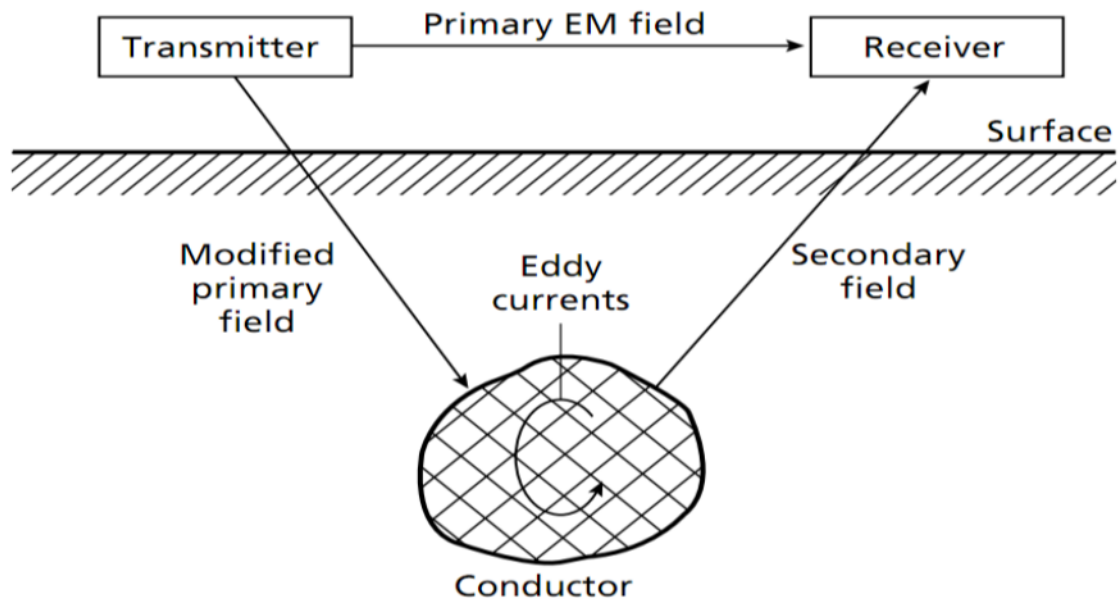


Figure 14: Electromagnetic operating principle (Marwan, 2015).

4.5 Summary of methods

Table 1 compares all the methods with regard to the amount of time it takes to collect data. This table indicates the sampling frequency for a specific period. Volumetric Water Content through sampling has the lowest rate of all the methods in order to determine the moisture values across the field. The Volumetric Water Content data collection process was also the only method that required additional laboratory analysis to determine the final result before data processing could commence.

The CMD Mini-Explorer has proven itself to be the best method regarding its data collection rate, data processing and ease of operation.

The Neutron Probe is a poor method regarding its data collection rate. The calculated rate excludes the time for augering the hole and fitting an access tube. The instrument itself is cumbersome making it difficult to carry around the field. The Neutron Probe also requires calibration before data collection can start.

The Diviner 2000 has a significantly high data collection rate. It is easy to operate and is lightweight. One drawback of the Diviner 2000 is the fact that a data collection hole needs to be augered as well as an access tube that needs to be installed, similar to the case of the Neutron Probe.

Table 1: Comparison of field procedures for each method.

Soil Moisture Measuring Method	Data Collection Rate (in field)	Data Collection Rate (in lab)	Data Processing	Total Data (1-Collection Period)	Ease of Operation
Volumetric Water Content Sampling	± 2 Values/5min	± 10 Values/ 5min	±4 hrs	±350 Values	Very Hard
CMD Mini-Explorer	1800 Values/5 min	none	±0,5 hrs	±150000 Values	Very Easy
Neutron Probe	± 16 Values/5min	none	±0,5hrs	±350 Values	Hard
Diviner 2000	± 200 Values/5min	none	±0,5hrs	± 700 Values	Easy

5. Results

5.1. Soil Characteristics and Classification

5.1.1 Topography

The elevation is the highest in the south-east and gets lower towards the north-west as indicated by Figure 15. Minor depressions exist in the east. Two small hills also exist on the western side of the field. The topography plays a great part in the direction and velocity of runoff and soil moisture flow.

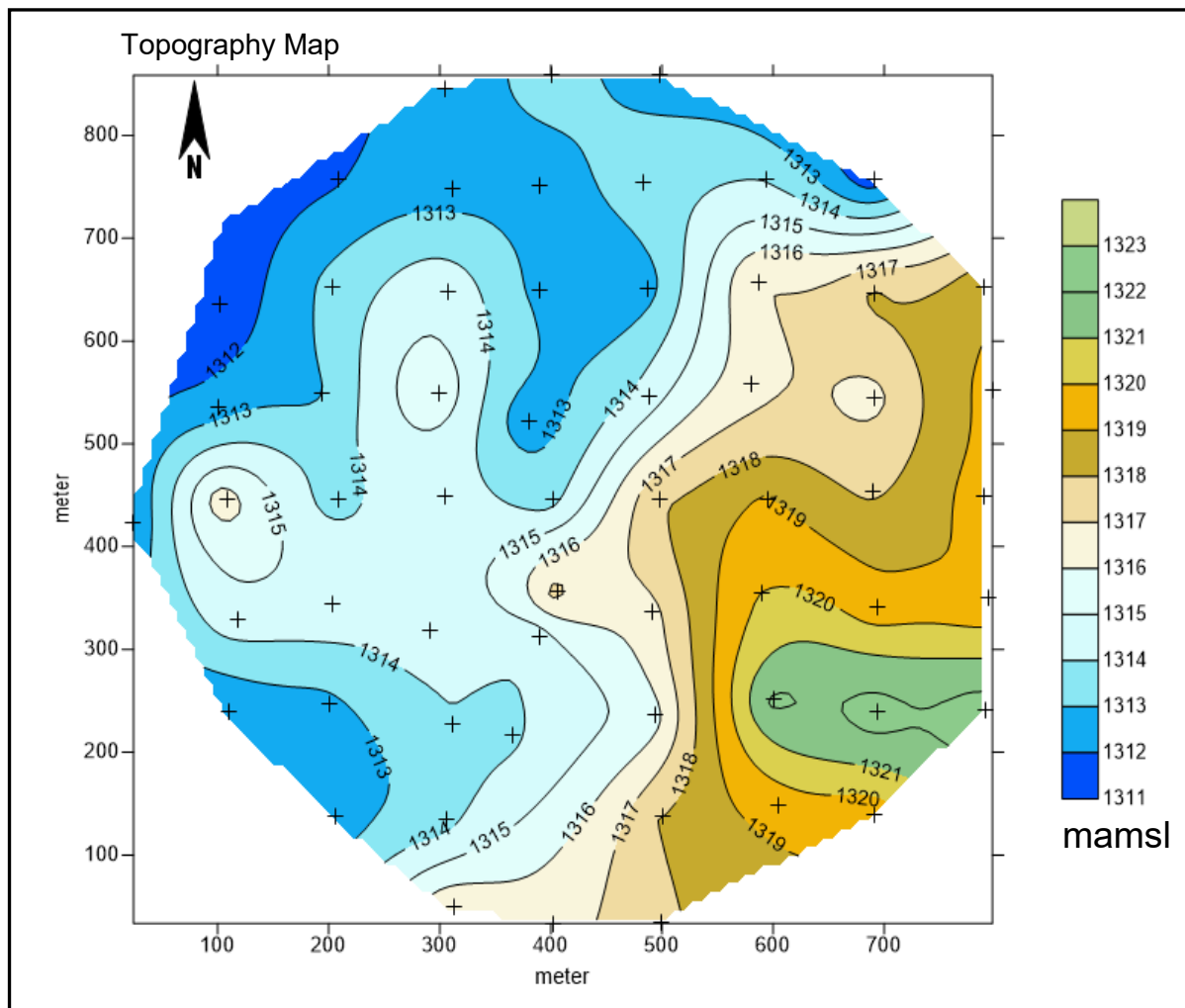


Figure 15: Map indicating the topography of the study area

5.1.2 Absolute Soil Depth

It is noted in Figure 16 that the soil depth is significantly higher to the north, north-west in comparison to the south. This has been determined during the soil classification process. The soil depth tends to correlate well with the concretion map regarding the fact that the concretions tend to be situated where the soil is shallow. Deeper soils are associated with the Avalon, Westleigh and Constantia soil forms.

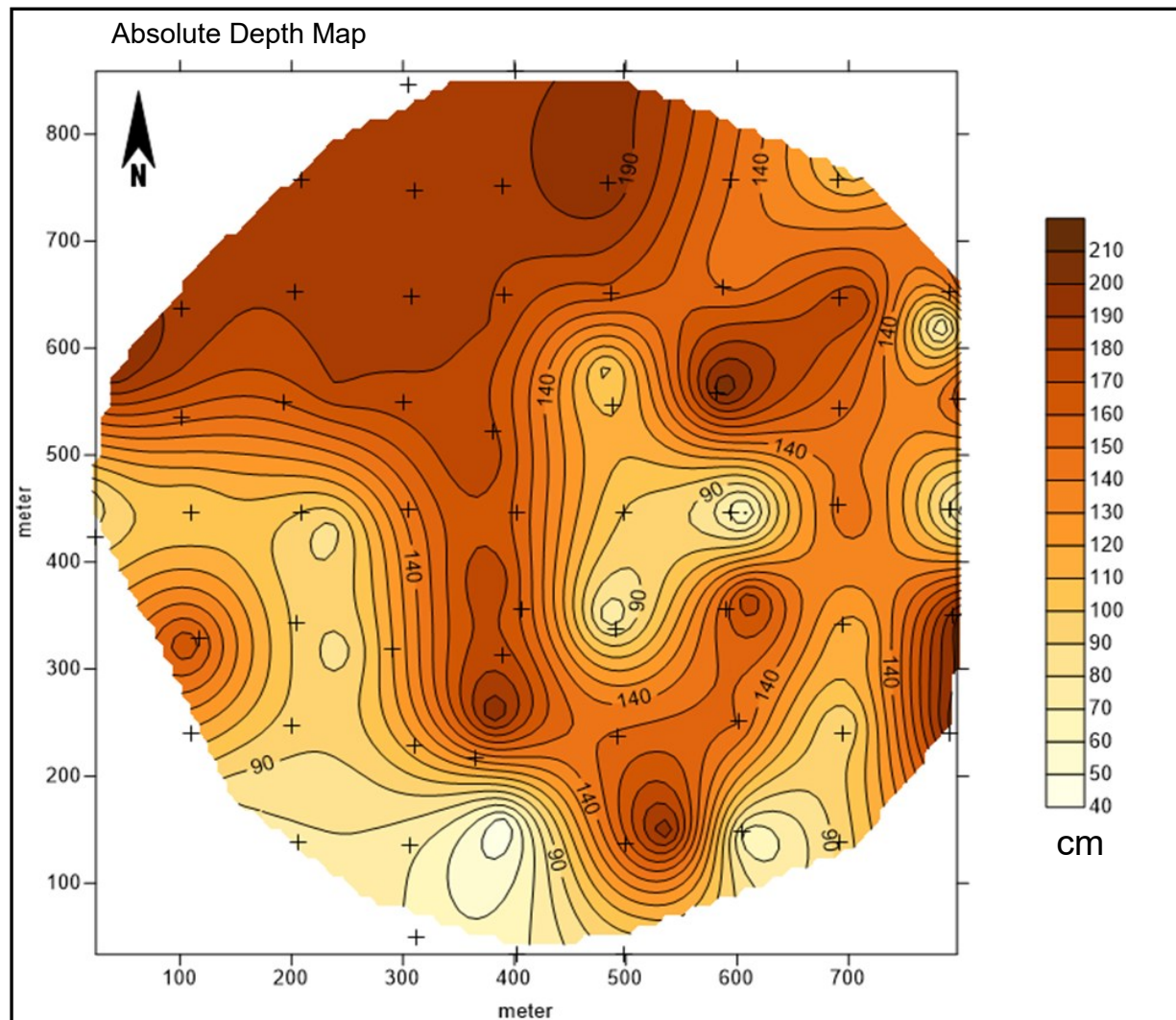


Figure 16: Map indicating the absolute depth of the study area.

5.1.3 Clay & Silt Content

Clay & Silt content has been determined during the soil classification procedure. Due to the sandy nature of the soil, clay content was relatively low across the field. Only five anomalies of relatively high clay content were encountered, indicated in Figure 17. The most substantial anomaly present was towards the north-western corner. A logical explanation for this anomaly could be due to the topography as noted in Figure 15, this anomaly finds itself in the lowest part of the field. Clay particles remain much longer in suspension and therefore would be deposited much later downstream than larger particles, therefore the large clay anomaly in the lowest part of the field. The two anomalies to the south can be regarded as outliers, due to the very shallow soils in which they exist and where it is situated in the topography. The large anomaly just off the centre of the field and to the north-east of the field is most likely due to the deeper soils that exist from the centre of the field towards the north. Clay content tends to increase in the areas where soils are much deeper. This is due to the high water-holding capacity properties that clay possess.

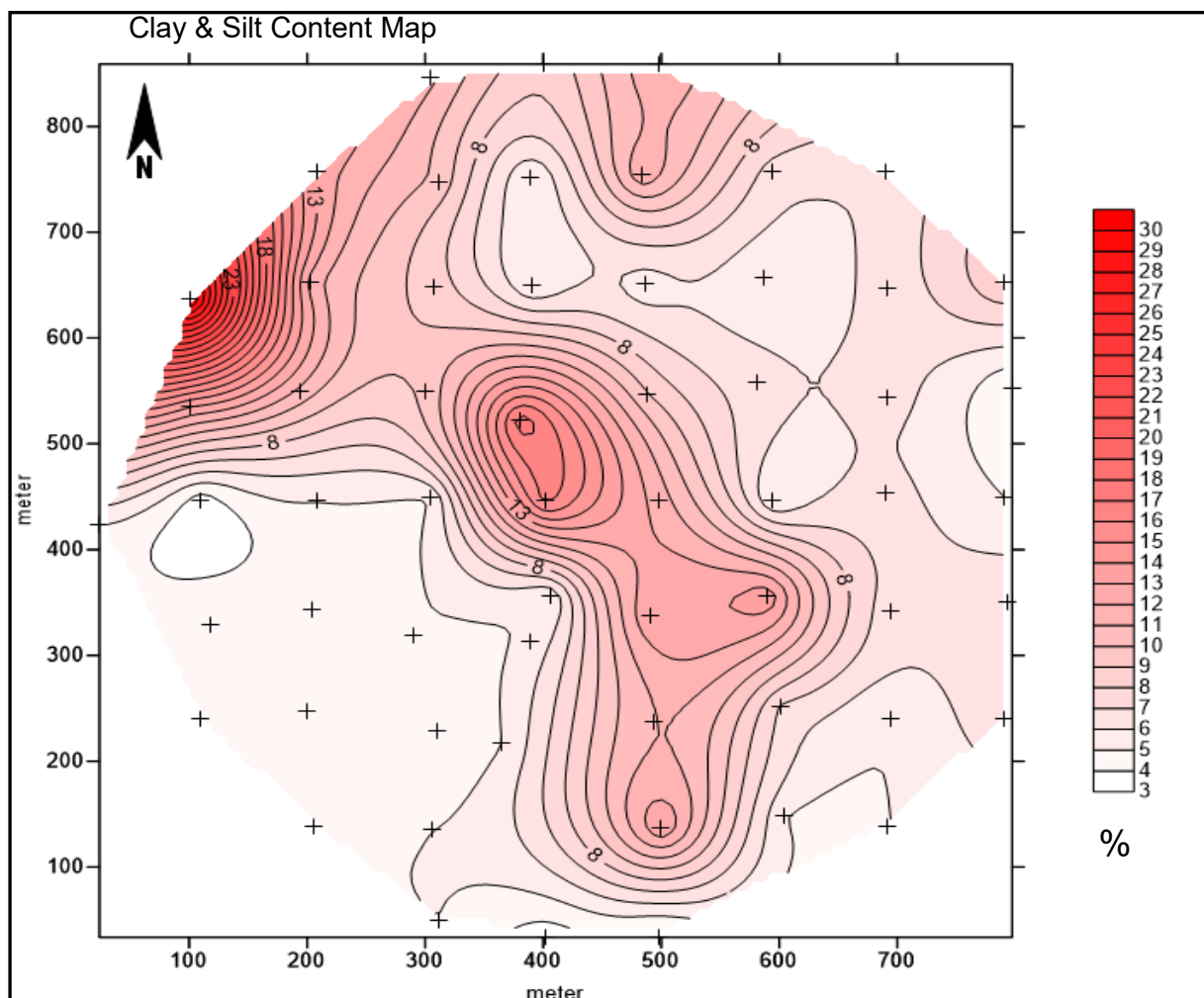


Figure 17: Map indicating clay and silt content of the study area.

5.1.4 Sand Fraction

The sand fraction of the soils has been determined by particle size distribution (PSD). Relative to clay & silt content much higher sand fraction values were acquired. The high sand fraction is a direct result of the weathering of the siliciclastic parent material found in this region. Sand anomalies existed across the whole field with very few outliers except for one towards the south that was present within shallow (closer to the weathering parent material) soils as shown in Figure 18.

