DETERMINATION OF EVAPORATION RATE IN A SABKHA IN THE EASTERN PROVINCE, SAUDI ARABIA.

BY

MATTHEW ARMOH

A Thesis Presented to the
DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

ENVIRONMENTAL SCIENCES

DECEMBER 2015

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN- 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

This thesis, written by **MATTHEW ARMOH** under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfilment of the requirements for the degree of **MASTER OF SCIENCE IN ENVIRONMENTAL SCIENCE.**

Dr. Abdulaziz Al-Shaibani

(Advisor)

Dr. Abdulaziz Al-Shaibani

(Department Chairman)

Dr. Mohammad Makkawi

(Member)

Dr. Salam A. Zummo

Dean of Graduate Studies

Dr. Bassam Tawabini

(Member)

11/1/16

Date

Prof. Warren W. Wood

(Member)

Prof. Omar S. B. Al-Amoudi

(Member)

Dedicated to my mother, Ama Aboagyewaah Ampong,

My wife, Vida Serwaah Nkrumah, my son, Michael Armoh, my aunt, Akua Bonney,

My siblings and to the memory of my beloved father, Francis Armoh.

ACKNOWLEDGMENTS

‘In the name of God, the Most Merciful and the Most Compassionate’

First and foremost, I would like to express my deepest gratitude upon God Almighty for giving me strength, wisdom, understanding and directing me to achieve this feat. A special appreciation goes to my supervisor, Dr. Abdulaziz Al-Shaibani, for his support, encouragement, guidance, critics and friendliness. My sincere gratitude goes to my committee members, Professor Omar S. B. Al-Amoudi, Professor Warren Wood, Dr. Mohammad Makkawi and Dr. Bassam Tawabini, for contributing their priceless time in constructively criticizing this thesis to ensure its success. I would like to thank the Saudi Arabian Basic Industries Corporation (SABIC) for funding this research under Project No. FT141008. Thanks also go to Kind Fahd University of Petroleum and Minerals for providing all the necessary logistical and technical support.

A lot of thanks go to friends and colleagues, especially Mr. Richard Osei Aning, Mr. Nestor Kodzo Ankah, Mr. Kamarudeen Masawudu Wahid, Mr. Mushabbab Q. Yahya, Mr. Mohammad Otabi and Mr. Azizulla Khan, for their assistance. I thank my mother, brothers, sisters and the Ghanaian community at KFUPM for their support and assistance in diverse ways. My final appreciation goes to my wife, Vida, and my child, Michael, for their love, understanding, patience and encouragement. They have been a source of motivation for the successful completion of my degree.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

EC	:	Electrical conductivity
ECe	:	Soil Saturated Paste Extract
ET	:	Evapotranspiration
NSTIP	:	National Science, Technology and Innovation Plan
RH	:	Relative Humidity
TDS	:	Total Dissolved Solids

ABSTRACT

Full Name: Matthew Armoh

Thesis Title: Determination of Evaporation Rate in a Sabkha in the Eastern Province, Saudi Arabia

Major Field: Environmental Science

Date of Degree: December 2015

Estimating evaporation rate from sabkhas is critical for understanding water resources of these features that occupy large areas of Saudi Arabia's landscape. An evaporation rate is important for predicting water yields, designing irrigation and supply projects, managing water quality, quantity, and associated environmental concerns, and negotiating disputes, contracts, or treaties involving water.

In this study, a direct evaporation rate was measured for Sabkha Jayb Uwayyid in the Eastern Province of Saudi Arabia using a portable humidity chamber. Seasonal evaporation rates of 0.25 mm/day (winter); 0.47 mm/day (spring); and 0.50 mm/day (summer) were obtained. The mean daily evaporation rate of 0.40 mm/day yields an average annual evaporation rate of about 145 mm. The soil characteristics and salinity of the water in the sabkha aquifer contribute to reduction of evaporation rate relative to pan evaporation of 3590 mm/year. Evaporation rate correlates with weather data considered for this study, however, relative humidity, gust speed and temperature are found to be more significant in the determination of evaporation rate compared to wind speed.

الخلاصـة

الاسم: ماثيو أرموه

عنوان الرسالة: تحديد معدّل التبخّر لإحدى السبخات في المنطقة الشرقية في المملكة العربية السعودية

التخصص: العلوم البيئية

تاريخ الدرجة: ديسمبر 2015م

يعتبر حساب معدل التبخّر في الأراضي السبخية ضرورياً جداً من أجل فهم ومعرفة مصادر المياه بها، حيث أن هذه السبخات تحتل مساحة كبيرة من أرض المملكة العربية السعودية. وكذلك يعتبر تقدير التبخر ضرورياً للتنبؤ بعائدات المياه، تصميم مشاريع الري، إدارة جودة وكمية المياه والمخاطر البيئية المرتبطة بها وكذلك مناقشة النزاعات والعقود أو المعاهدات المتعلقة بالمياه.

تم في هذه الدراسة قياس معدل التبخّر بصورة مباشرة لسبخة "جيب عويد" في المنطقة الشرقية من المملكة العربية السعودية باستخدام جهاز قياس الرطوبة المحمول. وكانت معدلات التبخر الموسمية التي تم قياسها كالتالي: 0.25 مم/اليوم (في فصل الشتاء)، 0.47 مم/اليوم (في فصل الربيع) و 0.50 مم/اليوم (في فصل الصيف). ويبلغ متوسط معدل التبخر اليومي 0.40 مم/اليوم، مما يعطي معدل تبخّر سنوي بمقدار 145 مم. وتساهم خصائص الطبقة السطحية، مثل خصائص التربة وملوحة المياه في السبخة، في الحدّ من معدل التبخر بالنسبة إلى معدل التبخر المقاس بالطرق التقليدية (مثل الخزان المفتوح) والبالغ 3590 مم/سنة. وقد أتضّح من هذه الدراسة ان لمعدل التبخّر مظاهاة جيدة مع عناصر الطقس المختلفة، غير أن الرطوبة النسبية والسرعة العاصفة (Gust Speed) ودرجة الحرارة كانت أكثر فعالية في تحديد معدل التبخّر مقارنة بسرعة الرياح.

CHAPTER 1

INTRODUCTION

It is important to understand and manage water resources due to their scarcity, especially in arid and semi-arid regions of the world such as Saudi Arabia. Evaporation and transpiration are important processes in the hydrological cycle globally and more significant in arid regions because, due to these two processes, up to 90% of the annual precipitation in these regions is lost to the atmosphere [1]. Water lost from both the soil and the leaves of a plant together is termed evapotranspiration [1].

Generally, the rate of evaporation is affected by temperature, wind, atmospheric pressure, humidity, water salinity, water depth, soil type and properties, and the shape of ground surface [1]. Most often, the rate of actual evaporation from a soil surface depends on the capacity of the soil to transmit water. Actual evaporation will be equal to potential evaporation when the soil is saturated. In the case of water being a limiting factor for evaporation, actual evaporation will be less than potential evaporation. For instance, sandy soil is known to have less capillary rise than clayey soil and as such the soil surface becomes less saturated, and there will be rapid decrease of evaporation with soil moisture content. Contrarily, clayey soils have finer soil texture and, hence, have higher capillary rise and may transport water from deeper soil zone to the soil surface. Due to this, with decreasing saturation, the actual evaporation reduces slowly as compared to sandy soil.

Moreover, clayey soil has a larger porosity compared to sandy soil, and clayey soil may contain a larger amount of water than sandy soil [2].

There are different methods for estimation of evaporation that can be broadly considered as either direct or indirect methods. The various indirect methods of measurements were developed to estimate evaporation and evapotranspiration from large water or land surfaces [1]. Evaporation pans, lysimeters and chambers are categorized under the direct methods. Water-budget, the energy-budget/Bowen ratio, the aerodynamic approach or some combination of these are examples of indirect methods for estimation of evaporation and evapotranspiration. Due to the bulky nature of evaporation estimation from indirect methods, empirical formulae have been developed. For instance, Priestley Taylor, Kimberly Penman, Penman Montieth and Hargreaves have all developed various empirical formulae [3]. Any of these methods has its own challenges [4] that range from cost, accuracy of the method, and the availability of weather data [5].

Regarding limitations, soil water balance requires large spatial data and, as a result, it is difficult to be applied when the drainage and capillary rising are important. Further, it is difficult to measure soil moisture in soil with cracks on the surface. Concerning energy budget/Bowen ratio, it is difficult to have correct measurement of the wet temperature if a psychrometer is used and, as such, the method requires the sensors to be inverted to help reduce biases in the results [3]. The Aerodynamic approach, on the other hand, needs to be corrected in order to be stable and also is not suitable for tall crops. Weighing lysimeter, which is a direct measurement method, is rigid, difficult to maintain, and the data obtained could not be representative of the plot area and, moreover, expensive to use. Lack of sufficient weather data in most locations renders Penman’s theory, which is expressed as an empirical formula, ineffective and the theory applies better in humid conditions than in arid regions with low humidity [3]. The portable chamber method has also been developed to measure evaporation and evapotranspiration.

1.1 Problem Statement

Accurate measurement and estimation of evaporation plays an important role in hydrological studies and in planning, operation and management of water resources [4]. The significance of evaporation in the hydrologic cycle generally increases with increasing the aridity [6,7]. Measurements of evaporation are critical when estimating the effect of soil and atmosphere on the hydrological processes in arid environments. In arid and semi-arid regions, evaporation often consumes large parts of precipitation, and the timing of evaporation can greatly affect stream flow and groundwater recharge. Therefore, understanding of evaporation rates can be an essential part of understanding the hydrological system. However, little literature is available within the Kingdom of Saudi Arabia on evaporation and evapotranspiration measurements. Though other methods such as lysimeters [8,9], US-class A evaporation pan [10] and empirical methods [11] have been used for the determination of evaporation and evapotranspiration in Saudi Arabia; however, no reports are available on evaporation determination using the portable chamber technique in Saudi Arabia. The absence of such data represents, a research gap regarding this highly relevant issue to the Kingdom. Further, Al-Shaibani [12] reported that the evaporation rate on Sabkha Jayb Uwayyid is required to determine the economic viability of using brine for salt production.