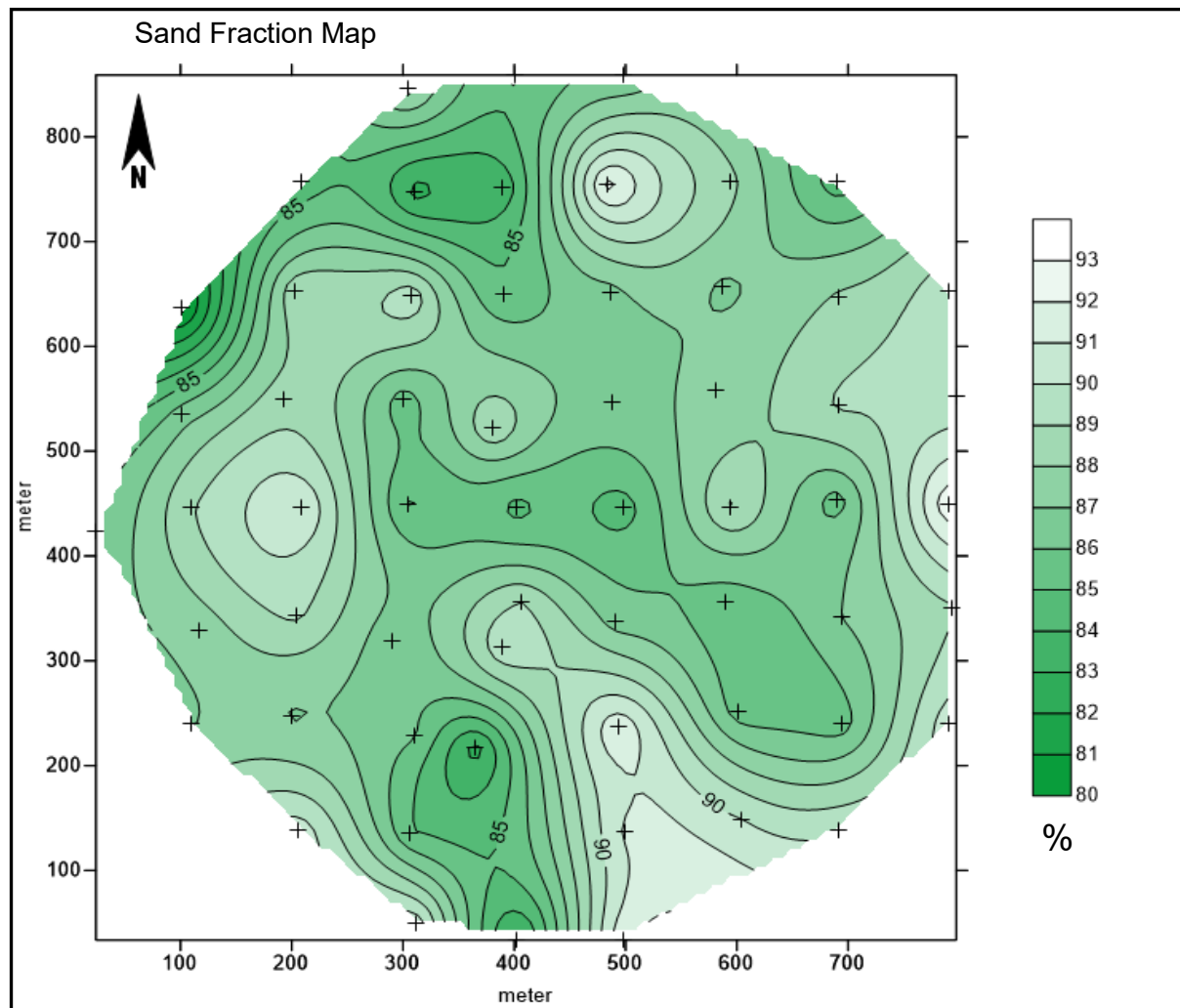


Figure 18: Map indicating the sand fraction across the study area.

5.1.5 Concretions

The concretions present within the field indicated by Figure 19 tends to be an indication of where the shallow soils are present within the field. In comparison to the soil classification map (Figure 4), a good correlation exists between the concretions and the Wasbank soil form which contains a hard plinthite horizon on the bottom. The plinthite is an iron-rich substance containing siliciclastic minerals. It usually forms where considerable contact with water was made over long time periods. No significant correlation exists between volumetric water content and the concretions.

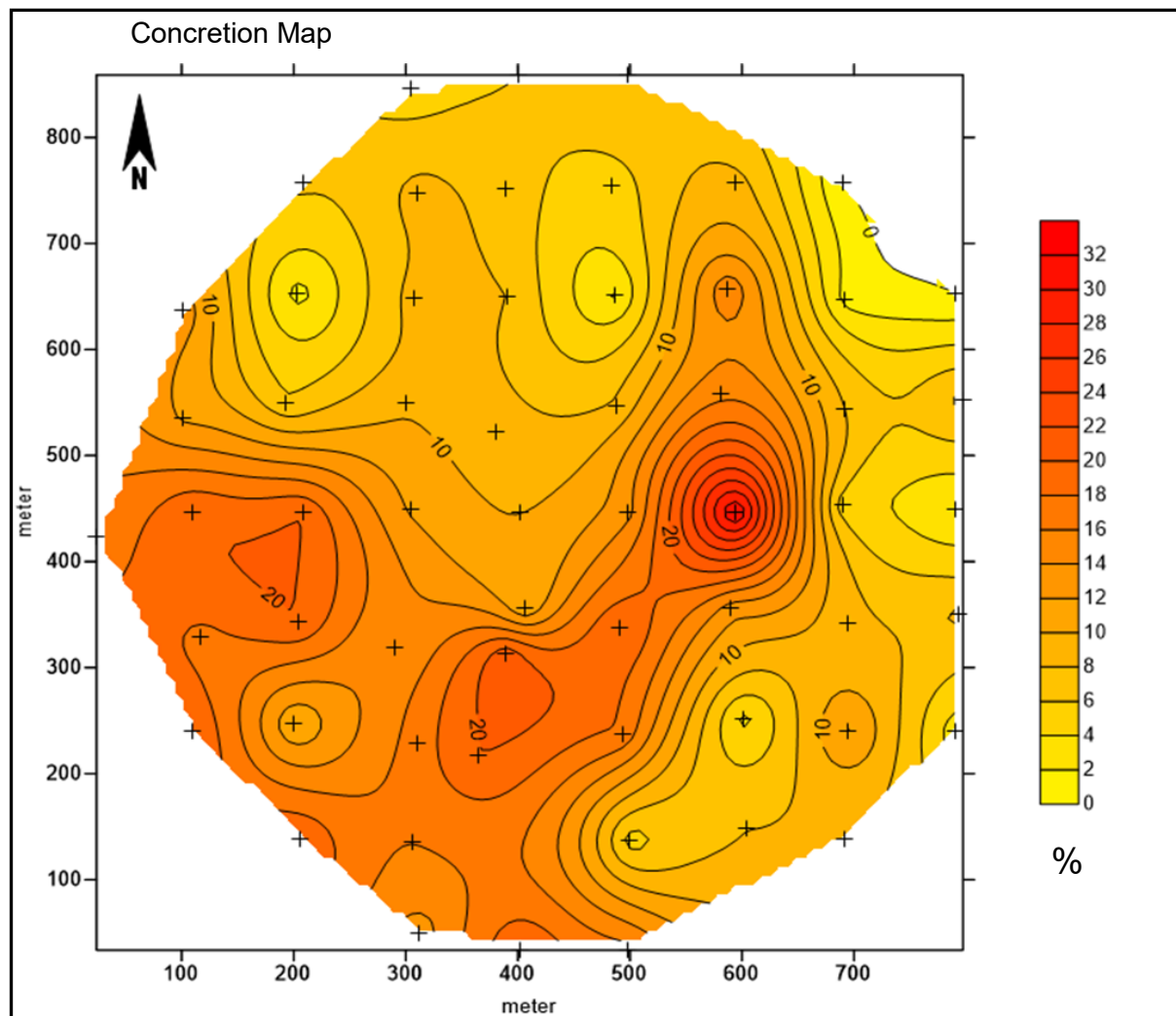


Figure 19: Average concretions across all depths.

5.1.6 Absolute Density

Due to the majority of the field being mainly sandy, the density tends to remain uniform throughout except for two anomalies towards the north and north-east. These two anomalies tend to correlate well with the Avalon soil form which consists of an orthic A -, Yellow/Brown apedal - and soft plinthite horizon and are also present in deeper soils. The density of sand is higher than clay due to the available pore space in clay being significantly more than in sand.

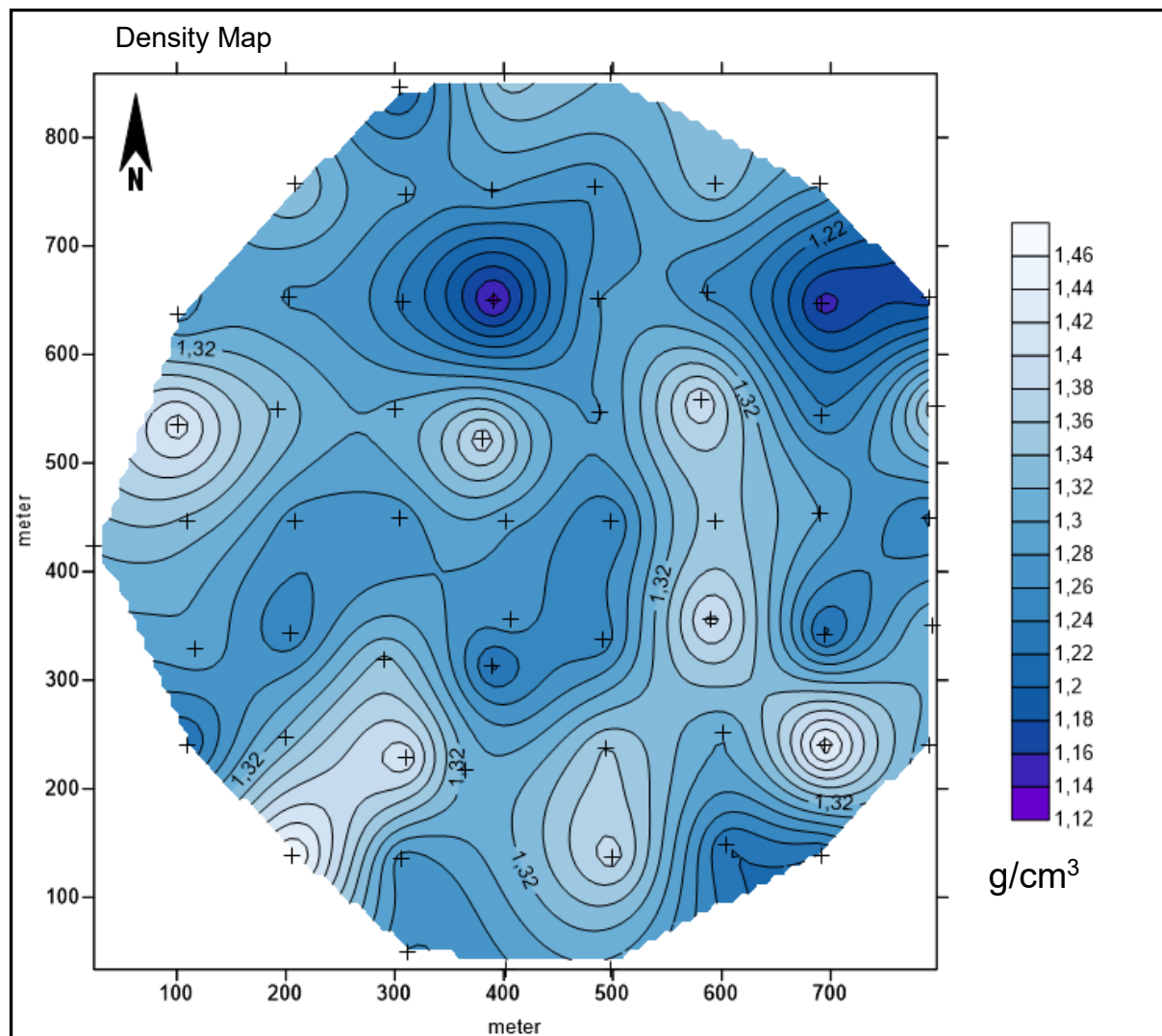
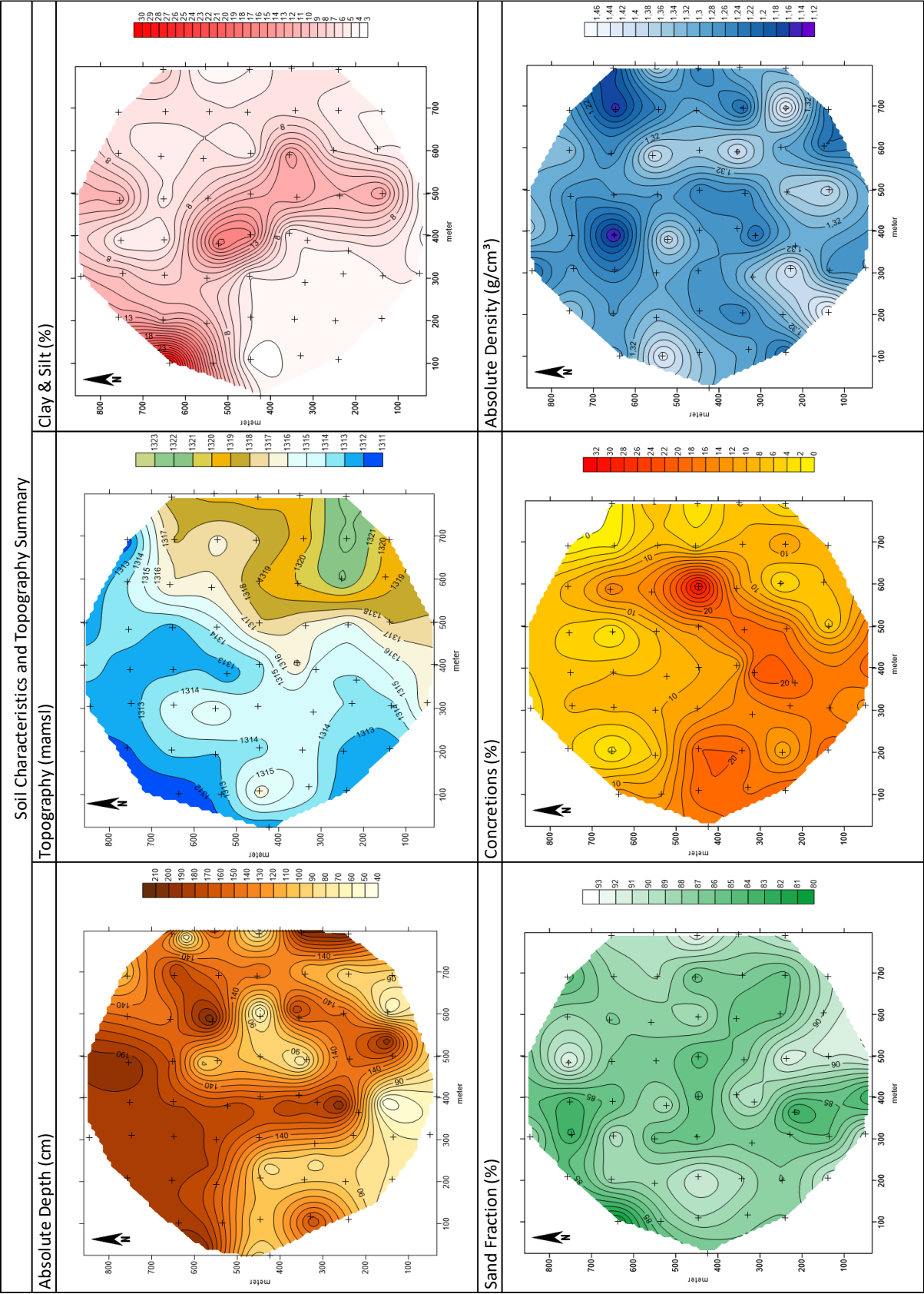


Figure 20: Map indicating the density of the soil in the study area

5.1.7 Summary of Soil Characteristics

Table 2: Soil Characteristics Summary.



5.2 Hydro-geophysical Data Analysis

The three hydrogeophysical methods (EMI, FDR and Neutron Scattering) that were examined have been evaluated separately regarding their potential to provide information about the subsurface moisture content within an agricultural field. The variations in the measured responses were assessed concerning both the spatial and temporal changes and compared to available hydrological data which included gravimetric and volumetric water content. The qualitative relationship between the hydrogeophysical responses and the hydrogeological information (i.e., topographical water flow, volumetric- and, gravimetric water contents) were examined. Additionally, the relationship between the FDR, Neutron Probe and EMI responses were quantitatively compared to the gravimetric data that was collected throughout the study to determine the most appropriate method for soil moisture management.

5.2.1 Volumetric Water Content Results

The volumetric soil water content as displayed in Figure 21 and Figure 22 is the volume of water per unit sample ($\text{cm}^3 \cdot \text{cm}^{-3}$). Volumetric soil samples vary between 0 and 0.23 over the entire data collection period. Each layer in each figure represents a certain depth in 20cm intervals. The shallowest depth is 20cm and the deepest being 160cm.