1.2 Significance of This Study

Evaporation measurement is important for predicting water yields, designing irrigation and supply projects, managing water quality and quantity, and associated environmental concerns, and negotiating disputes, contracts, or treaties involving water [13]. Due to the scarcity of water resources in the Kingdom, water related issues are considered the most strategic of research in the National Science, Technology and Innovation Plan (NSTIP) of the Kingdom. Results from this study are expected to add to the literature on water resources in the Kingdom of Saudi Arabia.

1.3 Research Objectives

The overall objective of this study was to determine the evaporation rate on Sabkha Jayb Uwayyid in the Eastern Province of Saudi Arabia, while the specific objectives were as follows:

1. To design and fabricate a purpose-built portable chamber;
2. To determine the evaporation rate;
3. To assess the effect of soil and brine salinity, soil moisture and texture on evaporation rate;
4. To compare seasonal variation of evaporation rate; and
5. To correlate the evaporation rate with weather data.

CHAPTER 2

LITERATURE REVIEW

Several research works have been carried out on the measurement of evaporation and evapotranspiration using portable chamber techniques. Some of these studies have found chamber flux measurement coherent with other methods of evaporation and evapotranspiration measurement. For instance, Reicosky [14] found the portable chamber method to be satisfactory for measurement of evapotranspiration when compared with the weighing lysimeter method. Reth et al. [15] reported acceptable agreement ($r^2 = 0.69$) between modelled chamber measurement and eddy covariance measurement (EC). Eddy covariance (sometimes called eddy correlation) is a technique used in determining the exchange rate of fluxes across the boundary between the atmosphere and a plant canopy by measuring the covariance between fluctuations in vertical wind velocity and fluxes mixing ratio [16]. In the same way, Grau [17] reported chamber measurement to be highly associated with actual measurement obtained using gravimetric water loss approach though the chamber ET measurement which was found to be 25% higher than gravimetric water loss. Mcjannet, et al. [18] found a strong correlation between evaporation dome and microlysimeter for the measurement of soil and litter (ground surface of forest floor) evaporation, which enhanced the reliability of the use of portable evaporation chambers for the measurement of soil evaporation. Similarly, according to Angell et al. [19], the chamber is a valid technique and can be used to attain a reliable measurement of water flux. This was reported after chamber measurement had been found to be highly correlated with Bowen ratio/energy balance method for the determination of carbon dioxide fluxes.

However, little correlation was observed between the two techniques (energy balance and chamber method) during hot and dry summer conditions. In a related scenario, Stannard and Weltz [6] reported that chamber measurements of ET were well associated with eddy-correlation measurement though ET measurement via a portable chamber which was about 26% higher than simultaneous eddy-correlation. On the contrary, Pickering et al. [20] reported that chamber measurement overestimated ET to an error of 0.13 mm/h under varying light conditions when compared with lysimeter. However, during clear sky conditions, chamber was highly correlated with both instantaneous and hourly lysimeter ET measurement with r^2 of 0.90 [20].

The portable chamber has been criticized because it changes the environmental conditions of the plant-soil being measured [3]. The main reasons for the criticism were ascribe to alteration solar radiation and water vapor balance (microclimate) during measurement. Also the wind speed could strongly be reduced [3]. Soil variability, size of the chamber and how it was placed were also criticized [21]. Portable chamber measurement has also been found to show sensitivity to the selection of the fan speed. Similarly, a study conducted by Dugas et al. [22] revealed that portable chamber measurement of latent heat flux is affected by the surrounding conditions.

Importantly, solutions have been found to most of the above criticisms of the portable chamber method. McLeod et al. [23] found a slow fan speed that gave an air velocity of 2.7 km/h to be satisfactory to produce the nearest correlation with the Bowen ratio method. According to Stannard [24], setting the internal wind speed to the average wind speed on the measurement site by adjusting the internal wind speed with a rheostat helps minimize the error. Denmead and Reicosky [21] reported a variable correlation between chamber measurement and micrometeorological methods depending on the wind speed and found a wind speed of 2.27 m/s was suitable for their studies. A measurement time of 1 to 2 minutes was found to be sufficient for the calculation of vapor flux after closure of the chamber [25].

Notwithstanding the rapid nature of taking the measurement, some disturbance usually remains. Commonly, chamber studies emphasize comparative studies instead of absolute results, to largely eliminate the effects of bias [6]. Sanford and Wood [26] used the portable chamber technique to determine an average evaporation rate of 69 mm/year in Sabkha Matti in Abu Dhabi, United Arab Emirate. Similarly, the portable chamber was used to determine ET from diverse vegetation types of varied communities [27].

This thesis research was designed to determine direct evaporation on bare soil using the portable chamber technique, a direct method which is used to estimate evaporation and ET components. A portable chamber was selected over the other methods due to the suitability for evaporation measurement within small areas (less than 1 m^2), the speed by which the instantaneous evaporation rate is obtained (less than 1 min.). Further, instantaneous evaporation measurement can be repeated throughout the day from the same area of measurement; the portability of the enclosed portable chamber, the basis of measuring the actual water flux from evaporating soil rather than extrapolating or deducing it from climatic parameters [23] and, finally, its cost efficiency when compared with the lysimeter method [14].

CHAPTER 3

STUDY AREA, STUDY DESIGN AND METHODS

3.1 Study Area

The study was conducted at Sabkha Jayb Uwayyid, which is an inland sabkha located in the eastern Saudi Arabia [28]. This sabkha developed without a contemporary association of marine sedimentology. This site was selected to complement the research work of Al-Shaibani [12] on the same site, which noted that an evaporation rate is required to determine the economic viability of its brine. The sabkha is located between latitudes 26º 15' 23" and 26º 20' 15" N and longitudes 49º 49' 25" and 49º 55' 10" E, about 25 km west of the city of Dhahran, (Figure 3.1). It has a surface elevation of approximately 10 m above sea level. The site has a levelled surface with windblown sand, as shown in Figure 3.2. There are three separate sand dunes with the height of approximately 10 m higher than the sabkha surfaces. An industrial complex has recently been developed at the eastern part of the sabkha [29]. The region has a hyper-arid climate with an average annual rainfall of 90 mm, far less than the average annual potential evaporation of about 3,590 mm/year with a maximum potential evaporation of 15 mm/day in June and a minimum of 5 mm in January in the Eastern Province [12]. The average monthly maximum air temperature falls within the range of 42 ºC in July to 20.1 ºC in January with an annual mean of 32.3 ºC. The monthly minimum air temperature recorded ranges from 26.9 ºC in June to 10.2 ºC in January with an annual mean of 19.9 ºC. Air relative humidity is the lowest during the month of June (36%) and reaches its highest monthly average of 78% in February with an annual mean of 59.4% [29].

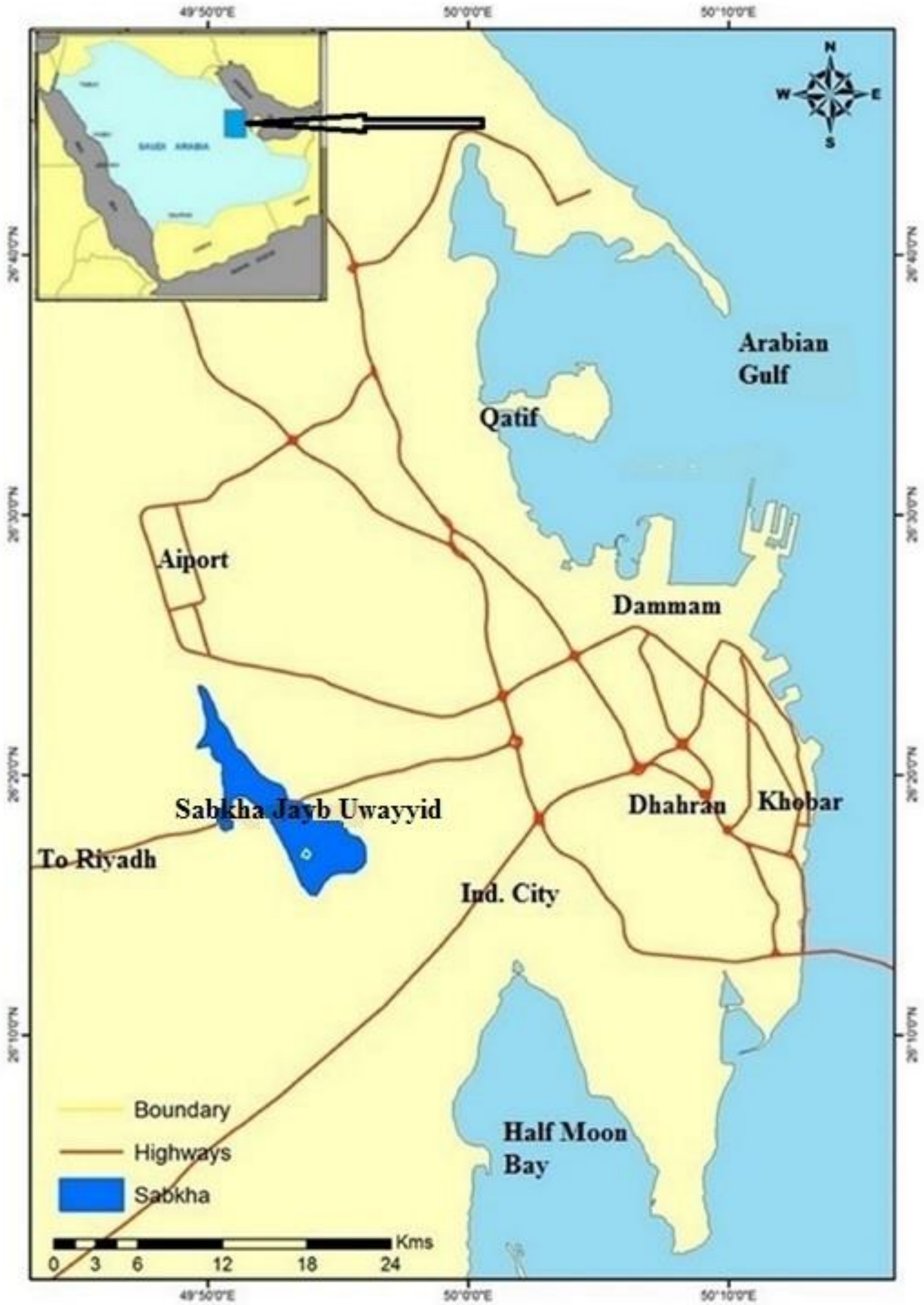


Figure 3.1: Locations of Sabkha Jayb Uwayyid in the Eastern Province of Saudi Arabia.

Figure 3.2: A view of a Sabkha Jayb Uwayyid.

Sabkha soils are geotechnically considered as highly variable, particularly regarding grain size and shape, the degree of cementation, texture, diagenetic minerals, compaction and layering. The reasons for the variations were due to various processes that led to the formation of the sabkha soil. These processes include climatic (rainfall, temperature, humidity, and wind condition at the time), geochemical (this includes both diagenetic minerals and brine chemistry), geomorphological (comprises surface gradient and groundwater table), hydrological (which are affected by climatic, geochemical and geomorphological factors) and biological (algae mats and burrowers) [30].

A sabkha is an Arabic term describing a flat soil with high concentrations of salt. The salt is ascribed to the high capillary rise and excessive evaporation in the inland and coastal sabkhas. Warren [31] defined sabkha as “hydrological settings where resurging groundwater form displacive and replacive evaporite minerals (gypsum, anhydrite, halite, polyhalite, glauberite, etc.) in the capillary fringe above a saline water table or in the brine-saturated muds immediately below”. The whole capillary arrangement is typically made of 50% plus non-evaporite matrix and has on top of it an erosion surface. Sabkhas are hydrologically categorized into coastal and inland (continental) sabkhas [29]. The inland sabkhas cover large areas of both developed and undeveloped lands. They are topographical depressions evaporating groundwater from either shallow water table or from deeper upward leakage [29]. The description of sabkhas is not unique to Saudi Arabia. For instance, it has been described along the coast of Baja California, Great Salt Lake, the coast of Sinai, and several other areas of the world [28].

Seismic refraction survey shows that, stratigraphically, the Sabkha Jayb Uwayyid is composed of three main layers, as shown in Figure 3.3. The first layer is a sandy soil layer with an average thickness of 15 m and the second layer is 113 m, followed by a third layer. The uppermost part of the first layer has a partially saturated clean sandy soil. Beneath this uppermost layer is a completely saturated sandy soil, which is also part of the first layer. This is followed by a second layer, which is found below the water table (found at a depth of about 1 m) and finally third layer [28]. Within the partially saturated clean sand is a bed of halite found at a depth of about 2.8 to 4.3 m. It has a thickness of about 0.3 to 3.7 m and extends approximately 5 km in length and 1.8 km in width [29].

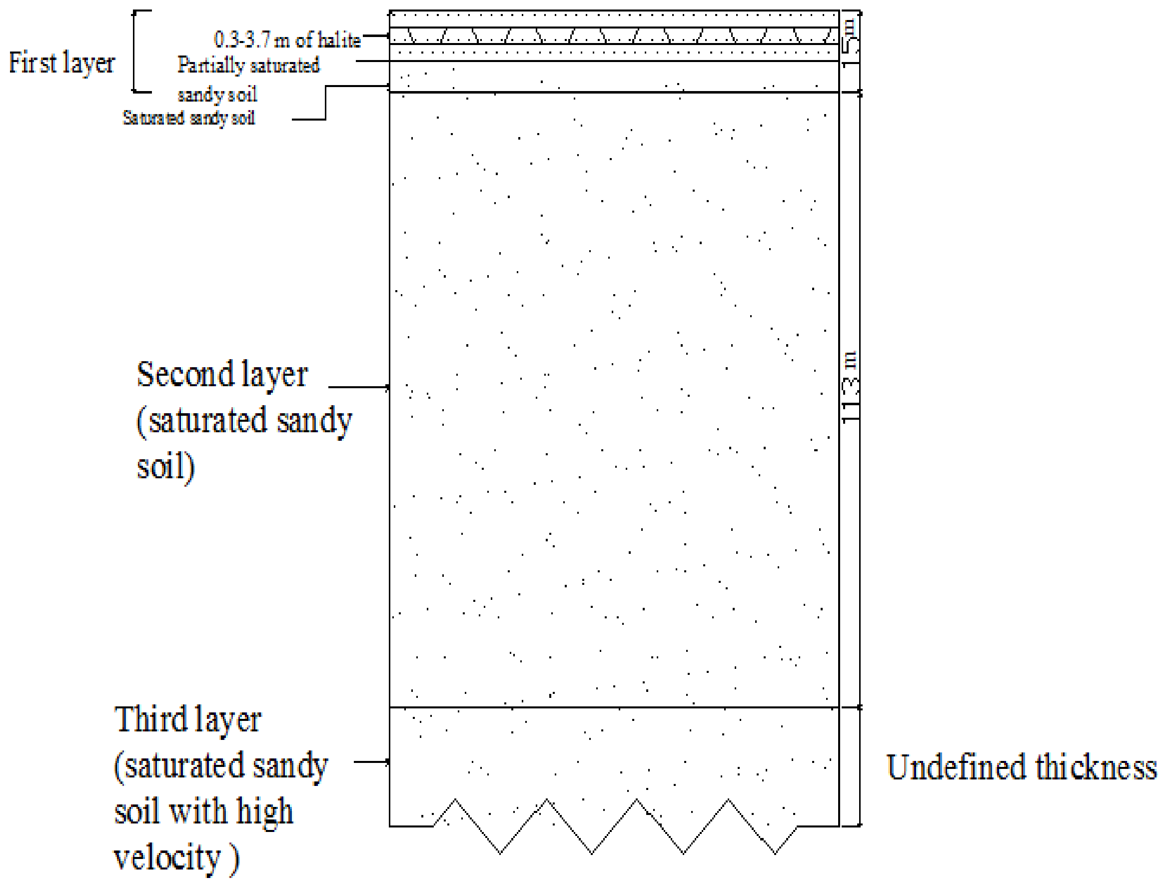


Figure 3.3: Detailed cross-section of the uppermost layer Sabkha Jayb Uwayyid showing generalized stratigraphy (Alsaaran 2008; Al-Shuhail and Al-Shaibani 2011)

3.2 Portable Chamber Fabrication

A trimmed box-shaped chamber shown in Figure 3.4 was designed, with side lengths of 0.75 m by 0.75 m, made of 4 mm thick Plexiglas™. The chamber was beveled to avoid sharp internal angles so as to facilitate internal air circulation and minimize air entrapment. The Plexiglas™ has a transmittance to light of 92% at a thickness of 0.375 mm [6]. The total height of the chamber at the center is 500 mm and covers a land surface area of 0.6 m^2. Two 12-volt fans were mounted inside the chamber opposite to each other to stir the inside air. The fan speed inside the chamber could be adjusted to approximate the average wind speed at the study sites. The external wind speed was also measured using a portable wind gauge installed at one-half the height of the chamber height. Vapor density was measured using a temperature and relative humidity data logger placed between the fans.

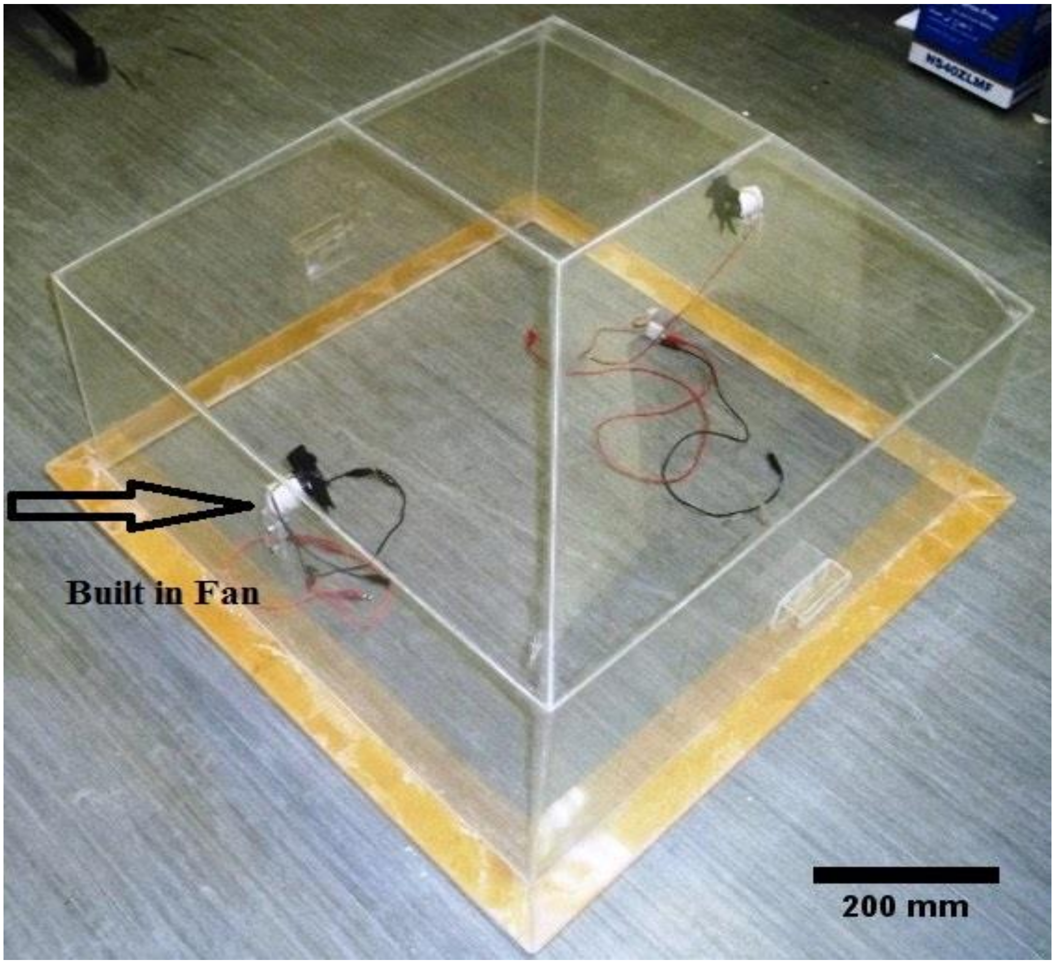


Figure 3.4: A trimmed box chamber constructed of clear acrylic.