The January samples were acquired within the rainy season following irrigation applications throughout the growing season of crops. The application of water is evident throughout most of the soil samples due to the maximum recording of 23% volumetric soil moisture over the entire data collection period. Top layers of soil tend to have less soil moisture due to high evaporation rates taking place during this specific season. Soil moisture is more evident with an increase in depth due to the infiltration settlement and the increase of clay content with depth especially in areas where anomalies are present. Areas outside anomalies are more likely to contain less water due to the presence of a high sand fraction with minor water holding capabilities and higher hydraulic conductivity as well as to be more prone to higher evaporation of water. The March results (Appendix A), tend to have an overall increase in volumetric water content with depth which due to the more extended infiltration period, inflow and settling of soil moisture over time following the irrigation period and high precipitation rates between January and March. A definite reduction in soil moisture can be seen in the June results which is a confirmation to the end of the wet season. Evident anomalies tend to be smaller in comparison to January and March. This trend can be attributable to the outflow of soil moisture and prolonged evaporation and the lack of precipitation and irrigation between March and June.

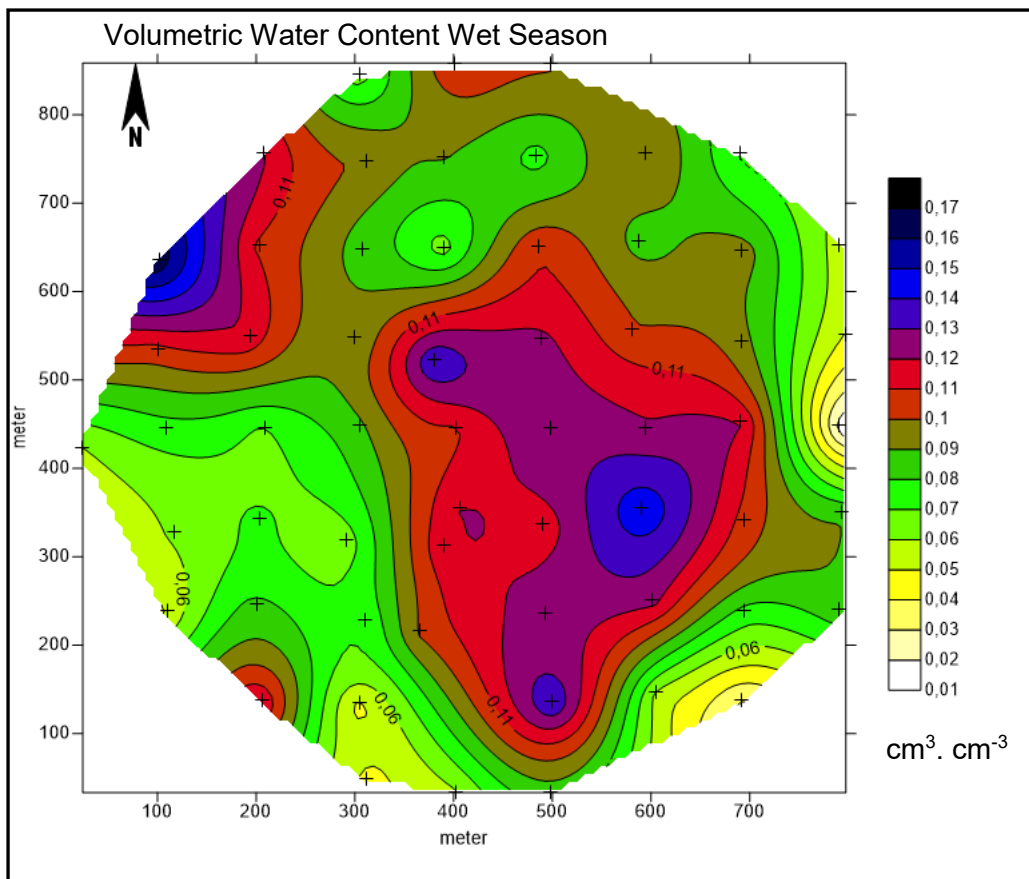


Figure 21: Volumetric water content for wet season.

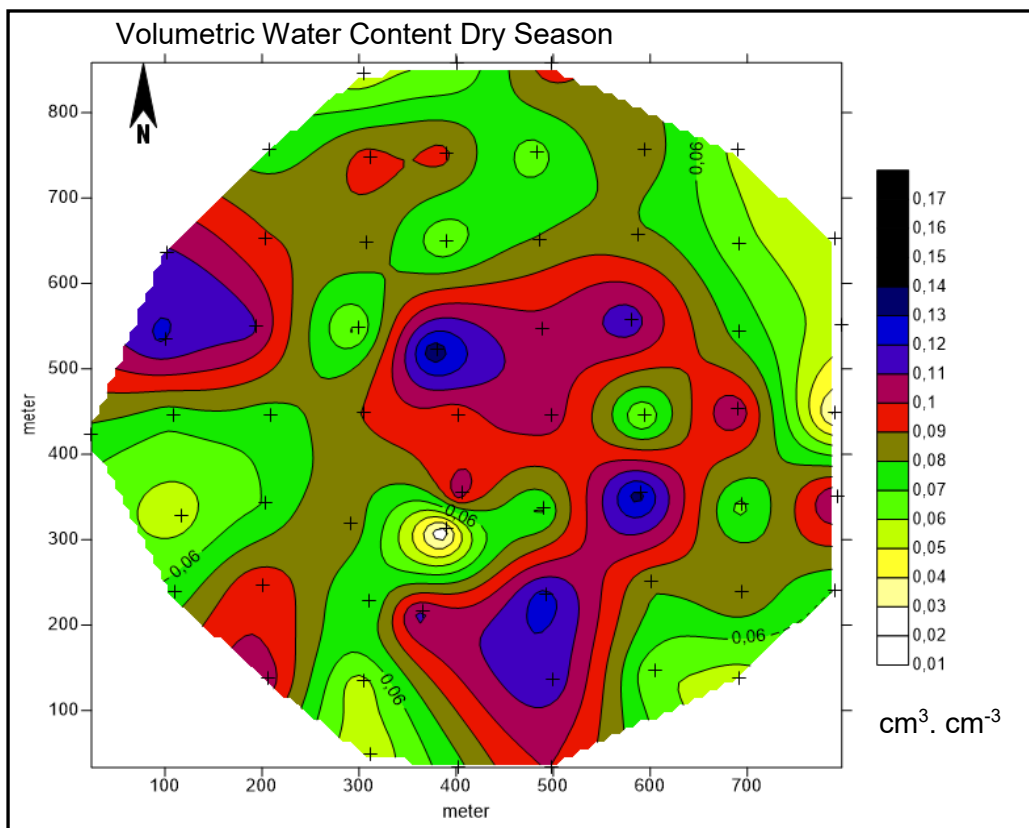


Figure 22: Volumetric water content for dry season.

5.2.2 Electromagnetic Induction Results

Apparent conductivity readings were obtained using the CMD Mini-Explorer and CMD Explorer along the entire grid that covered the field. As discussed in Chapter 2; the EM instruments are susceptible to changes in the subsurface conductivity. The CMD Mini-Explorer data collected along the survey grid has been plotted and interpolated for January (Wet Season) to illustrate the effects of varying seasonal and irrigation conditions. The maps of both seasons represent an average of conductivity values throughout the depth profile. A map of each depth of measurement can be seen in Appendix B. Due to the current inducing nature of the CMD Mini-Explorer physical contact is not necessary and is therefore not limited by any barriers that may be present within the soil profile. A complete dataset of conductivity was acquired for each specific measurement depth in comparison with other methods.

The CMD Mini-Explorer surveys were only carried out during January 2018 and June 2018 in comparison with other methods that were carried out during January 2018, March 2018 and June 2018. Even though data for March is not acquired, a seasonal difference can still be noted between the wet season (January) and the dry Season (June).

The apparent conductivities measured with the CMD Mini-Explorer using the vertical dipole correspond to a depth of 1.8m. The dataset contained 50800 conductivity values for each of the three depths more than any other method used during the fieldwork period. The maps for each depth displayed in Table 8 had the highest resolution of all methods. However, the 50800 conductivity values have been desampled to 60 conductivity values for comparison purposes with the other methods that consist of only 60 data values.

The results displayed in Figure 23 was obtained during the first week of January 2018 which falls within the summer rainfall period. This period was also the end of the harvest season on the specific field. With the last irrigation being 30 days before the final harvest. Results displayed by Figure 24 was obtained at the end of June 2018. Following a rest period with cover crops in the western half. Apparent conductivity values declined over time due to the reduction of water content from January (Wet Season) towards June (Dry Season) due to a reduction in overall soil moisture. Even though soil moisture conductivities declined over time, anomalies tend to remain stationary across the field. This phenomenon is due to the clay content present within the areas of anomalies which have high water holding capabilities. The anomaly for both time periods across all depths towards the north-west of the field is a result of the topography of the area. When taking the topography and the location of the anomaly, it is clear that the soil water runs along the downward-, north-western sloping path and accumulates at the location of the anomaly. This specific anomaly also has a very high clay content, which is due to the run-off pattern of the field where clay particles tend to settle at the

very lowest part of the field. To determine the contribution of water content, the conductivity values gained by the CMD Mini-Explorer was compared with the volumetric water content at the specific depths, where both datasets have available data at namely, 0.5m; 1.0m and 1.8m for both time periods.

Conductivity values in the most buried layer are lower overall than the previous shallower layer. Dry hard plinthite concretions are responsible for this observation. The concretions tend to be impenetrable for water and remains drier than the topsoil. Therefore conductivity values are smaller than the preceding layer. High values of conductivity exist in the second layer which is due to the volume water and volume soil ratio in areas where the hard plinthite layer tends to be very shallow. An excess amount of water is present in comparison with the amount of soil making the topsoil saturated with water. This can be assumed for anomalies towards the south-southeastern parts of the field when compared with the absolute depth.

As seen on the legend of both figures, negative values are present mainly in the shallowest depth of the surveyed field. This is due to human error when conducting the field survey when the orientation of the CMD is not kept parallel with the soil surface resulting in conductivity values that are taken in the air.

The EM data provided insight towards the variations seen in the average apparent conductivities across the surveyed lines and throughout the surveying period.

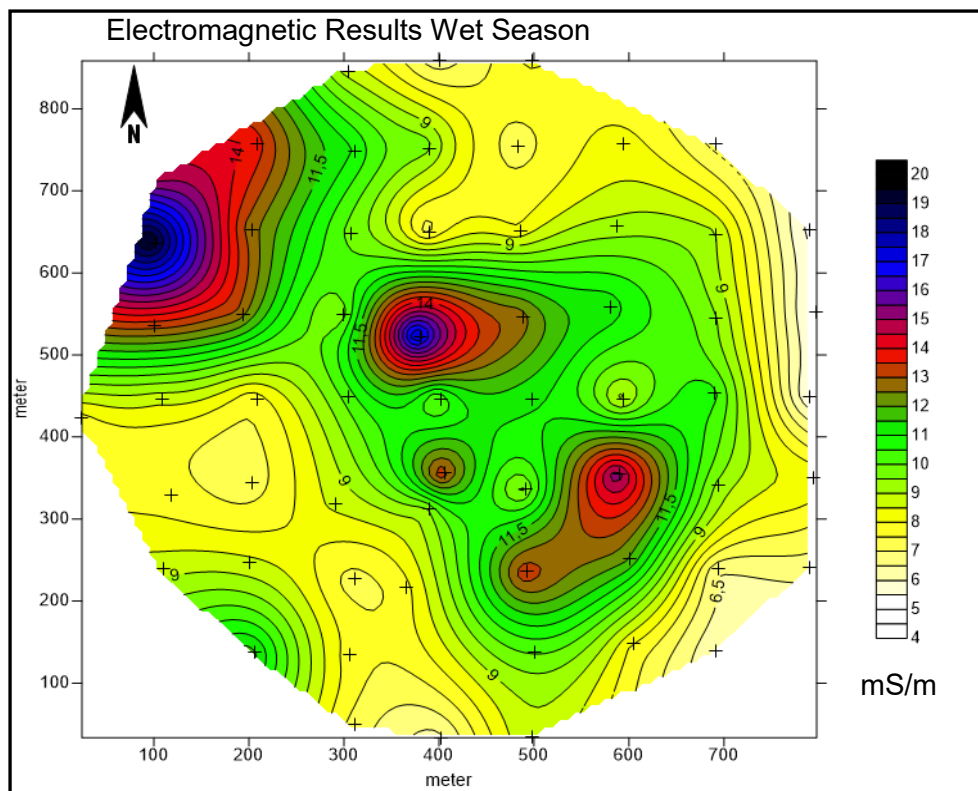


Figure 23: Map indicating the electromagnetic results for the wet season.

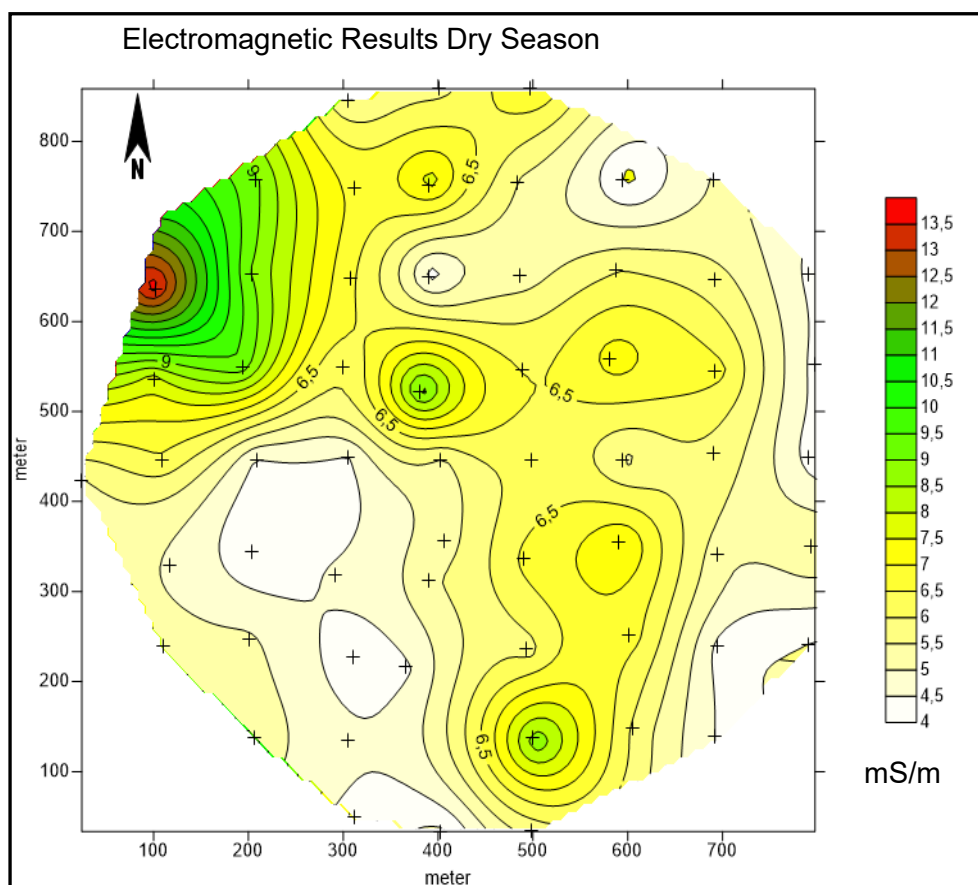


Figure 24: Map indicating the electromagnetic results for the dry season.

5.2.3 Neutron Probe Results

Comparing the results from each data collection period, it can be seen that the number of moisture counts declined from the wet season towards the dry season. Another definite trend that is noticed is the increase in moisture counts with depth across the entire data collection period. Some moisture count anomalies exist in the field and tend to remain relatively stationary throughout the entire data collection period with just the intensity of moisture counts varying across time from the wet- to the dry season. consists of the results obtained through the density calibration process as discussed in Chapter 4. These values were plotted against each other to obtain the density calibration equation displayed in Figure 25, to convert density counts to absolute density values.

Figure 26 and Figure 27 is the result of interpolated maps of the average values per data collection hole over the whole depth profile. Such maps were created for each data collection period to enhance comparison between the different time periods of data collection for the Neutron Probe. The map of each depth can be seen in Appendix C. It also eases the process for comparing the Neutron Probe with other methods.

Interpreting this map, it can be noted that very high moisture count values exist outside of the preferred soil water accumulation areas, towards the north-east present in both Figure 26 and . The Neutron probe creates this outlier of soil moisture due to the low density in that area. The Neutron probe counts are dependent on the density to give accurate results. To rectify that anomaly the Neutron Probe needed to be recalibrated for that area to normalise the results which will lead to much lower moisture count values towards the north-eastern part of the field. Results obtained in March can be viewed in Appendix C.