3.3 Calibration of the Chamber

Due to the hydrophilicity of the portable chamber, the chamber was calibrated to take care of the water that will naturally be absorbed by the chamber and data logger error prior to field measurement.

The procedure for the calibration of the portable chamber is the modified version of the one described by Stannard [24]. This involved boiling water in a beaker placed inside the chamber at a variety of rates while measuring the weight of water loss with time. A calibrated data logger (™HOBO Prov v2 temp/RH Onset make) was used to measure the increase in vapor density inside the chamber. The water loss from the chamber was evaluated against the increase in vapor density inside the chamber.

A 600 ml beaker was then filled with water until the total weight was slightly less than the digital balance (range 0 to 600 g, readability to 0.01 g). The beaker filled with water was placed on top of the balance which is placed on a levelled surface. A heated coil was suspended into the water and was clamped to a ring stand. Care was taken to avoid the coil touching the beaker. An approximate evaporation rate ranging from 0.2 to 0.3 g/min was established at a given voltage setting as determined by timing the weight loss displayed on the balance. A fan inside the chamber was turned on together with the data logger to record time, temperature and relative humidity at a logging cycle of 2 seconds.

The chamber was emplaced over the apparatus, noting the time the chamber touched flat surface; this was recorded as the start time. Balance display was read at an equal time interval of 5 seconds for a period of 2 min. Data collection was stopped and the chamber raised up to obtain ambient humidity inside the chamber. This was repeated at the same rate after waiting for a few minutes.

A graph of water loss and accumulated vapor was plotted against time for each measurement, as shown in Figure 3.5. The accumulated vapor was calculated using a formula described by Stannard [24] as follows:

$$Va = pvV, \qquad (1)$$

Where;

Va, is accumulated vapor, in grams;

pv, is vapor density as measured by chamber, g/m^3;

V, is volume inside the chamber, minus the volume of apparatus inside the chamber, in m^3;

The time period when the steady slope was achieved for both water loss and accumulated vapor was determined. These slopes represented the vapor production and accumulation rates. A graph of vapor accumulated was then plotted against vapour production rates for all measurement and best-fit line that passes through the origin was determined. The slope of the best fit line is the calibration factor used for the calculation of evaporation rate. A calibration factor of 1.91 was obtained, which is slightly higher than 1.53 obtained by McLeod [23]. This is probably due to the shape of the chamber constructed for this study as the trimmed edges are likely to entrap more air.

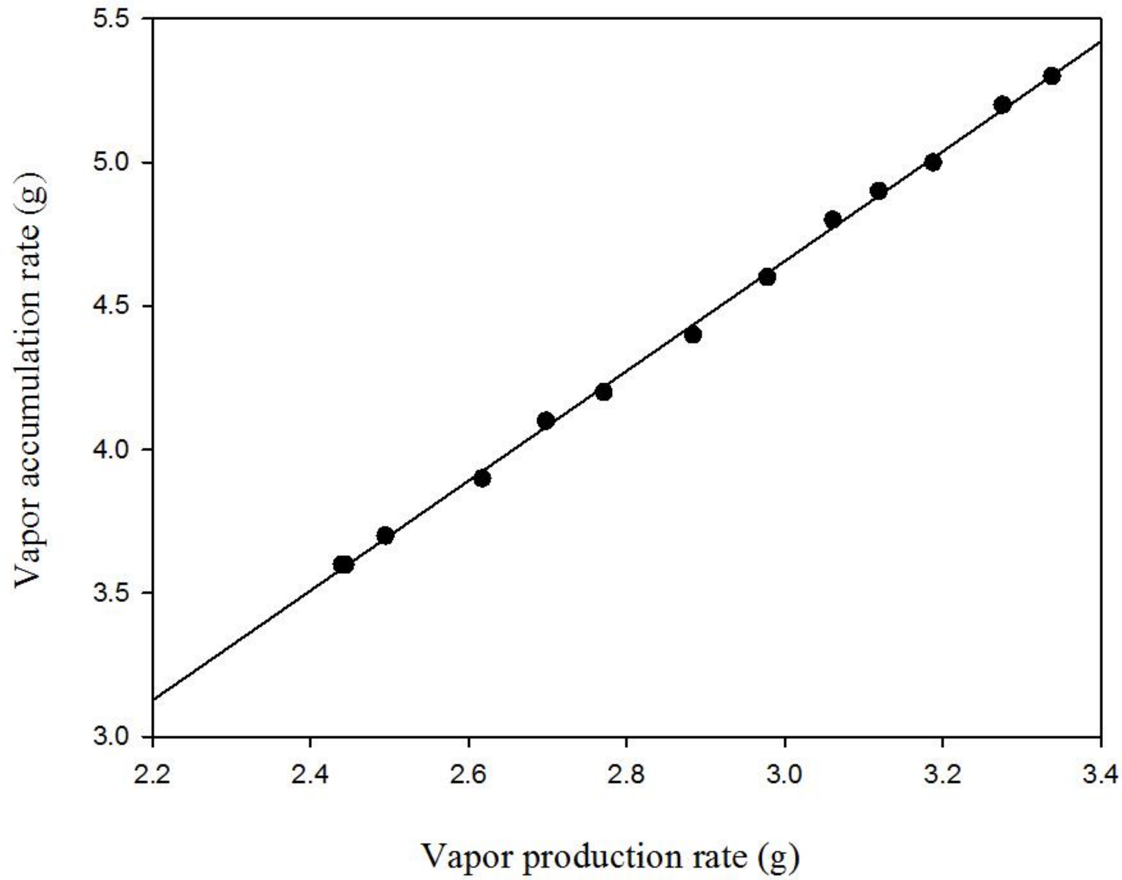


Figure 3.5: Graph of vapor accumulation rate and vapor production rate.

3.4 Field Experimental Work

An area of about 400 x 400 m of the study site was defined using a GPS. In order to ensure that the location selected for the evaporation measurement was typical of the surrounding area regarding soil characteristics, soil moisture content and texture were checked for the selected location and the surrounding areas using a calibrated dielectric aqua-meter sensor. Also, evaporation measurement location was sited beyond the influence of individual buildings and trees. A distance of not less than 100 m from the boundaries of the sabkha site was considered. It was again not more than 3 to 4 km from the meteorological station installed at the study site. Soil samples for analysis were taken within 50 m radius of the measurement location [1]. Portable chamber measurements of evaporation were collected at two different locations at the study site. This was to help obtain an average measurement for the site and to examine geological variations between locations, such as due to heterogeneity and anisotropic properties. A homogeneous geologic formation is a geologic formation that has the same properties at all locations. For instance, in order for a sandstone formation to exhibit homogeneous properties, the grain-size distribution, porosity, degree of cementation and thickness, and the hydrogeologic values of transmissivity and storativity (the ability of the geological formation to transmit and store water) of the unit should be about the same at all locations.

Similarly, to have an isotropic geological phenomenon, the intrinsic evaporation of the unit must be the same in all directions in a porous medium made of spheres of the same diameter packed uniformly [32]. However, because geologic processes generally operate in varying rates and produce an uneven landscape, heterogeneity normally results. This is when hydraulic properties change spatially. For instance, if there is a change in thickness of a media such as sandstone, even if porosity, hydraulic conductivity, and specific storage remain constant, the media still remains nonhomogeneous. In a related scenario, if the geometry of the voids is non-uniform, there may be a direction in which the intrinsic evaporation would be greater. For example, a porous medium composed of book-shaped grains assembled in a sub-parallel manner is likely to have a greater permeability to the grains than crossing the grain direction due to the direction of groundwater flow [32]. The measurement was again conducted on three different seasons; February in winter, April in spring and August in summer; all in 2015, to compare the results of seasonal variation. To obtain the measurement location, the site was divided into two blocks and the location randomly selected from each block, as shown in Figure 3.6.

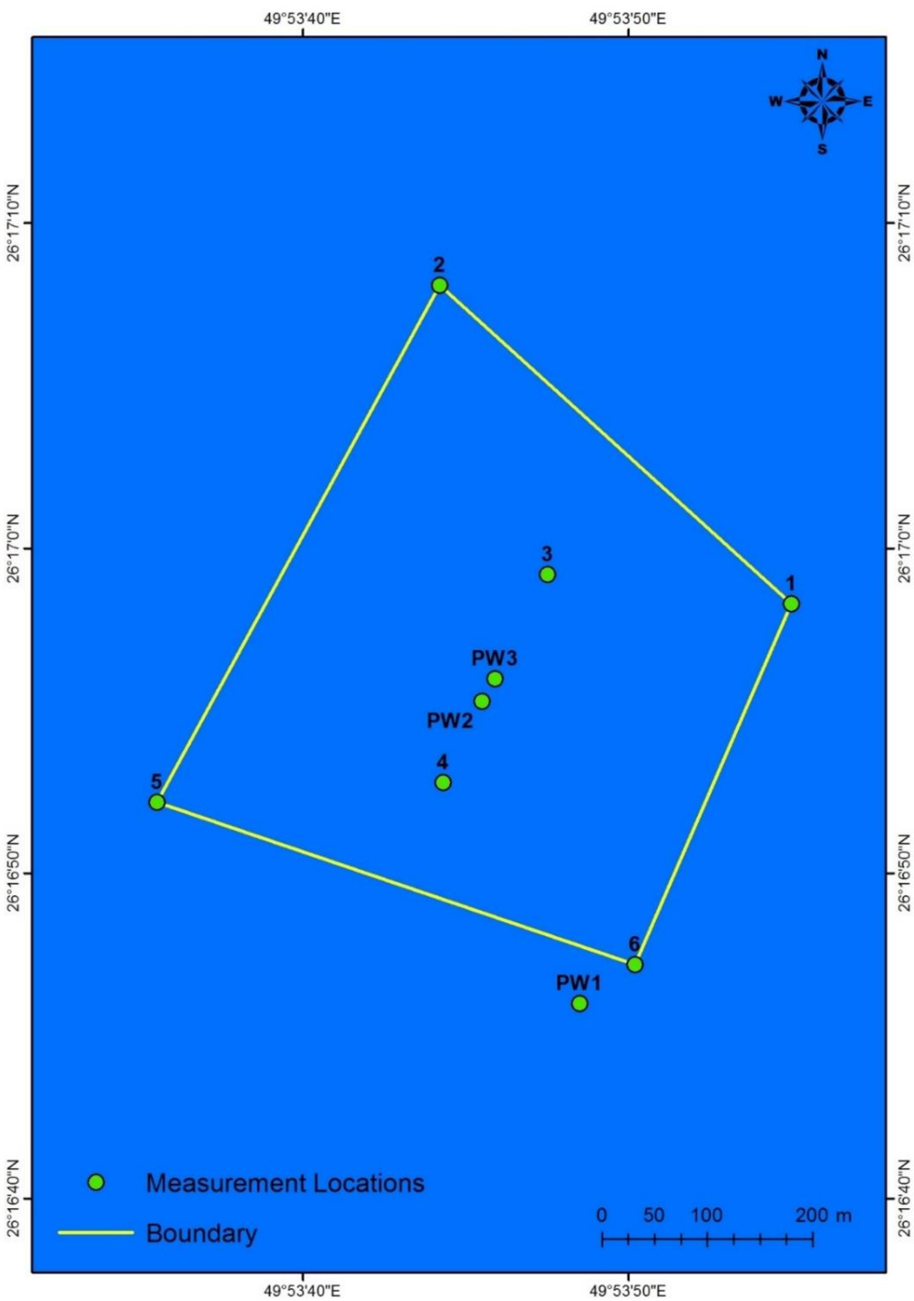
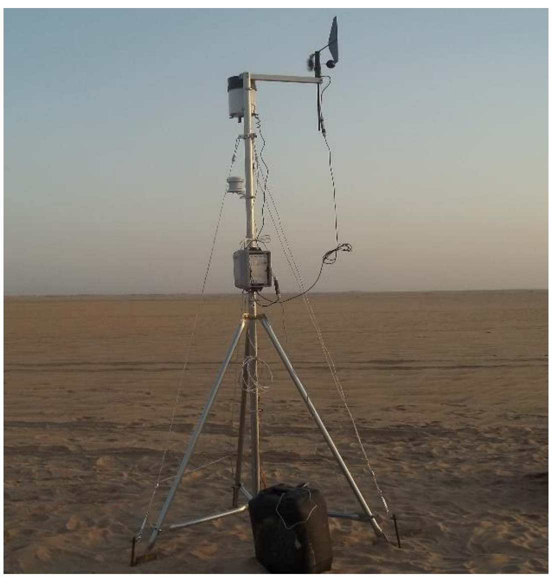


Figure 3.6: The boundaries of the study site and measurement location (1, 2, 5, and 6 defines the measurement area and 3, 4 are the evaporation measurement locations and PW1, 2, 3 are location of piezometer wells).

The chamber was emplaced over the soil while the data logger collected measurement in 2-seconds intervals for 2 minutes, as shown in Figure 3.7. In order to obtain ambient humidity and air temperature inside the chamber, the chamber was raised above the land surface to a height of about 1 m. The chamber together with the other measurement equipment was moved to the second location and measurement taken following the same procedure as previously described. Humidity measurements were taken every hour per location throughout the day. The time difference between two consecutive measurements within an hour ranged from twenty to thirty minutes due to the distance between the two measurement locations.



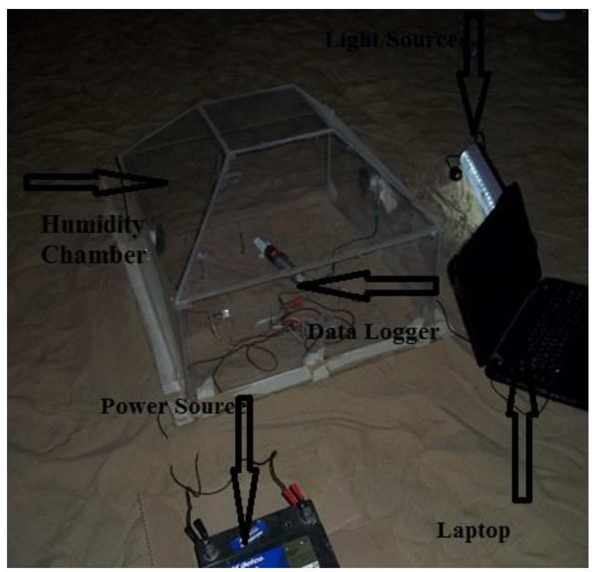


Figure 3.7: Weather station, portable chamber with support equipment for measurement

Among the factors affecting evaporation is the dissolved salt in either the soil or brine. The presence of dissolved salt in soil or brine reduces the saturation vapor pressure as a result of the decreased chemical potential of water or soil and, hence, reduce the evaporation rate [33]. According to the second law of thermodynamics, an increase in the ionic activity due to the presence of solutes reduces the chemical potential of a liquid solvent and the rate of unconstrained conversion of the liquid phase into the vapor phase [33].

A calibrated soil moisture sensor was used for the determination of soil moisture. The soil moisture was determined at four different locations at the study site. At each location, soil water content was determined at a depth of 0.1 m and 0.5 m at 30-minute intervals and the average was determined to represent the site. In determining the salinity and texture of the study site, a representative soil sample was taken. Generally, the larger the number of samples, the more representative is the results. Conversely, too few samples give an erroneous results. The site was divided into four strata and four sample locations were randomly selected within each stratum for sampling. A trial pit was dug and soil sampled at a depth of 0.1 m and 0.5 m at each of the sample locations. The different sampling depth was to assess the vertical and horizontal variation of salinity as salt concentration in soil may greatly vary vertically and horizontally and with time. Sampling was taken in each of the seasons considered in this study [34].

In obtaining groundwater samples for the determination of salinity, five piezometers, which were previously installed on the study site [12], were used. A bailer (groundwater sampling device) was used for water sampling. To obtain a representative sample of groundwater for salinity determination, groundwater was purged from the piezometer to achieve stabilization. In order to ascertain the achievement of stabilization, pumping of about 5 to 10 times the volume of the 200 mm piezometer was found to be sufficient to remove the stagnation. This was done while monitoring other parameters such as pH, temperature, and dissolved oxygen readings at specific intervals until four consecutive readings fell within the same range using Eutech PCD650 meter.

The depth to water table is a major factor in controlling the topography of the sabkha. It also contributes to evaporation rate and concentrating the salinity that remains. Prior to sampling of the groundwater, the water level in the various piezometers was measured using a water level meter.

A calibrated Weather Station (™HOBO) with 2 m tripod length was installed at the site to measure temperature, wind speed and direction, gust speed and relative humidity (RH). These measurements were taken whenever field measurement was carried out. To ensure that the calibrated weather station gave accurate results, the data obtained were correlated with data obtained by another weather station installed and monitored by the Center of Engineering Research at King Fahd University of Petroleum and Minerals (KFUPM) at the same date and time. Though the distance from KFUPM campus to the study site is about 25 km, correlation values ranging from 0.70 to 0.93 were obtained for all the parameters considered, signifying the high accuracy of the weather station.

3.5 Procedure for Calculating Instantaneous Evaporation Measurement

Data obtained from relative humidity and temperature were used to calculate the vapor density increase within the portable chamber based on the procedure suggested by Stannard [24].

The partial vapor pressure and saturation vapor pressure were first calculated. The calculated vapor density data were plotted against time and the slope of the straight line from the plots were used for the instantaneous (instant measurement) evaporation measurement, and the total daily evaporation rate (mm) as shown in Figure 3.8.