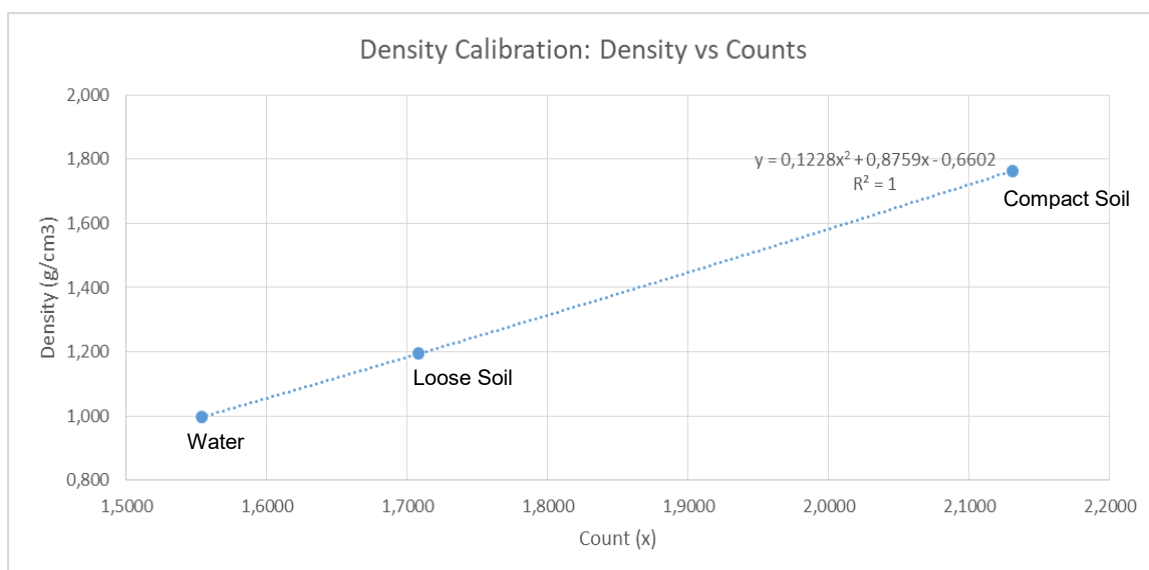


Figure 25: Density calibration graph.

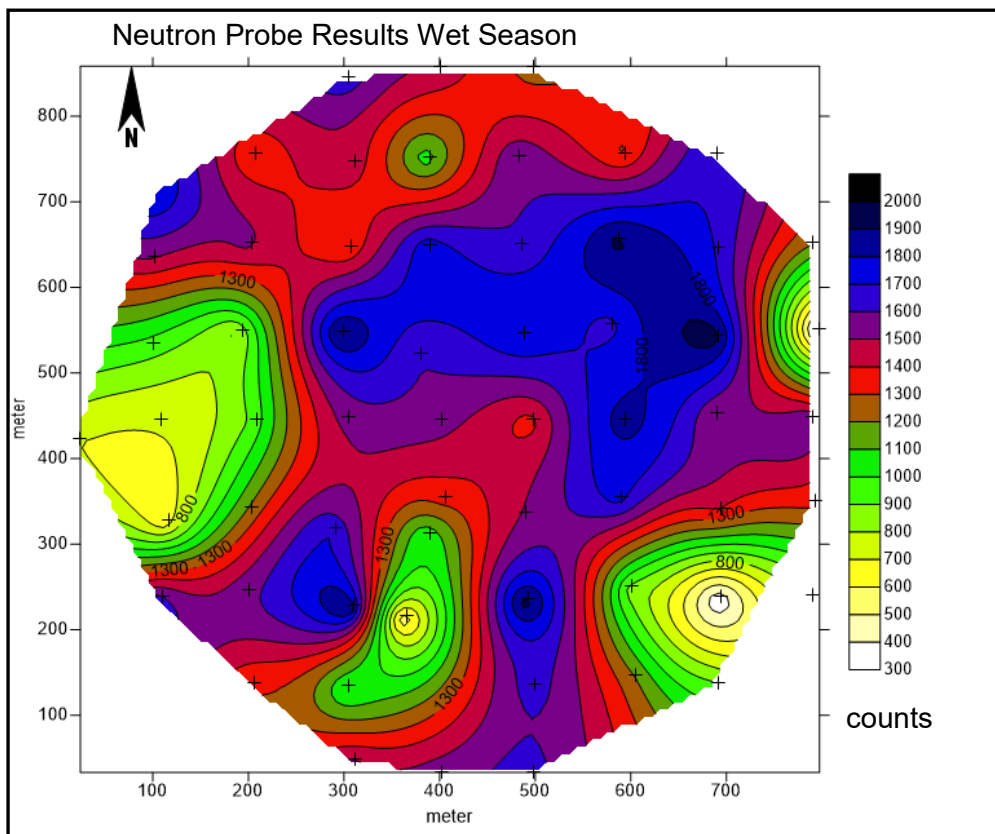


Figure 26: Map indicating neutron probe results for wet season.

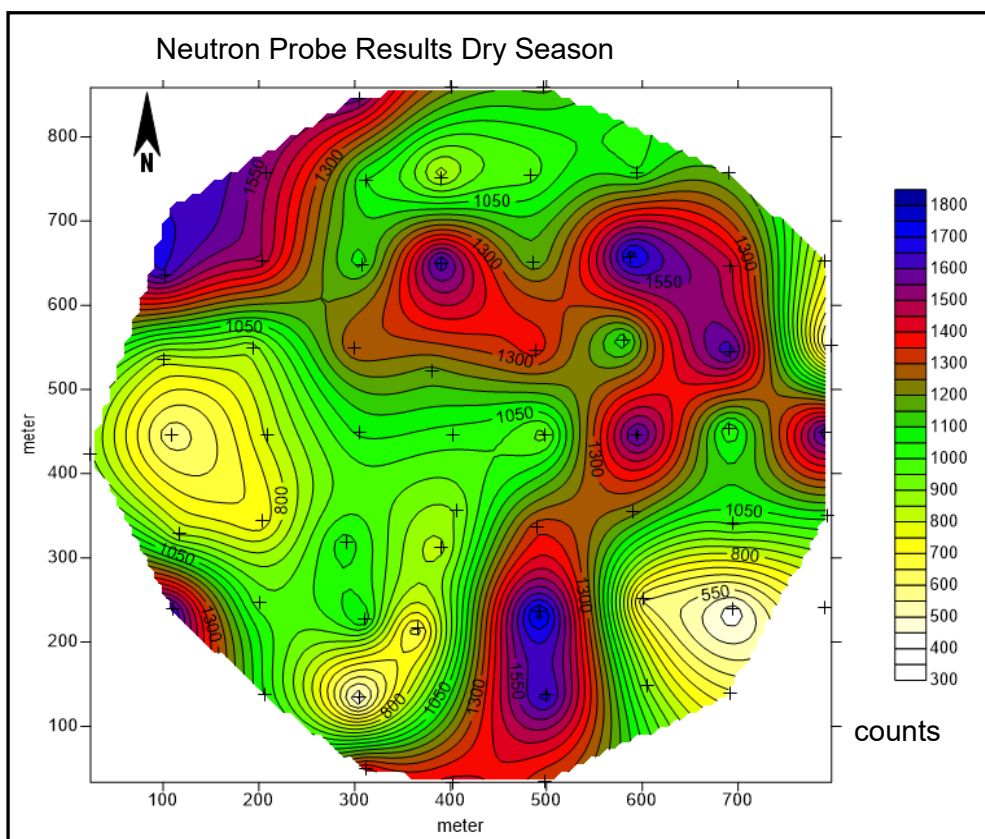


Figure 27: Map indicating neutron probe results for wet season.

5.2.4 Frequency Domain Reflectometry Results

Comparing moisture values in the form of scaled frequencies of the Diviner 2000 it can be noticed that the moisture amount in the field declined from the wet season (January) to the dry season (June) by referring to Figure 28 and Figure 29. A definite trend is observed regarding the increase of soil moisture with depth. Anomalies of high soil moisture values tend to decrease towards the dry season although, the majority tend to remain stationary with only differences in size and intensity. Diviner 2000 data can be found in Appendix D.

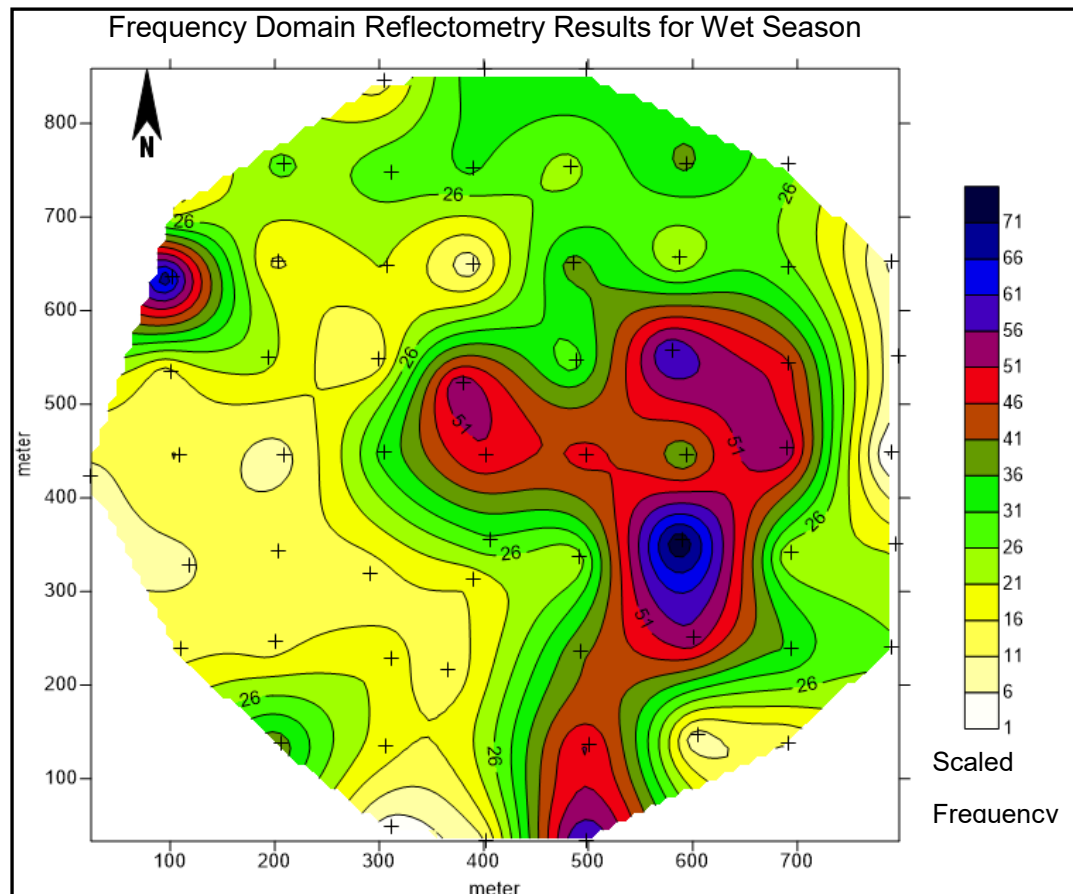


Figure 28: Map indicating FDR results for the wet season.

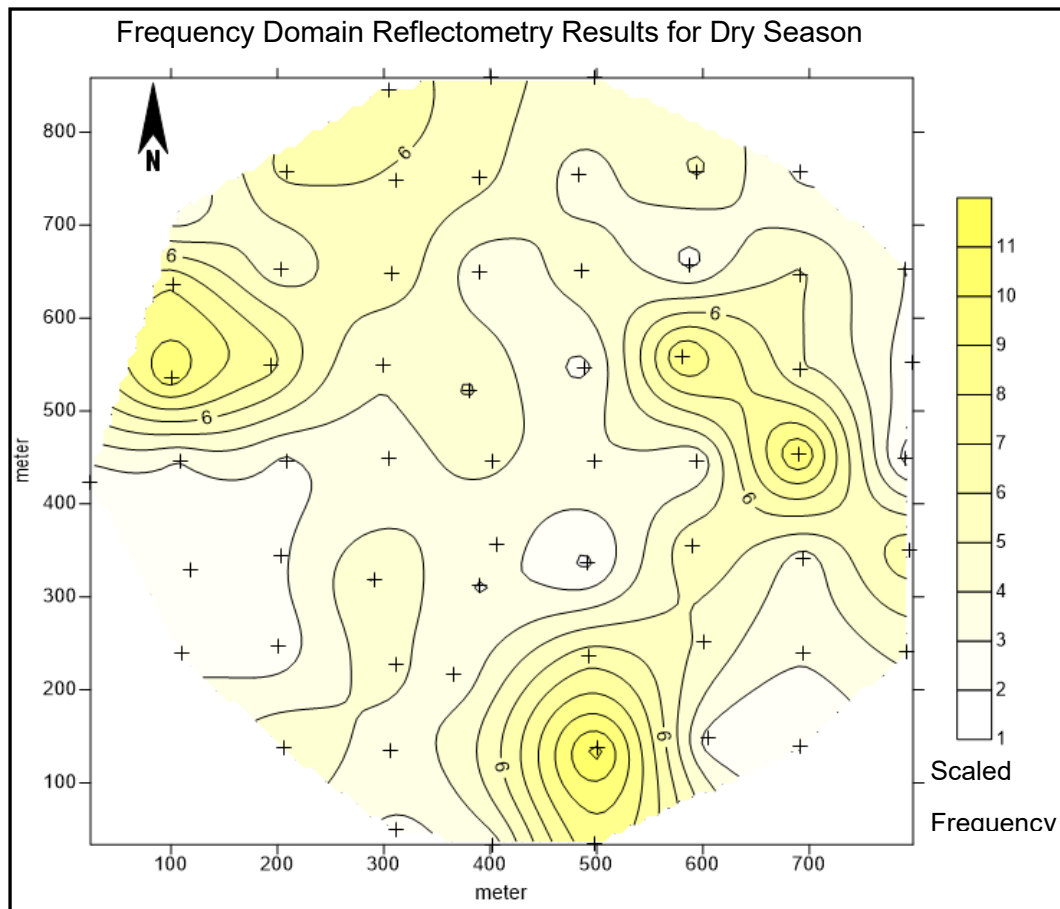


Figure 29: Map indicating FDR results for the dry season.

5.3 Results Comparison

A comparison was made between each method measuring soil water content shown in Table 3. Volumetric water content acts as the base to which each method is compared too as seen in Table 4. Similar anomalies occur throughout each method. An overall average of the wet season and dry season of each method throughout the whole sampling period across the whole depth profile has been created for a more profound comparison of each method.

Anomaly 1: Situated towards the north-western part of the field and is evident with each method. A clear correlation for this anomaly can be noted between Volumetric Water Content, CMD Mini-Explorer and Neutron probe. The Diviner 2000 results' anomaly is situated in the correct area but differs in size which might be due to the interpolation process. The most significant reason for this anomaly is due to the topography, the exact location of the anomaly is situated in the lowest part of the field. The soil moisture flows towards the area of lowest elevation and accumulates there due to the high clay content.

Anomaly 2: Situated just to the north-west of the centre of the field. This anomaly is also evident throughout each method which is caused by a leaking pipe feeding the pivot in an area of relatively high clay content.

Anomaly 3: Situated to the south-east of the pivot centre. This anomaly is caused by the shallow soil prevalent in the area causing a relatively high ratio of volume water for the amount of volume soil available. The accumulation at this anomaly is due to the higher clay content. It is present throughout each method.

Anomaly 4: Is a small anomaly towards the south-west of the field. The anomaly can be spotted throughout all the methods except for the soil characteristics map. The specific properties of soil contributing to the accumulation of soil water might have been missed during the sampling process.

Anomaly 5: It is situated towards the southern side of the field. This area also consists of very shallow soil with relative high clay content causing too much water to accumulate for the volume of soil available.

Anomaly 6: This anomaly is situated towards the east of the field. It has a relatively low intensity regarding moisture values but is still evident throughout all the methods. This anomaly is situated in an area with a moderate depth and clay content.

Most of the anomalies spotted on the volumetric water content map regarding size and position occurred throughout all the methods, confirming that each instrument or method can execute the primary purpose by obtaining soil moisture readings.

Table 3: Results Comparison.