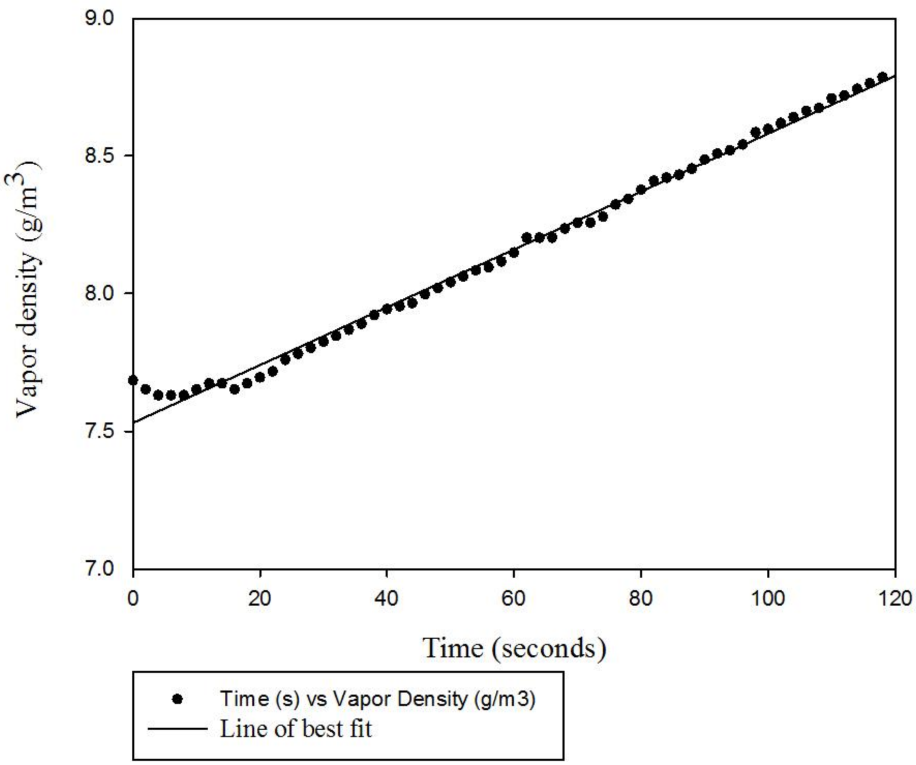


Figure 3.8: A graph of vapor density against time within the portable chamber for a two-minute measurement period.

The saturation vapor pressure for corresponding relative humidity and temperature were obtained from temperature, vapor pressure, and relative humidity diagrams developed by Fritschen and Lloyd [35] computed using the Magnus formula [36] as follows;

$$ew = 611.2\exp\left(\frac{17.62t}{243.12+t}\right) \qquad (2)$$

range -45 ^{o}C to 60 ^{o}C, where

ew is saturation vapor pressure in Pa

t is the temperature in °C

the formula gives uncertainty value of 0.6%

Partial vapor pressure, e (Pa), was calculated using information from relative humidity (RH):

$$e = ew\frac{RH}{100} \qquad (3)$$

where e is partial vapor pressure (Pa), ew is the saturation vapor pressure (Pa), RH is the relative humidity (%).

Vapor density, (pv), is calculated using the formula:

$$pv = \frac{e}{RvT} \qquad (4)$$

Where pv is vapor density (g/m^3), e is the partial vapor pressure (Pa), Rv is the specific gas constant for water vapor (461.5 J/kg K), and T is the absolute temperature (Kelvin) [35]. The slope of the straight line was obtained after plotting the vapor density against time using the method of least squares. Further, each soil evaporation rate was estimated using the method described by Stannard [24] as follows:

$$E = 86.4\left(\frac{MVC}{A}\right) \qquad (5)$$

E is the evaporation rate, mm/day,

M is the maximum slope of the vapor density series, g/m^3/s,

V is the volume inside the chamber, m^3,

C is the calibration factor of the chamber, dimensionless,

A is the land surface area covered by the chamber, m^2, and

86.4 is a factor that converts grams of water/m^2/s to a daily rate of mm/day.

3.6 Determination of Correlation Coefficient between Evaporation Rate and Weather Data

Pearson correlation coefficient and multiple regression technique were used to find the relationship between the evaporation rate and temperature, RH, wind speed and gust speed for the seasons considered using ™SPSS Statistics 20 and ™Minitab 16 software. The formula that was used to determine the sample correlation coefficient, r, between two variables, x and y, is denoted by r_{xy} and is computed as follows:

$$r_{xy}=\frac{cov(xy)}{\sqrt{var\ (x)}\sqrt{var\ (y)}} \tag{6}$$

where $\text{cov}(xy)$ is the sample variance of x and y

$\text{var}(x)$, is the sample variance of x

$\text{var}(y)$, is the sample variance for y

The correlation coefficient, r, and coefficient of determination, R^2, is related by $r = \sqrt{\ } R^2$ [38].

3.7 Procedure for Determination of Soil Salinity

Soil salinity values were determined from soil samples by measuring the electrical conductivity (EC) which is expressed as milli-siemens per centimeter (mS/cm). It was carried out by mixing a ratio of one part of soil to five parts deionized water on a volume basis. This mixture was shaken and then allowed to settle in order to measure the electrical conductivity of the clearer fluid at the top of the settled mixture (EC 1:5). The result from

1:5 soil-water ratio was converted to soil saturated paste extract (ECe) equivalent by multiplying the result by 14.0 for sandy soils [39]. The procedure for analysis of the soil sample is based on the modified version reported in [39]. It involved placing a sampled soil on a tray to dry in an oven. After drying, the sample was mixed thoroughly and 100 ml of soil taken and placed in a graduated cylinder and tapped gently to settle. A 500 ml volume of deionized water was measured and added to the 100 ml of soil sample and stirred for the sample to completely mix. The completely mixed sample was allowed to settle for about five minutes. The electrical conductivity was measured from the clearer fluid at the top of the mixture using a calibrated Eutech PCD650 meter. The measurement result was then multiplied by a factor of 14 because the soil type was sandy [39] and the result then converted to Total Dissolved Solids (TDS) equivalent. There are three standards used for conversion of EC to TDS (measured in part per million ppm). These include the American standard, European standard and Australian standard. However, the American standard is the most commonly used standard and hence was used for the conversions in this study. With this standard, 1.0 mS/cm (EC 1.0 = 500 ppm) [40].

3.8 Procedure for Determination of Grain Size Analysis

Soil type, sediment size, and other factors (mineralogy and permeability etc.) are critical factors in the determination of evaporation rate from the soil. This is as a result of the size affecting the speed of transmission of water through the soil profile to the surface for evaporation to occur [2]. In determining the grain size of the sabkha soil, a representative sample was obtained. A dry sieving method was used for the determination of the grain sieve distribution following standard sieve analysis procedure described by ASTM D 422.

This sample was quartered and a portion was taken for oven dry for 24 hrs at 105 ºC. The dried sample was cooled after oven drying and 400 g was sampled and sieved. Seven different sieves of sizes ranging from 4 mm to 0.063 mm and a pan were used for the sieving. An electronic sieve shaker model was used in shaking the samples in the arranged sieves for about 15 minutes and samples retained on each sieve were collected and weighed using a weighing scale that has a readability to 0.01 g. The sample retained on 63-micron sieve was collected in a container and soaked in a solution of 10 ml of Na_2CO_3. The soil solution was thoroughly washed until clean water passed through the sieve. This sample was then dried in an oven and the weight recorded. This was done to obtain the actual amount of sample retained on the 63-micron sieves. The percentage of material retained, the cumulative percentage retained on each sieve and percentage of finer material passing each sieve were then calculated. A grain size graph between particle size on the x-axis and percentage finer on the y-axis was plotted. Based on the shape of the graph obtained and other calculations, the sabkha soil was categorized.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Evaporation Rate

Results of evaporation rate for winter, spring and summer are shown in Figures 4.1, 4.3, and 4.5, respectively. From the winter evaporation rate results shown in Figure 4.1, an average daily evaporation rate of 0.25 mm was obtained. This was averaged from evaporation rates from two locations for each daily measurement obtained on the 5th and 9th of February, 2015. The hourly evaporation rate as obtained for the 5th and 9th of February, consistently followed a similar pattern. Highest evaporation rate was obtained for each of the measurement locations at 11:00 am. This gradually decreased from 11:00 am to 1:00 pm. There was a slight increase in evaporation rate at 2:00 pm and then the rate decreased again from 2:00 pm to 7:00 pm. In between the hours of 7:00 pm and 2:00 am, there were irregular patterns of evaporation rates of almost zero with condensation. From 2:00 am, the evaporation rate started increasing gradually in an undulating pattern until 10:00 am. The highest hourly evaporation rate of 1.47 mm and the lowest hourly evaporation rate of 0.01 mm were obtained for winter season. Evaporation rate is controlled by the difference between the thermodynamic activity of the atmosphere given by the relative humidity and the evaporating water determined largely by ion strength. Due to this thermodynamic principle, there was reversal or condensation at some hours in the night. The average evaporation rate at location 2 was found to be 15% lower than that obtained in location 1 possibly due to the heterogeneity and anisotropy behavior of the soil.

A minimum and a maximum temperature with its corresponding RH of 12.4 °C and 55% and 27.9 °C and 30% were recorded, respectively, during the winter measurement period in February 2015 (Figure 4.2).

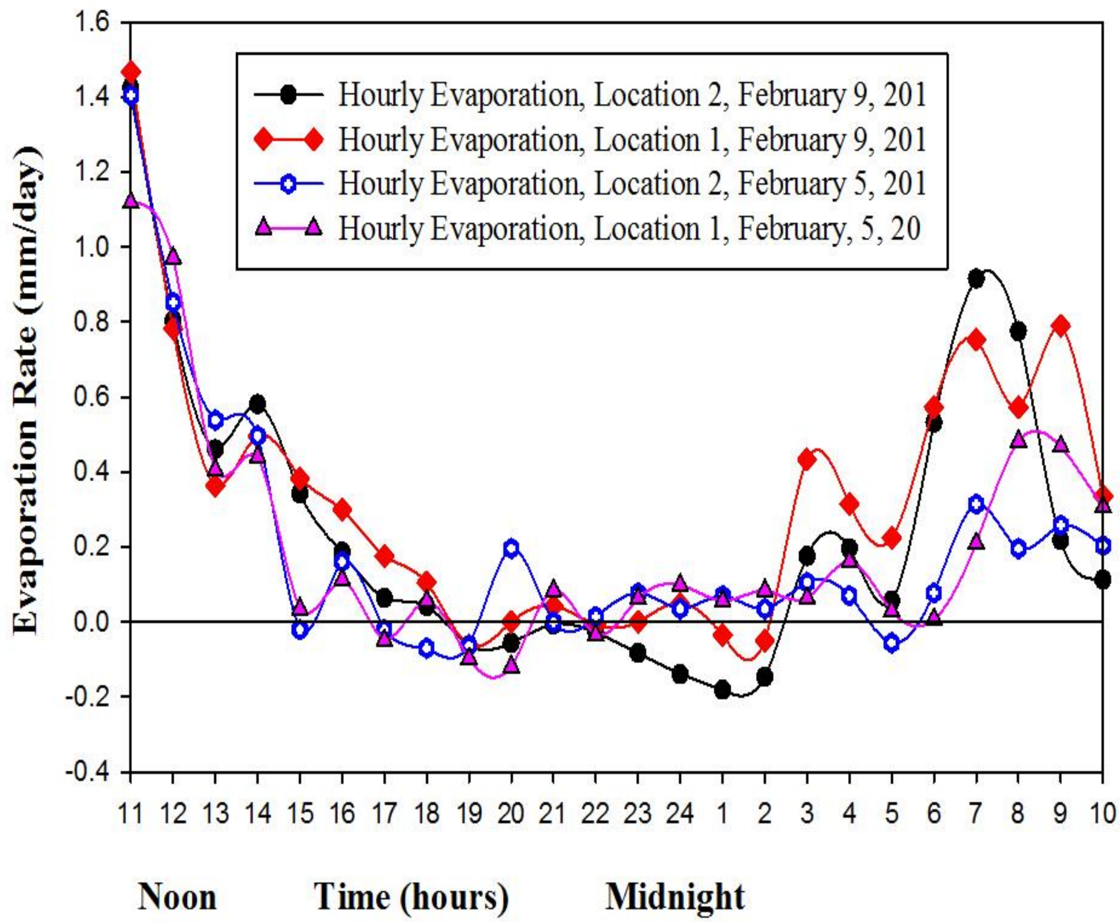


Figure 4.1: One day (24 hour) evaporation rate over time for the winter season.

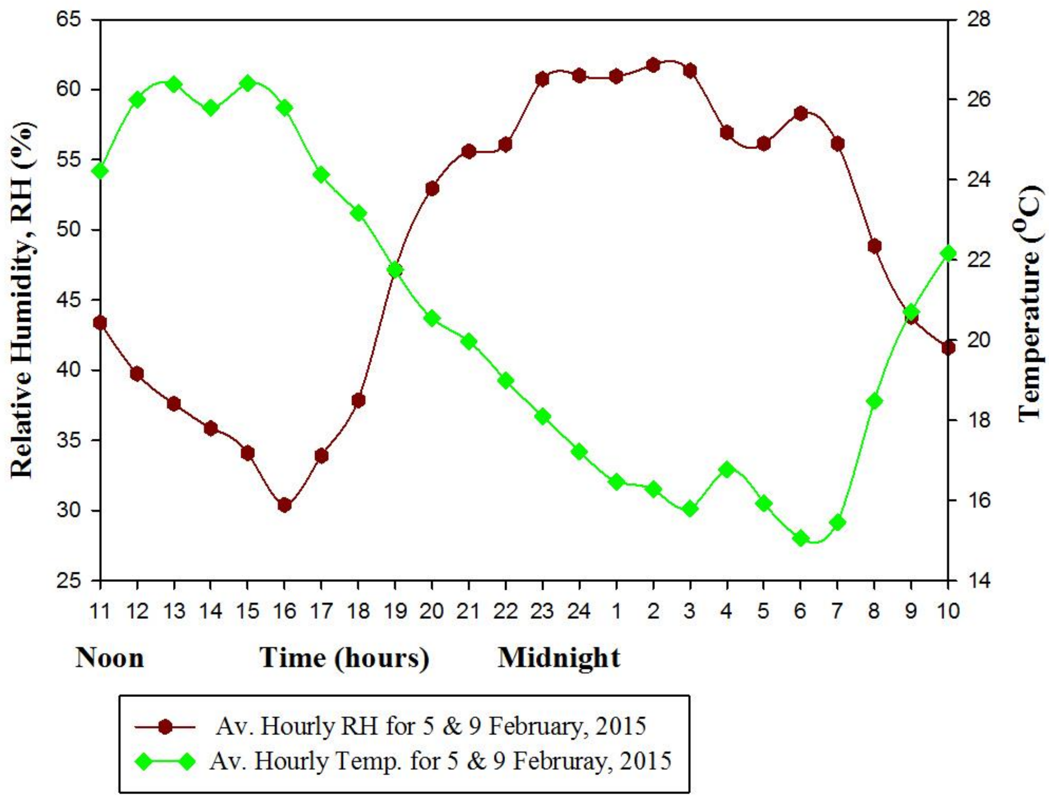


Figure 4.2: Hourly average temperature and RH over time for winter season.

Shown in Figure 4.3 is the spring hourly evaporation measurement conducted on 17th and 28th of April, 2015. The results of both dates could be compared in trend though the hourly evaporation rates for 28th April were slightly higher than that of 17th April due to slight change in weather data (temperature, RH, wind and gust speed). On average, an evaporation rate of 0.47 mm/day was obtained for spring comprising 0.37 mm/day for 17th April 2015 and 0.56 mm/day for 28th April 2015. The hourly evaporation rate increased from 11:00 am to 1:00 pm and then declined from 1:00 pm to 6:00 pm. Between the hours of 6:00 pm and 5:00 am, there was low hourly evaporation rate with the exception of hourly evaporation rate on April 17th at location 2 where there was reversal of evaporation (condensation) at 6:00 pm and between the hours of 12:00 am and 3:00 am. The hourly evaporation rate again increased from 3:00 am gently with a few undulating cases until 10:00 am. The highest hourly evaporation rate obtained for spring season was 2.00 mm/day with the lowest being 0.03 mm/day. Compared to the evaporation rates for winter measurement locations, the average evaporation rate obtained at location 2 was found to be 4.61% lower than that of location 1. The highest and minimum temperatures and their corresponding RH obtained for spring season which were measured in April 2015 were 42.10 $^{\circ}$C and 13.5% and 20.63 $^{\circ}$C and 59.7%, respectively (Figure 4.4).

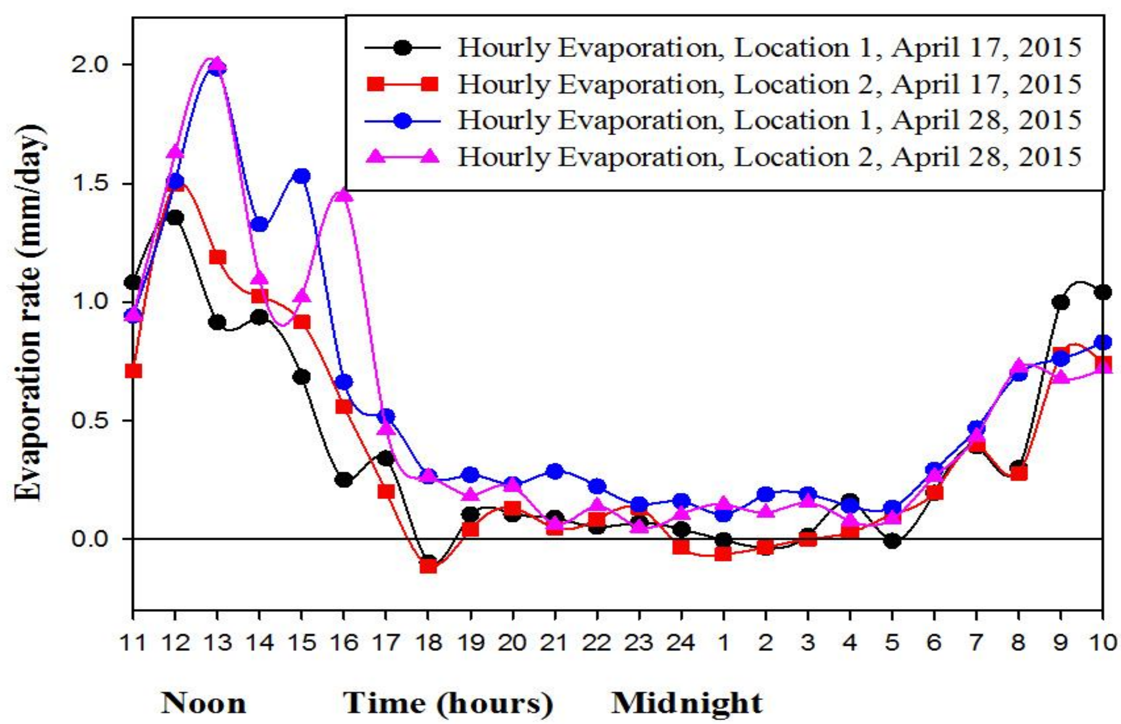


Figure 4.3: One day (24 hour) evaporation rate over time for the spring season.