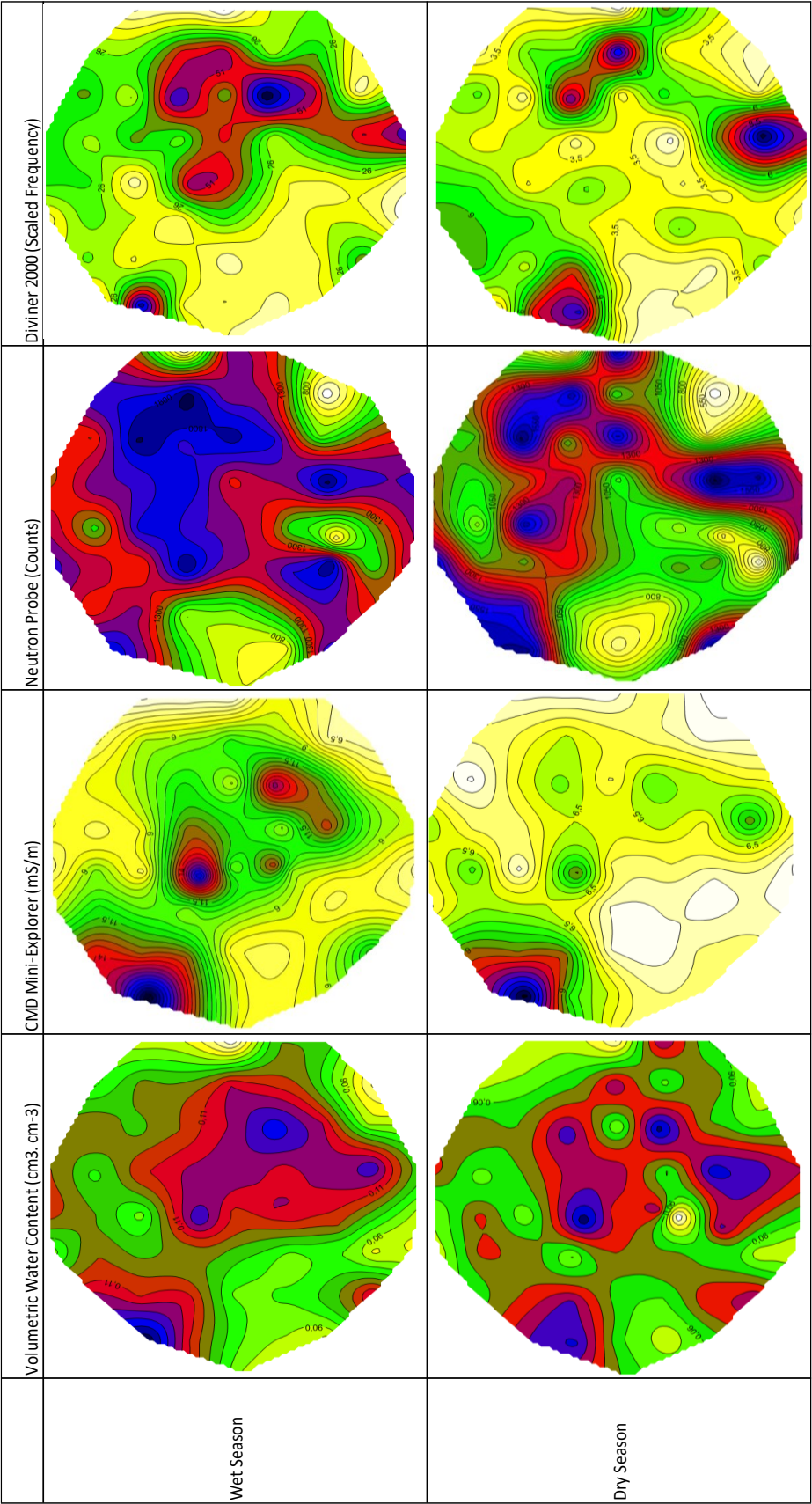
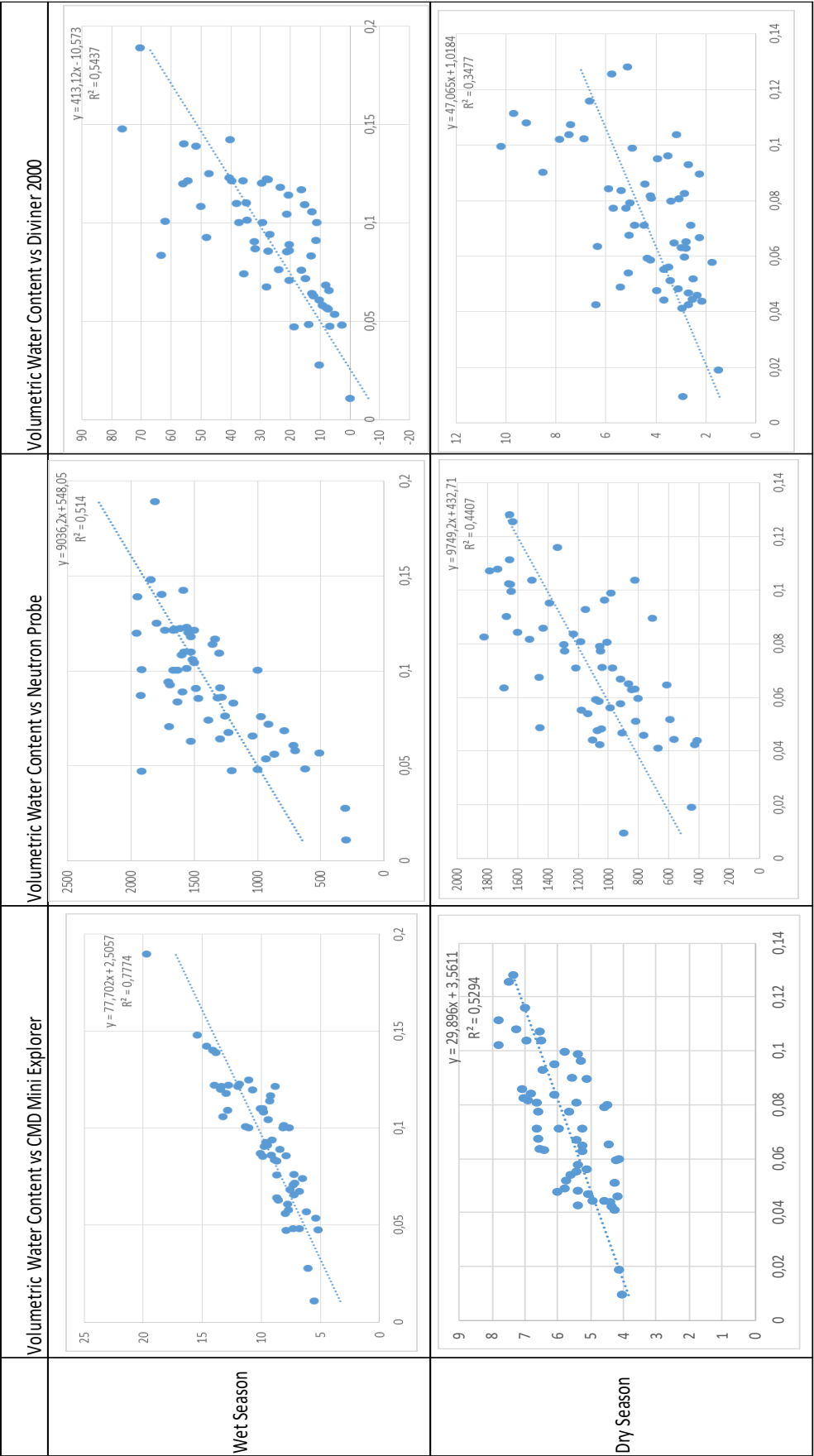


Table 4: Correlation graphs between volumetric water content and other methods.



CMD Mini-Explorer vs Volumetric Water Content

The CMD Mini-Explorer indicated the best relationship with volumetric water content for both the wet- and dry season (Table 4).

Table 5: CMD Mini-Explorer Correlation Values.

	R ² Value	Correlation/Pearson Value
Wet Season	0.7774	0.881704
Dry Season	0.5294	0.711626

Neutron Probe vs Volumetric Water Content

The Neutron Probe indicated a better correlation during the dry season in comparison with the Diviner 2000 (Table 4).

Table 6: Neutron Probe Correlation Values.

	R ² Value	Correlation/Pearson Value
Wet Season	0.514	0.716935
Dry Season	0.4407	0.663869

Diviner 2000 vs Volumetric Water Content

The Diviner 2000 indicated better correlation values during the wet season in comparison with the Neutron Probe (Table 4).

Table 7: Diviner 2000 Correlation Values.

	R ² Value	Correlation/Pearson Value
Wet Season	0.5437	0.737366
Dry Season	0.3477	0.589696

Comparing the wet season with the dry season, weaker correlations were obtained in the dry season for all three methods. Dry season correlations are lower due to various factors that appear when the soil is not saturated, like salination and unsaturated clay. The dry season data correlations can be improved by removing data points that fall within clay-rich areas that are prone to salination especially for the CMD Mini-Explorer and Diviner 2000 that operate on dielectric principles. Figure 30 indicates the new correlation that improved significantly when data points in clayey areas are removed for the CMD Mini-Explorer.

R^2 value= 0.6308; Correlation Value = 0.763976

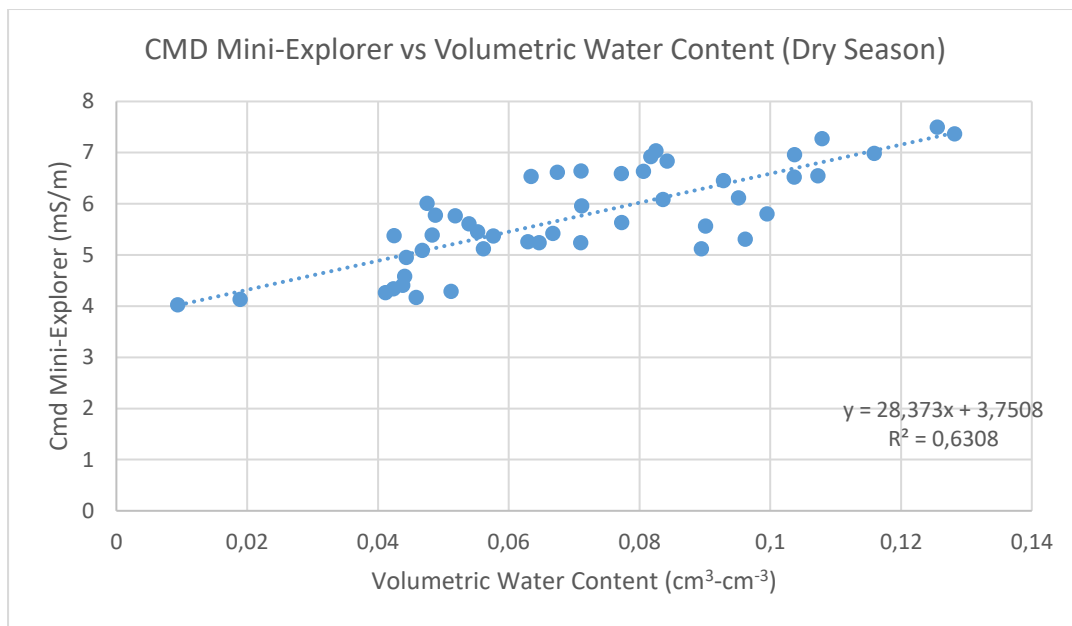


Figure 30: CMD Mini-Explorer dry season data excluding data points in clayey areas.

Figure 30 is a good indication of how clays that are unsaturated can influence electromagnetic data. Water content is not the only factor that can influence conductivity values, conductivity can also be increased by salination that appears when clays are unsaturated.

5.4 Soil Water Management Zones

Numerous variable rate irrigation systems exist. Variable rate irrigation systems come in various forms one such form is a speed control system where the pace at which the pivot runs around the field irrigating water at a constant rate is altered. The speed control system as shown in Figure 31, requires a field to be divided into the shape of a wagon wheel to manage and control certain areas in a field regarding soil moisture amounts. Each “spoke” of the wagon wheel would require a certain amount of water. This system would increase the speed of the pivot in areas where less water is required and vice versa. These systems are not as accurate as zone control systems where a specific patch (polygon) on a field can be irrigated to the necessary amount.

Zone control systems are GPS driven where the boundaries of each class can be georeferenced, once the pivot sprinkles intercept such specific class boundary assigned coordinate the sprinklers can alter itself to the moisture needs in that specific polygon, displayed by Figure 32. Different sprinkler rates from areas of very high moisture content to very little to no moisture content consists of:

- 1) completely closed or very little sprinkling
- 2) alternating sprinkling with long intervals
- 3) alternating spray with short intervals
- 4) regular spray and
- 5) high-pressure sprinkling

The management zones in this study are created explicitly for variable rate irrigation systems that operate on the zone control principle. The management zones in the field are divided into polygons according to the required irrigation needs. The method with the best correlation against volumetric water content has been chosen to create soil water management zones. The various water requirement classes would be generated by scaling the number of contours down until there are five different classes for the method with the highest correlation against volumetric water content.

As proven, the CMD Mini-Explorer indicated the most accurate correlation with volumetric soil moisture content, therefore, the CMD Mini-Explorer data values have been used to divide the field into five different classes of soil moisture content. The number of classes can be altered depending on the different variable irrigation rates a zone control system can accommodate, five different rates tend to be the norm for such systems.

Management zones can be created for each season or to the specific needs of a particular crop on the field. It must be kept in mind that the soil water management zones in Figure 33 and Figure 34 acts only as the basis (e.g hydrogeophysical data layer) towards the final product of speed or zone control systems as displayed in Figure 31 and Figure 32.

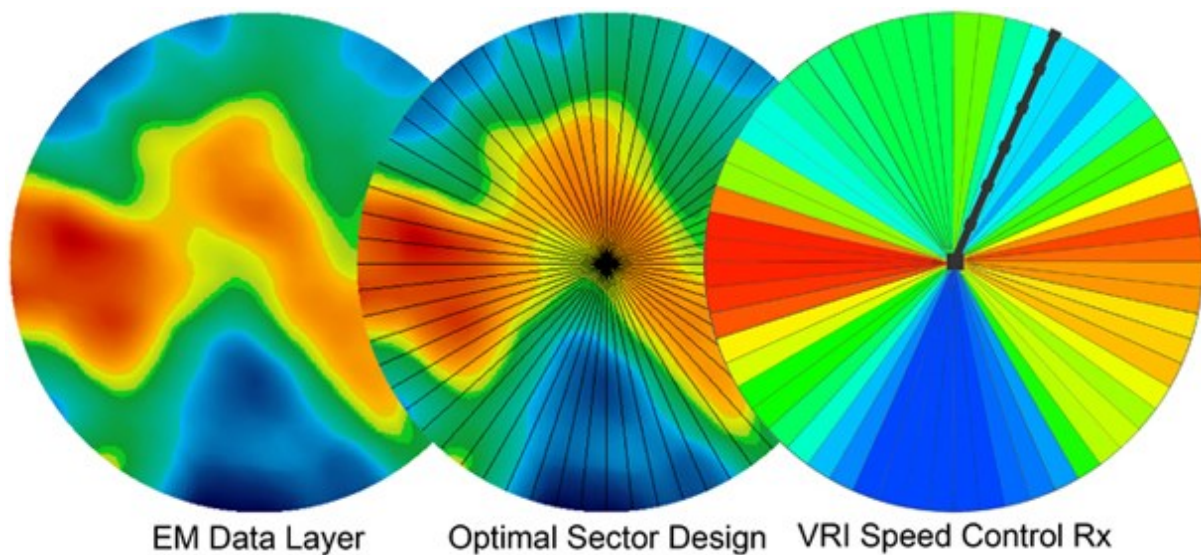


Figure 31: Example of a VRI Speed Control System (Precision Water Works Inc, 2018)

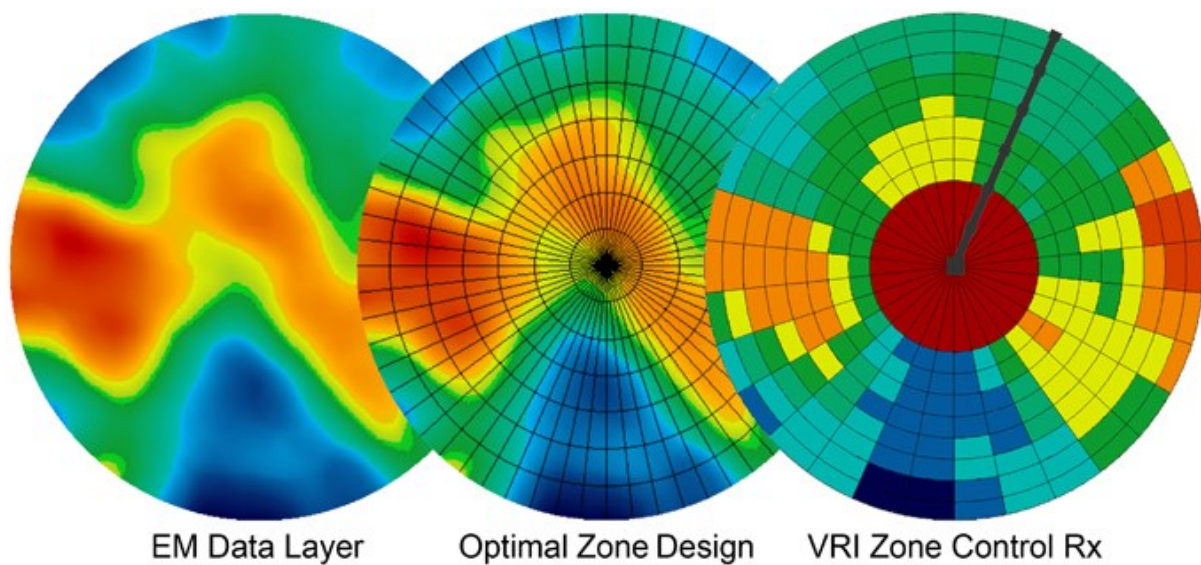


Figure 32: Example of a VRI Zone Control System (Precision Water Works Inc, 2018).

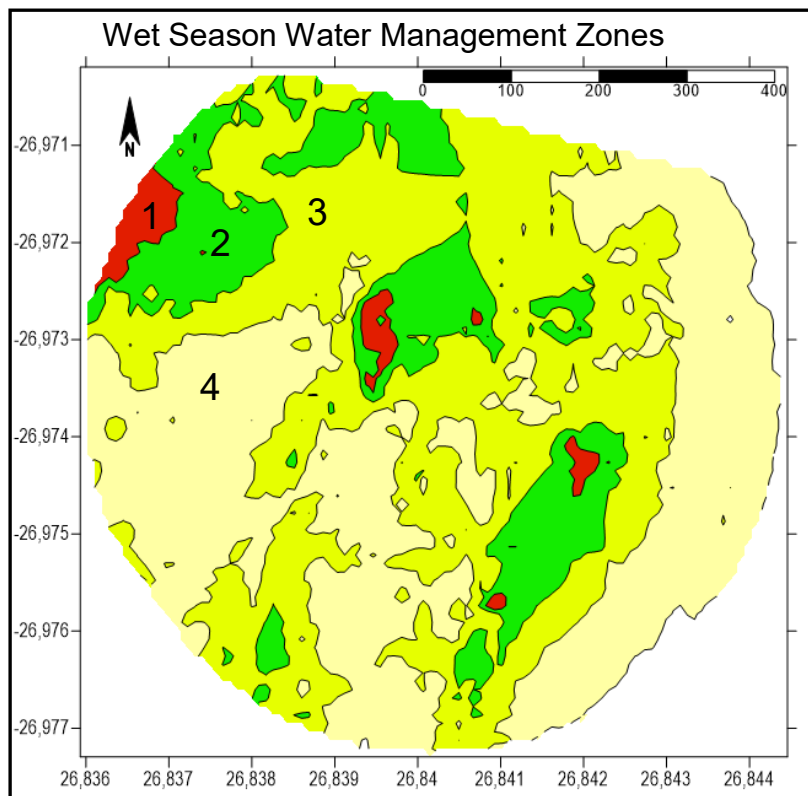


Figure 33: Water management zones for wet season

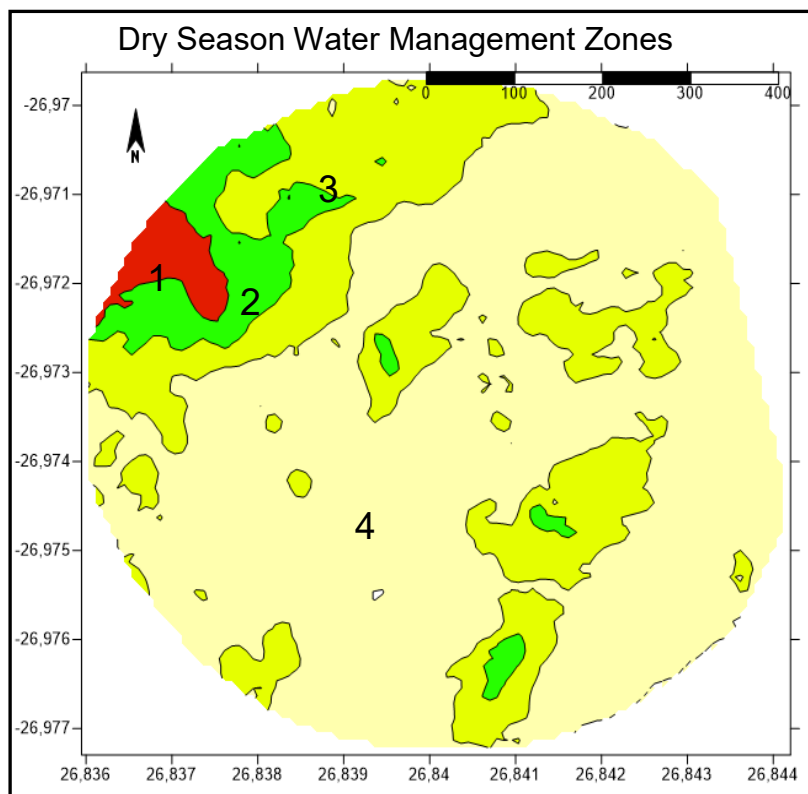


Figure 34: Water management zones for dry season

A clear difference between water requirements can be seen between the dry season Figure 32 and the wet season Figure 33. Anomalies tend to remain stationary throughout the two seasons with the only difference being the water requirements of the specific anomalies. The dry season requires much more water.

6. Conclusion

Soil water management has to be implemented on field C4 of the farm Cyferfontein. Various methods have been utilised to determine soil moisture values which included, conventional soil sampling; where a gravimetric analysis was conducted in order to obtain volumetric water content with density values acquired by the Neutron Probe; Electromagnetic Induction in the form of a CMD Mini-Explorer; Neutron Scattering in the form of the Neutron probe and Frequency Domain Reflectometry that was done with the Diviner 2000. These methods were not necessarily compared with each other but rather how a combination of all the methods can contribute towards the management of soil moisture. It can be regarded that all soil moisture measuring methods or instruments are designed and developed to measure or manage soil moisture.

The following objectives were met by identifying the cause of anomalies in electromagnetic induction (EMI) measurements by acquiring soil samples. Verifying soil moisture with gravimetric analysis, clay content, soil texture and soil density.

Verify soil moisture content in the field with hydrometric techniques utilising the Neutron Probe, Diviner 2000 and volumetric soil water content through sampling.

Creating a visual representation of hydrogeophysical soil moisture data in a centre pivot field, both spatially and temporally for crop irrigation management and delineating the field into management zones.

Determine whether EMI data is sufficient for soil water management in a variable rate irrigation system.

Through the soil sampling and other processes various soil properties have been identified which included, clay and silt content, sand fraction, concretions, absolute depth and density obtained by the Neutron Probe and last but not least Volumetric Soil Moisture. All these soil properties have been compared to the Electromagnetic Induction (CMD Mini-Explorer) results to determine the soil properties and factors that cause the anomalies. It has been determined that the most significant contributor to Electromagnetic Induction anomalies are Volumetric Soil Moisture that is caused by areas of high clay content that results in the accumulation of soil moisture.

The verification of soil moisture with hydrometric techniques has been successful. Definite correlations between the Neutron Probe, Diviner 2000 and Volumetric Soil Moisture data can be confirmed when comparing the Neutron Probe, Diviner 2000 and Volumetric Soil Moisture maps with each other.

Due to the significant correlation and accuracy obtained between the CMD Mini-Explorer and Volumetric Soil Moisture data it has been decided that the CMD Mini-Explorer would be the optimum method for creating a visual representation of soil water management zones due to the high data resolution and its ease of use. The field would consist of polygons that act as management zones. High conductivity values would be areas of high soil moisture resulting in a management zone that requires less water and vice versa. Surveys can be conducted at various times of the year to fine tune variable rate irrigation and to save even more water.

Electromagnetic induction data is more than sufficient to manage soil water through a variable rate irrigation system. It is cost effective when considering the rate at which it acquires data; it acquires the most considerable amount of data values in a specific period it has, therefore, a low consumption of time, and it is not very labour intensive, it only requires one operator.

It can be regarded that all soil moisture measuring methods or instruments are designed and developed to measure or manage soil moisture. In present times with populations and food demands growing agricultural industries and practices are continuously seeking improved methods for enhancing crop yields through various precision agricultural methods such as variable rate irrigation systems. Implementing the outcome of this study would not only improve crop yields but would also relieve some pressure on water resources especially when utilising soil moisture measuring equipment that is more cost-effective, less time consuming and less labour intensive.

7. Recommendations and Future Work

Despite excellent results obtained between soil moisture in the field and hydro-geophysical methods, there is still room for improvement. When conducting an electromagnetic survey during the dry season it is essential to identify the clay content spatially in order to improve the accuracy between conductivity and volumetric soil moisture, this is due to the fact that clay still has conductive properties whether it is due to salination or the clay itself without containing soil moisture.

Most studies regarding agriculture cannot be conducted without taking farming practices into account. For example, when collecting data in a field, scientists and researchers cannot be obstructive when the field needs to be ploughed, planted or harvested by the farmer, therefore, timing, planning and communication is required.

Improving the accuracy of this study, it should be done on a smaller scale unless a more considerable amount of time is available. A higher resolution of data could have been acquired with all methods improving the accuracy and most likely the correlation between all the methods.

Improvements that can be made is to conduct agricultural field data collection without intervening with the farmer and its practices. This can be acquired by implementing data collection methods that are less time consuming, less labour intensive and economically viable. One such method is Electromagnetic Induction due to its nature of operation where there is no need for making physical contact with the soil only a continuous current penetrating the soil in the form of a magnetic field. It is also advantageous because no holes need to be augered and that the resolution of data can easily be altered depending on the surveyed grid of interest. Various other methods remain obstructive to farming practices for example access tubes or in-field moisture measuring probes. The resolution of data in the field is dependent on the number of access tubes or probes that remain in the field, the more of these, the less economical.

It is essential to install a weather station in the centre of the pivot to obtain rainfall and evaporation data.

A recommendation for future studies regarding the relationship of data collection and farming practices, airborne methods should be taken into consideration. Various methods in the agricultural industry already exist regarding airborne methods for data collection, in the form of LiDAR, Hyperspectral and Aerial imagery mounted on an unmanned aerial vehicle, drone or aeroplane. All of these methods are most likely not able to obtain data in the subsurface of an agricultural field and is therefore not suitable for soil moisture management. A combination

of airborne vehicles and Electromagnetic Induction might be the answer to the most significant soil moisture measuring equipment. An Electromagnetic Induction instrument fitted to a drone would not interfere with farming practices, it will still have a high data resolution and would be able to conduct surveys much quicker. Only one area of concern would be the calibration of such an Electromagnetic unit to obtain the correct data value at the specific depth of interest which would be ideal for further research.

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Appendix A- Volumetric Water Content Results

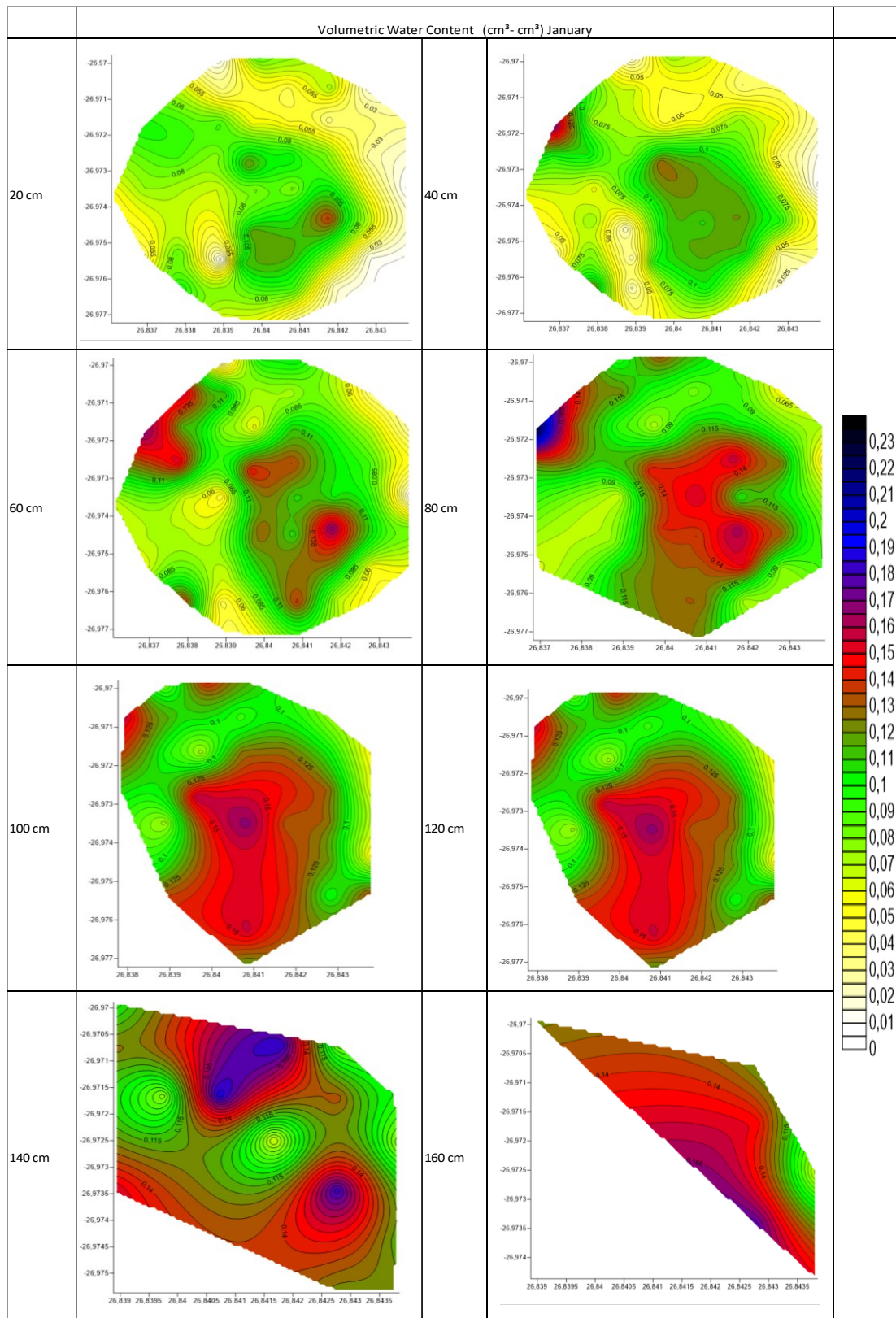


Figure 35: Volumetric Water Content Results January

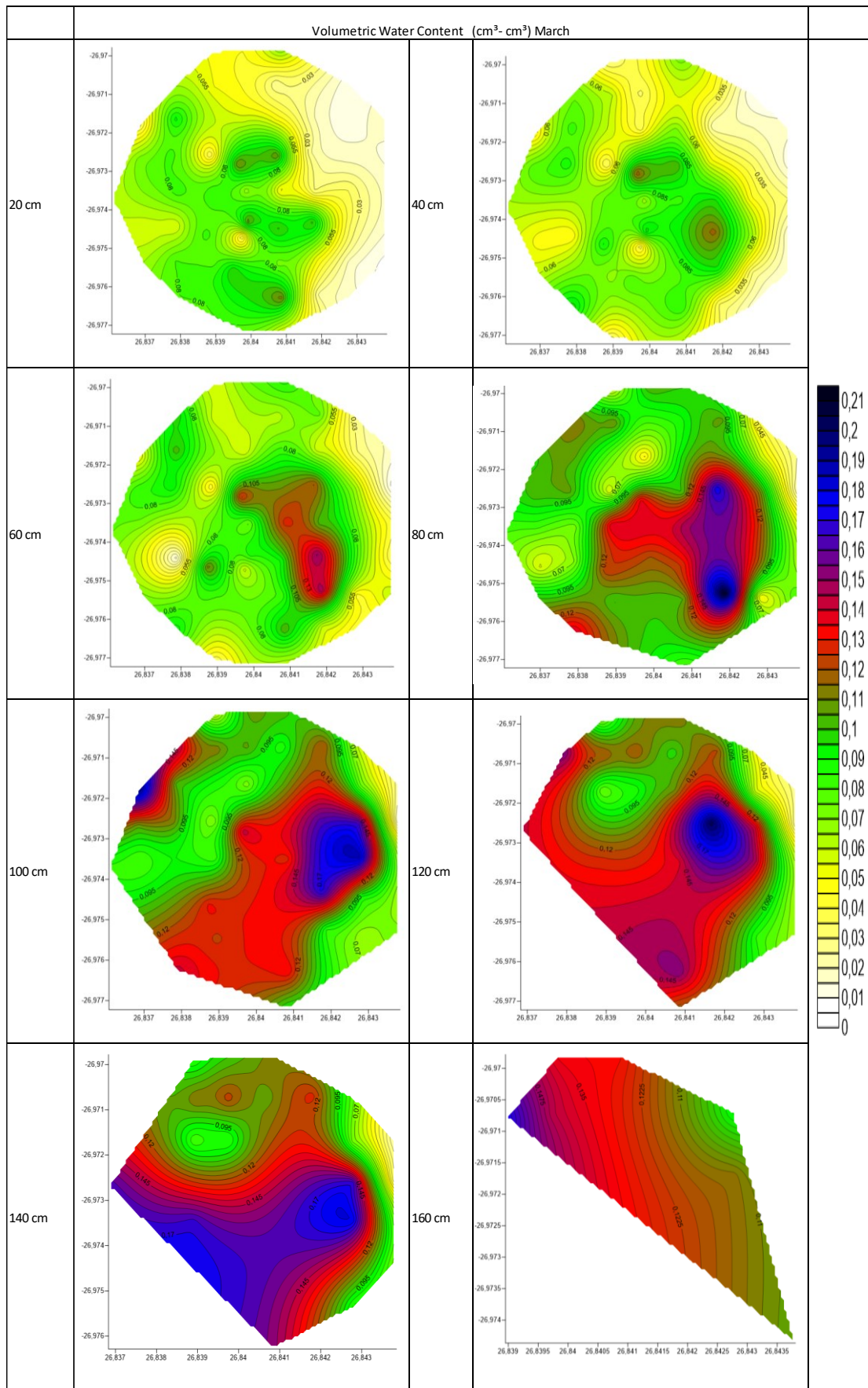


Figure 36: Volumetric Water Content Results March

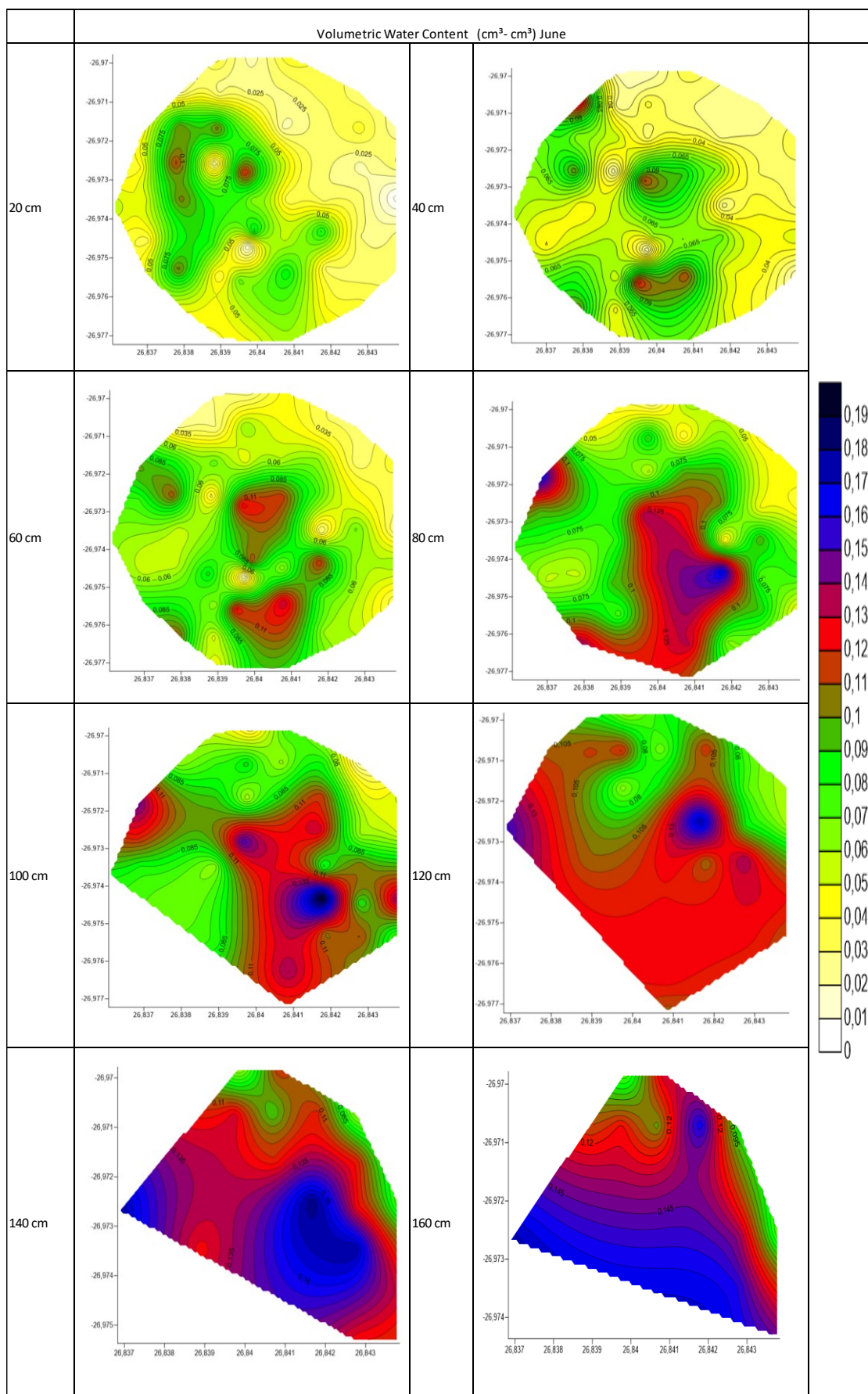


Figure 37: Volumetric Water Content Results June

Appendix B-CMD Mini-Explorer and Explorer Wet Season and Dry Season

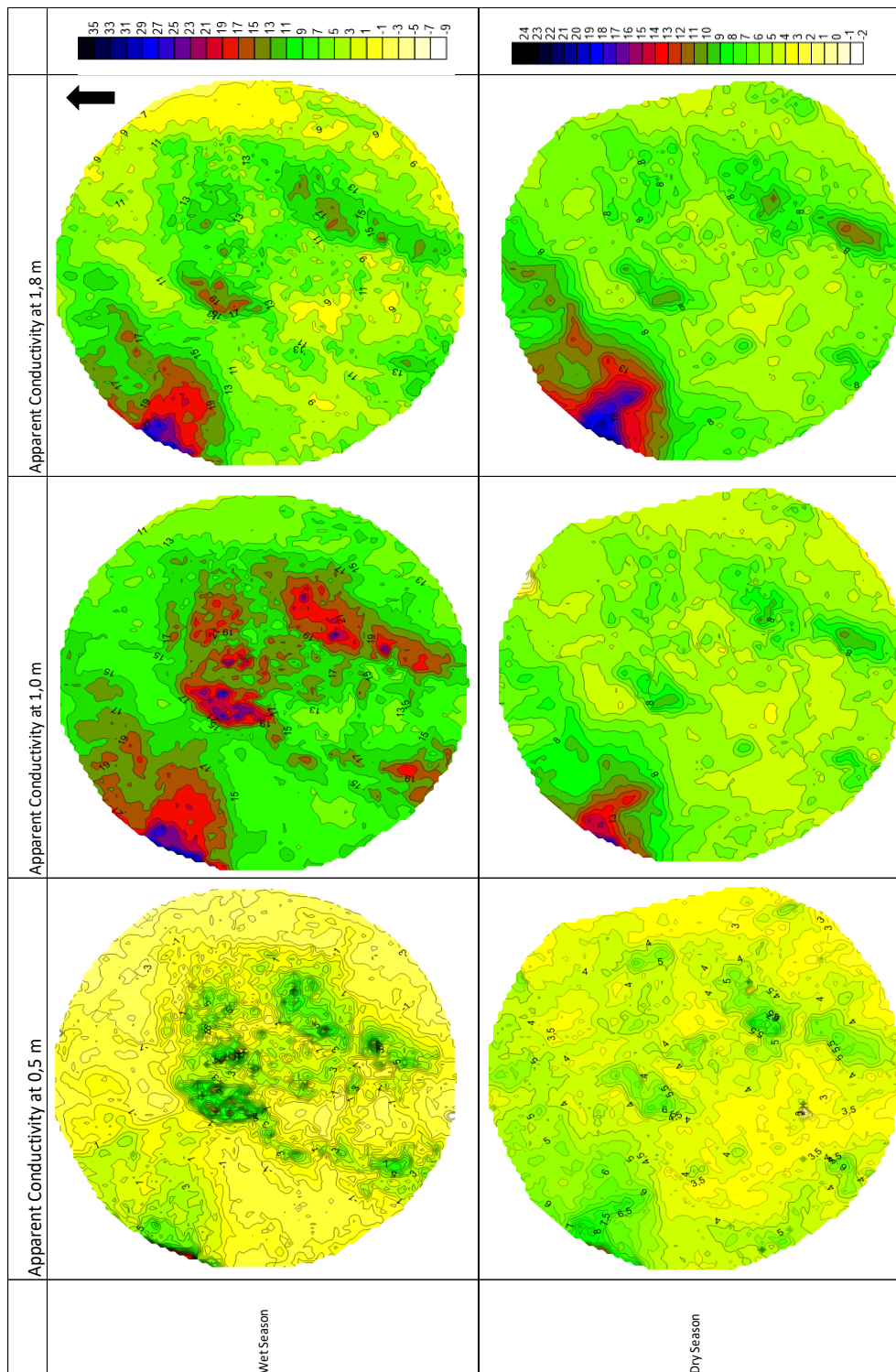


Figure 38: CMD Mini Explorer Data containing all data values for wet and dry season.

CMD Explorer Results

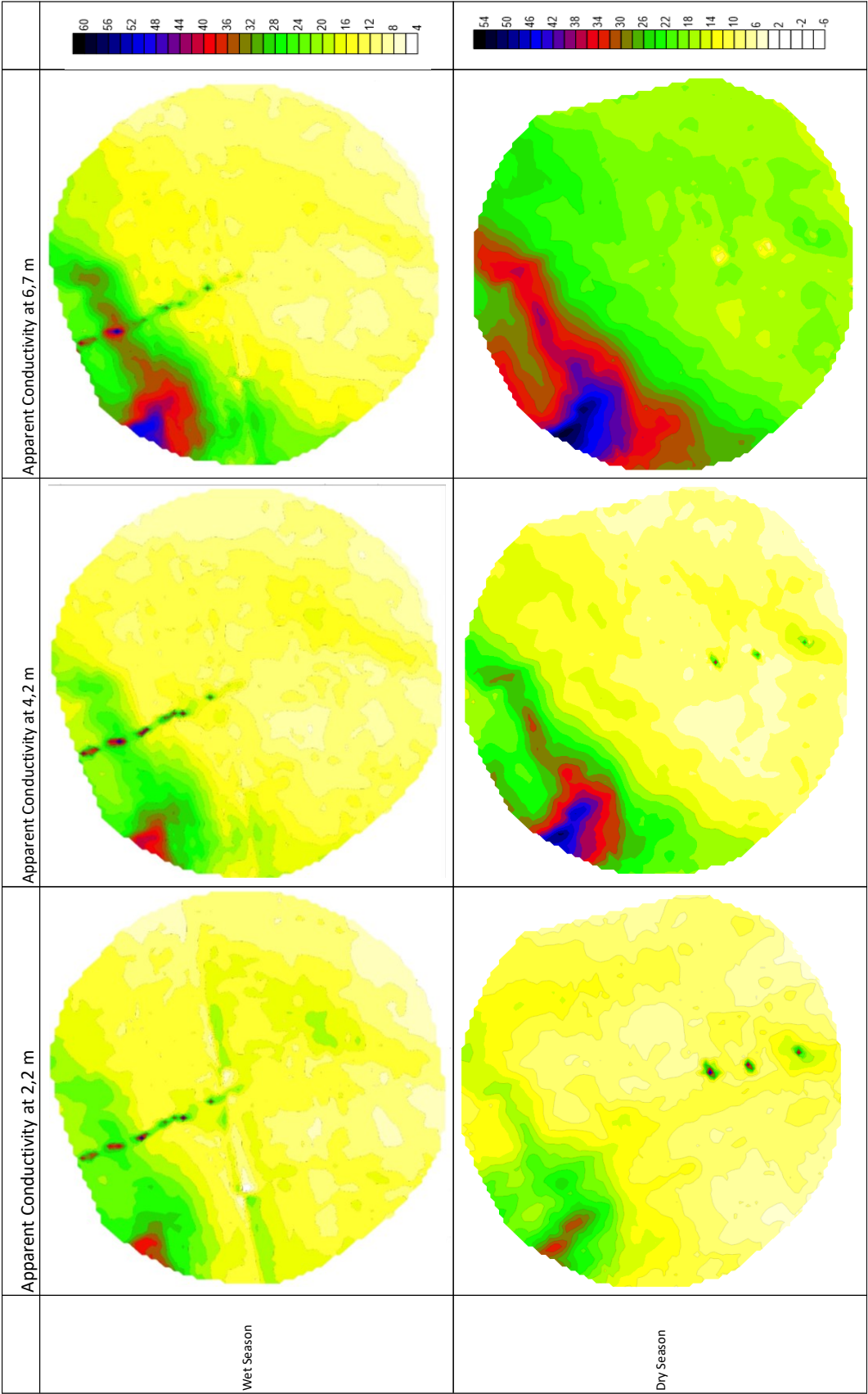


Figure 39: CMD Explorer Wet and Dry Season Results

Appendix C-Neutron Probe Results

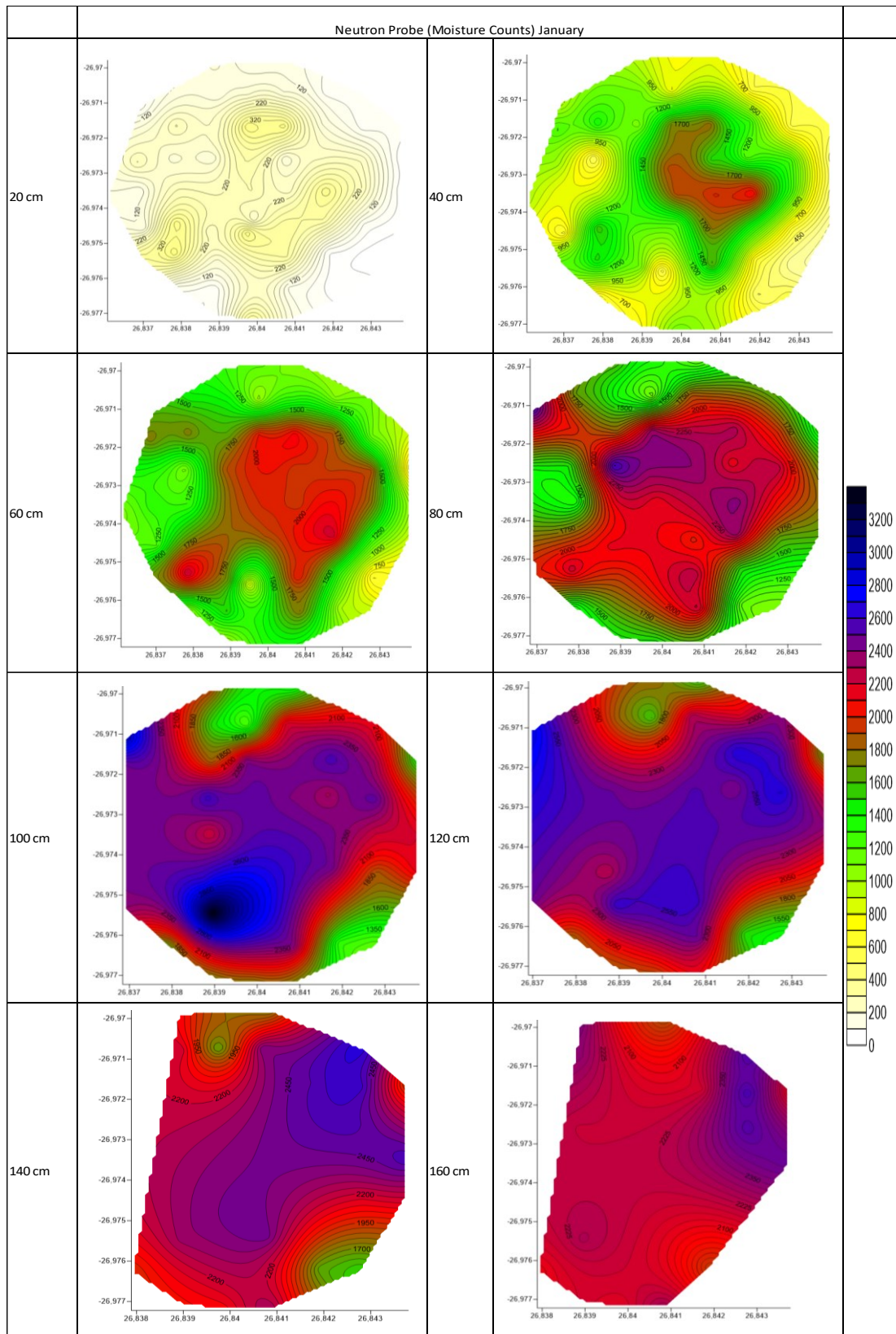


Figure 40: Neutron Probe Results January

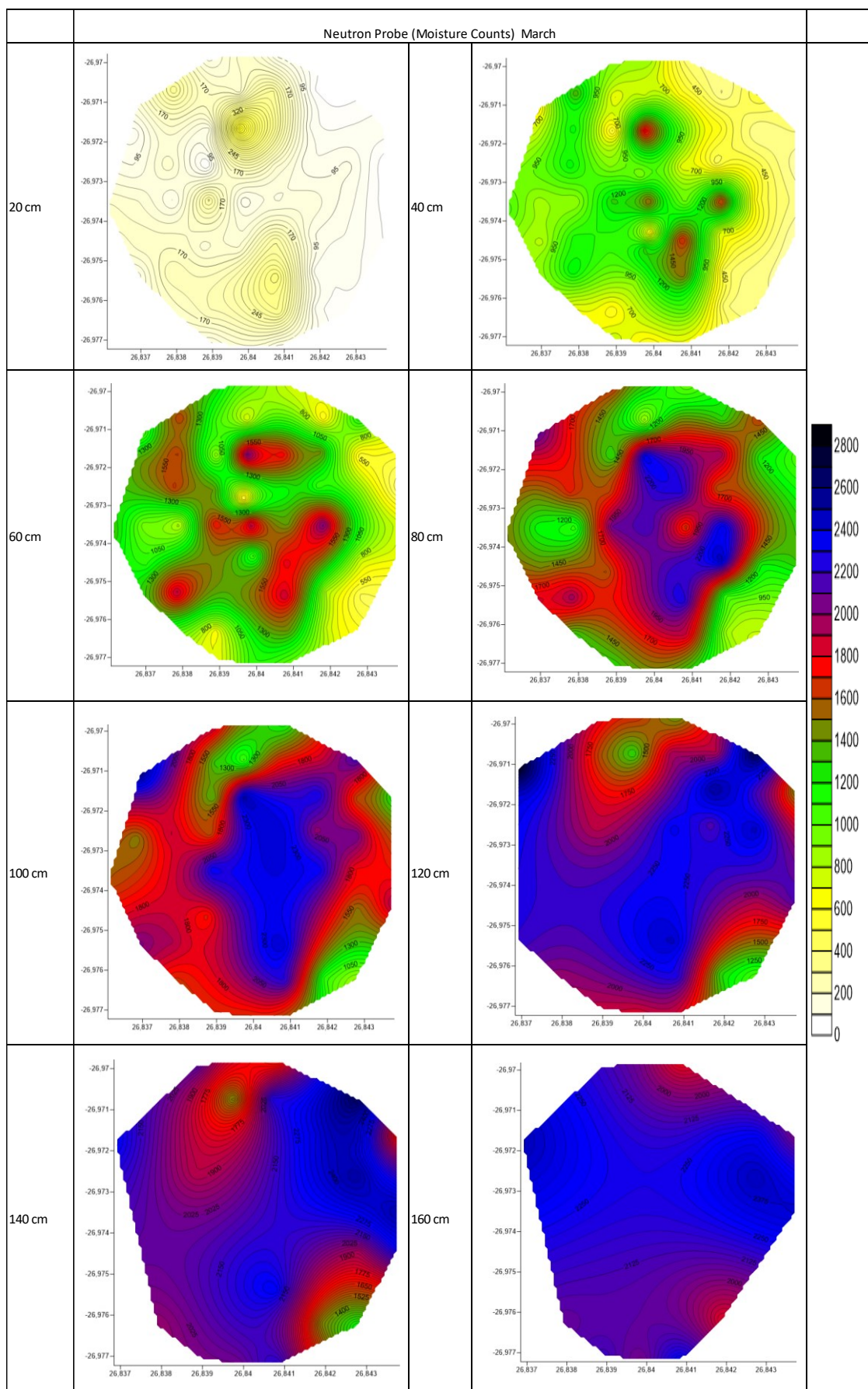


Figure 41: Neutron Probe Results March

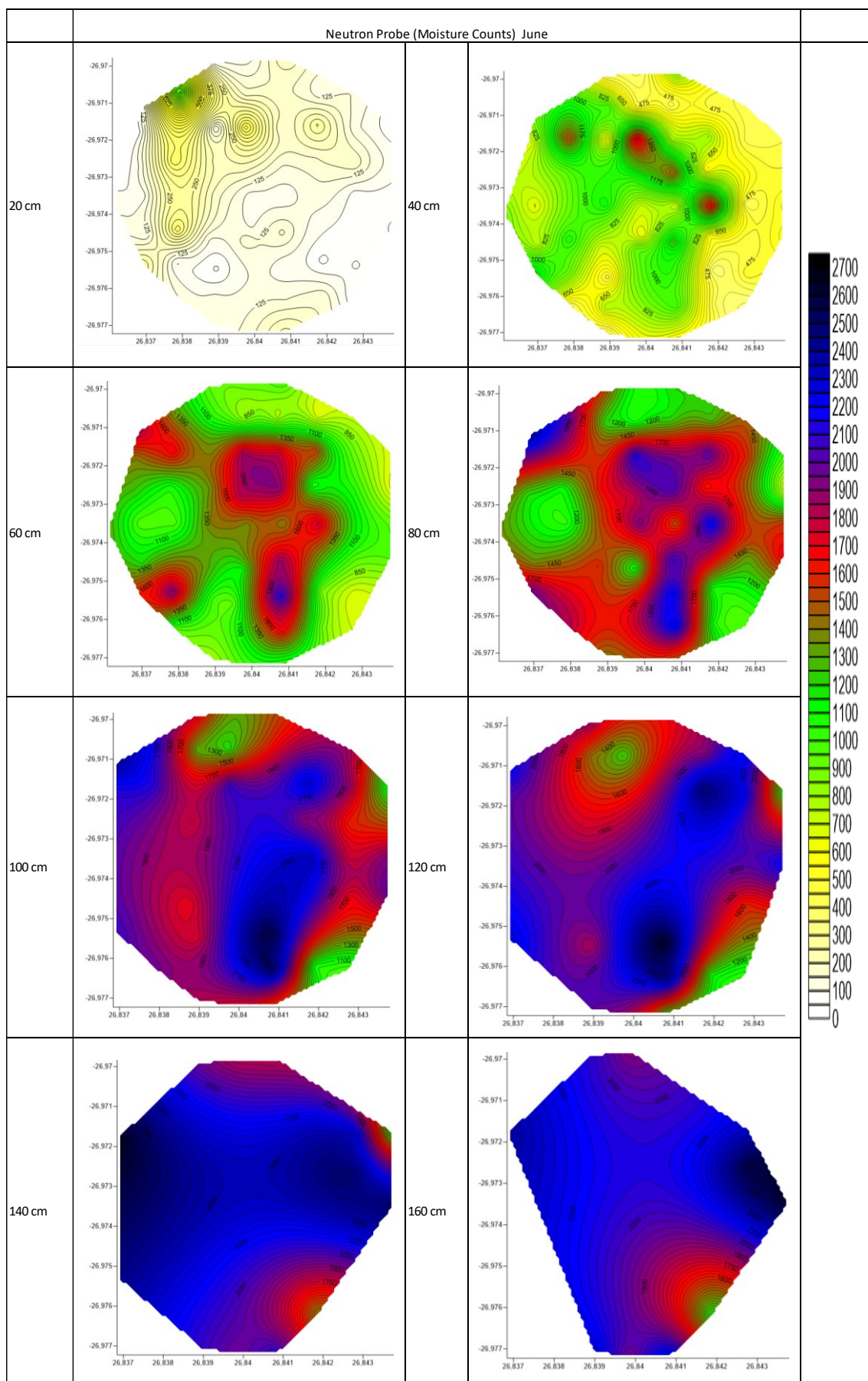


Figure 42: Neutron Probe Results June

Appendix D-Diviner 2000 Results

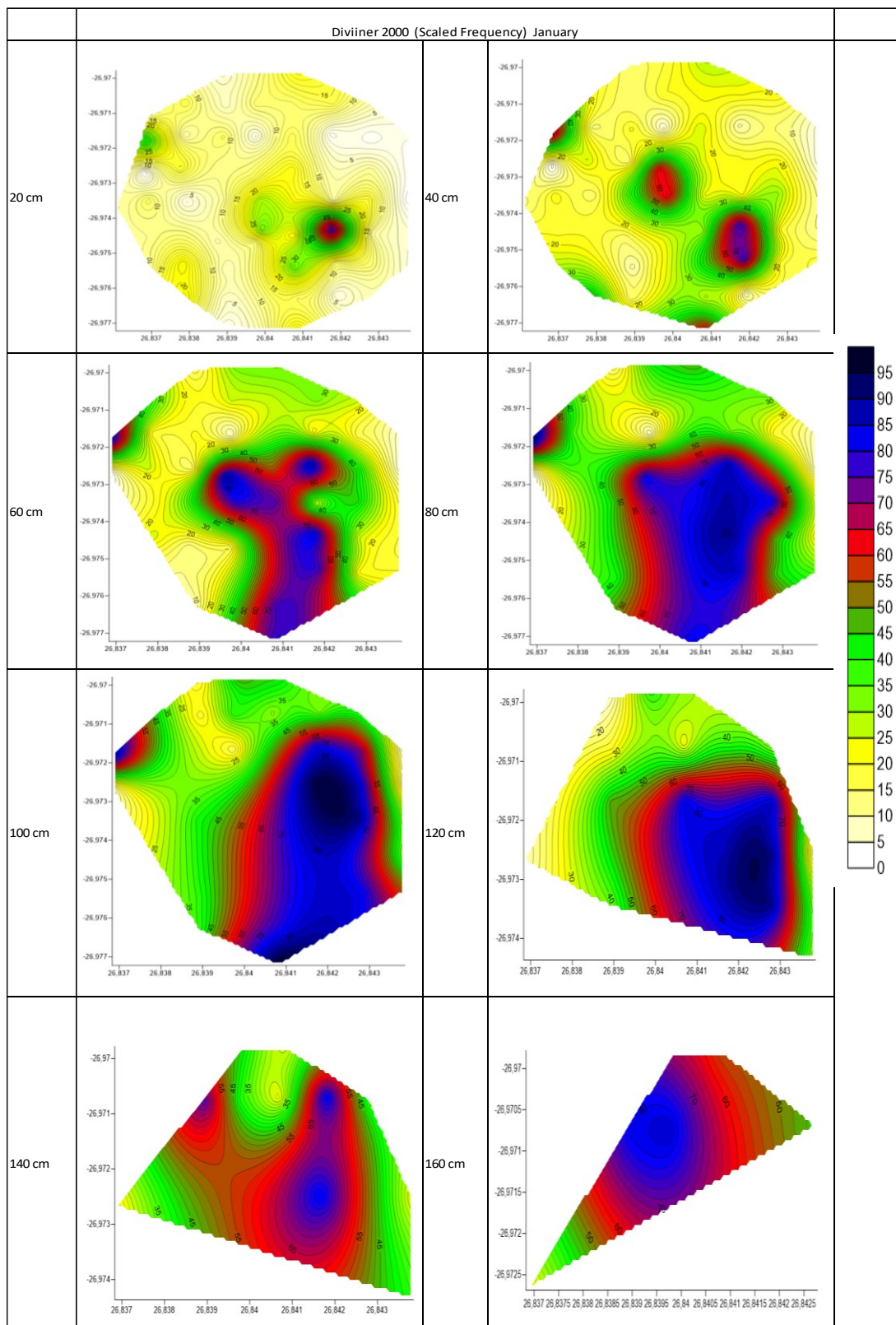


Figure 43: Diviner 2000 Results January

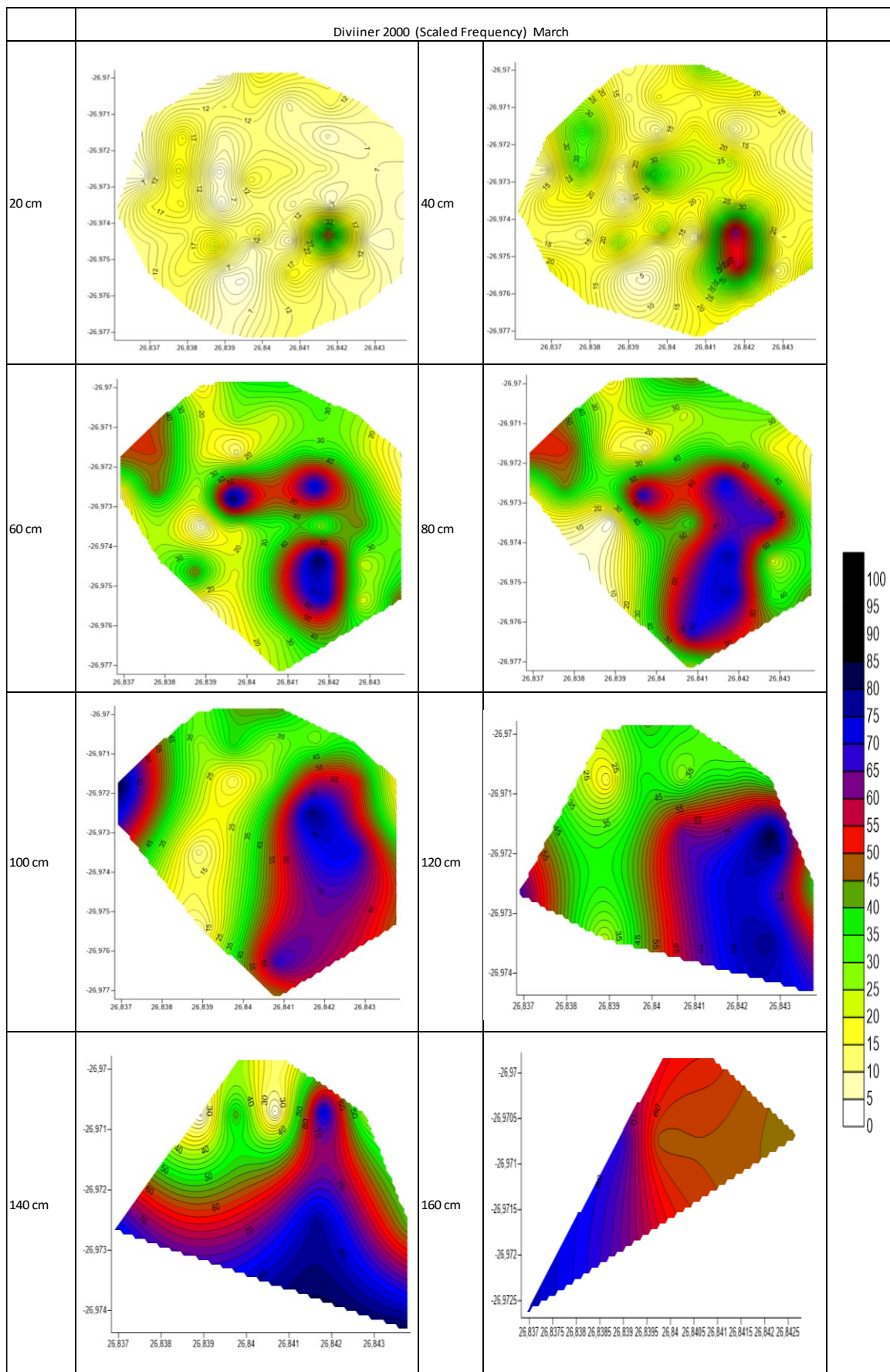


Figure 44: Diviner 2000 Results March

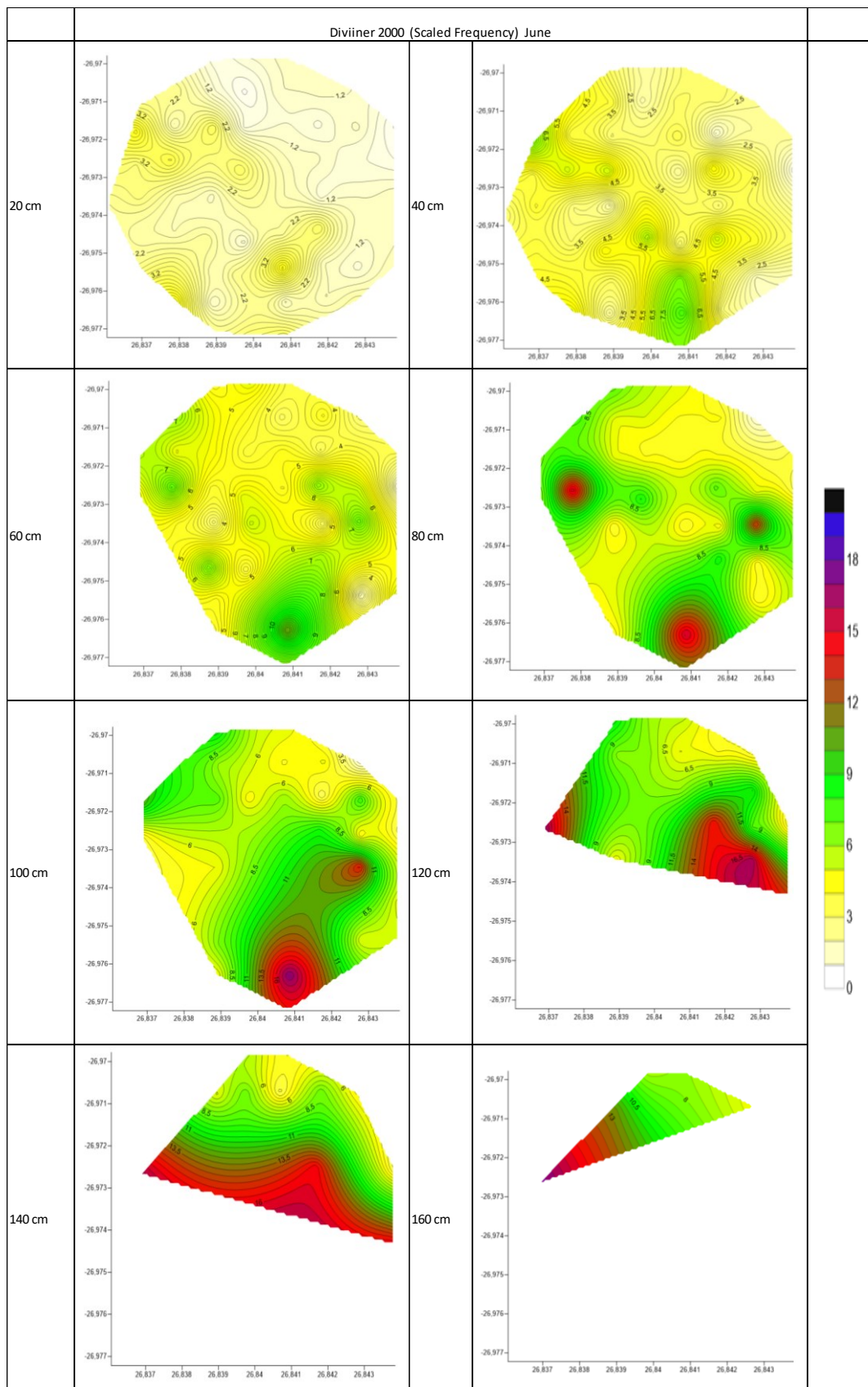


Figure 45: Diviner 2000 Results June