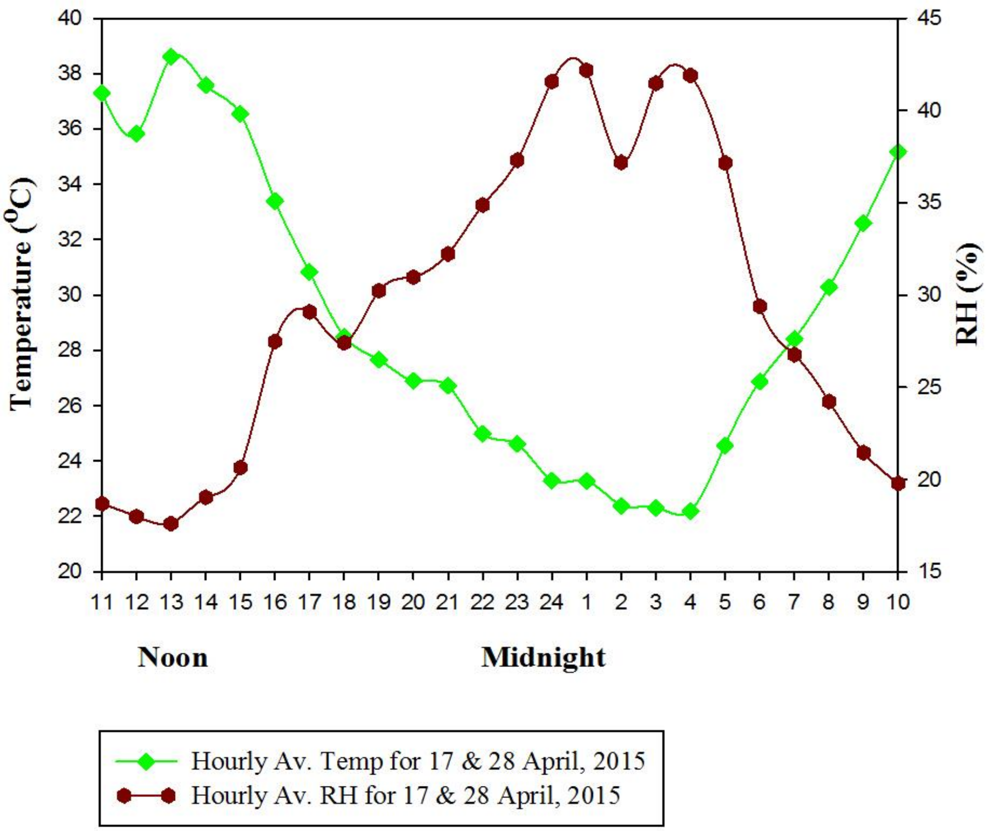


Figure 4.4: Hourly average temperature and RH over time for spring season.

The summer evaporation measurement was conducted on the 16th and 20th of August, 2015 (Figure 4.5). The results show a similarity in trend for both measurement occasions, however, evaporation rate on 20th August was slightly higher than that of 16th August, 2015. An average evaporation rate of 0.50 mm/day was obtained for summer season. This rate was averaged from 0.48 mm/day on August and 0.52 mm/day on 20th August, 2015. On 16th August, 2015, the hourly evaporation rate decreased from 7:00 am to 9:00 am whereas on the 20th August, 2015, there was an increase in the hourly evaporation rate from 7:00 am to 8:00 am and then the rate decreased to 9:00 am. Both measurements then increased on the two occasions from 9:00 am to 11:00 am and decreased gradually to 6:00

pm. Generally, there was an experience of condensation from 6:00 pm to 6:00 am though slight evaporation was experienced from 4:00 am to 6:00 am on 20th August at location 1. The highest hourly evaporation rate of 3.55 mm/day was obtained with the lowest being 0.10 mm/day for summer season. Similar to winter and spring seasons, the measurement for location 2 was 4.84% lower than that of location 1. The highest and lowest temperature of 46.3 °C and 29.0 °C, respectively, were obtained in summer season, while the highest and lowest RH of 81.2% and 16.0% were obtained for the same season (Figure 4.6).

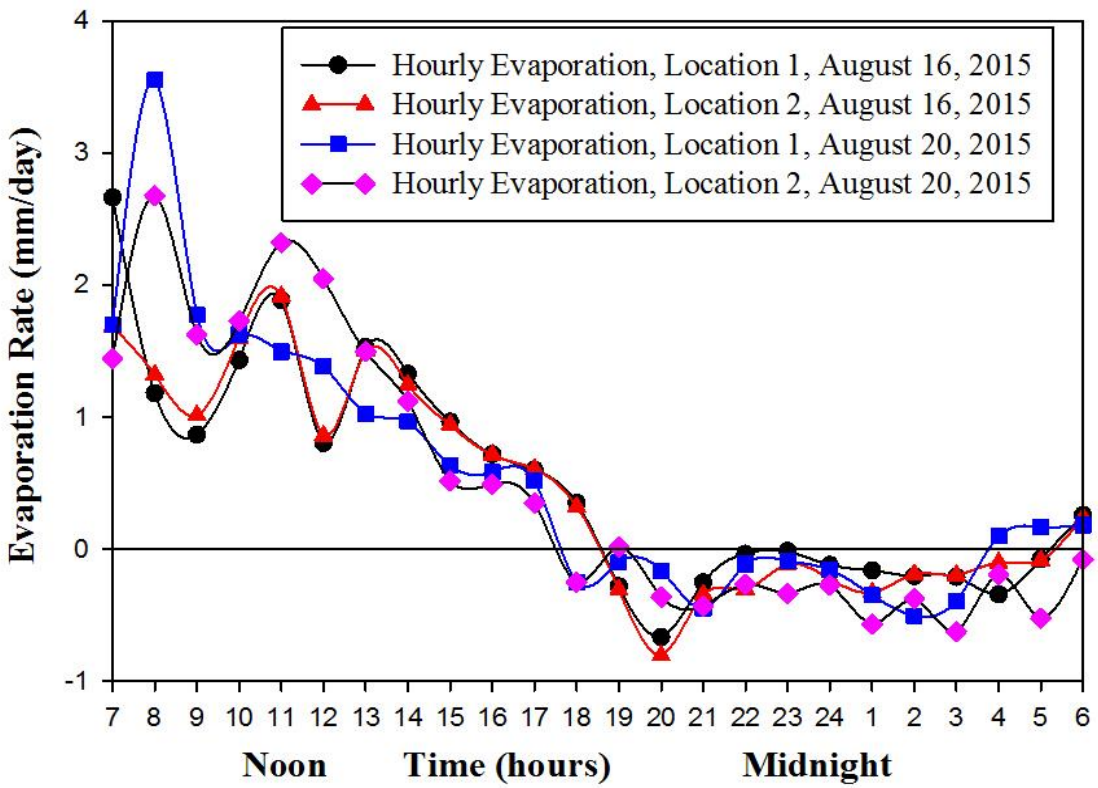


Figure 4.5: One day (24 hour) evaporation rate over time for the summer season.

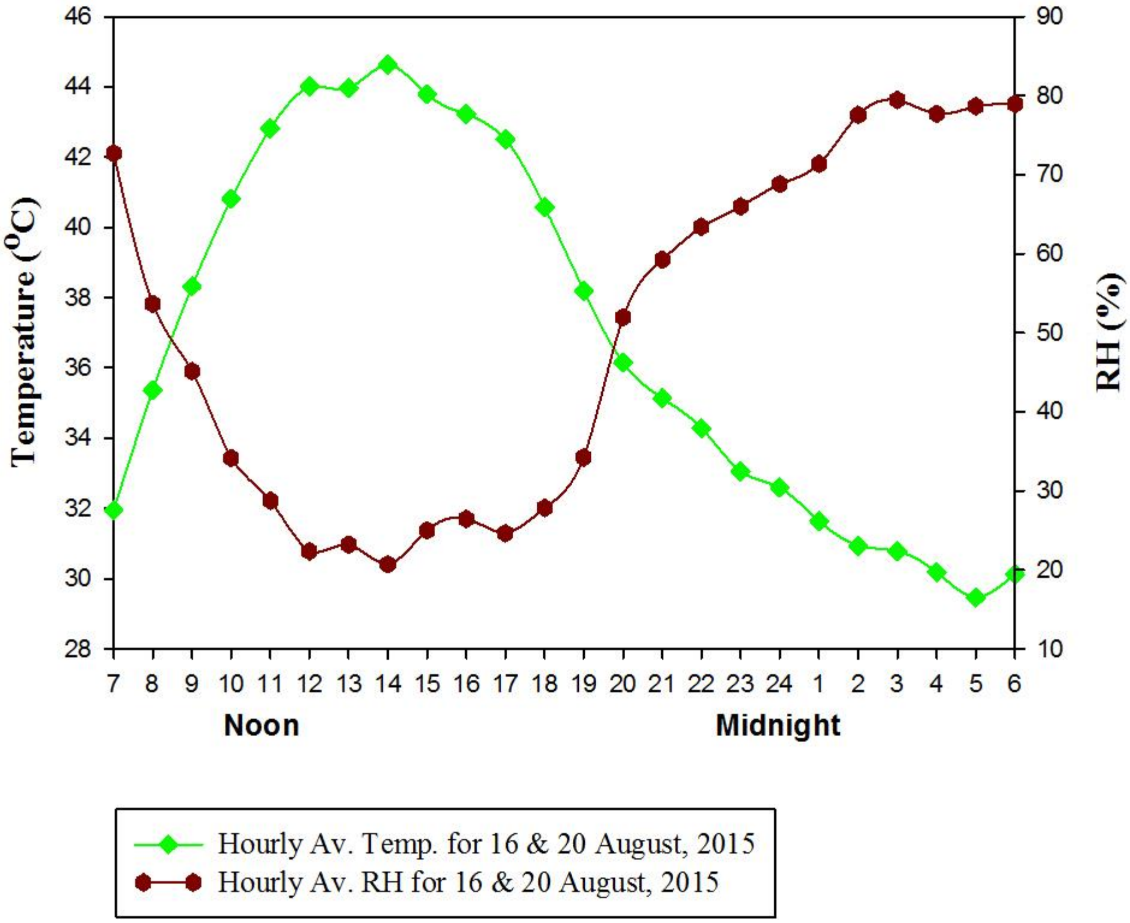


Figure 4.6: Hourly average temperature and RH over time for summer season.

In summary, an average evaporation rate of 0.41 mm/day was obtained for Sabkha Jayb Uwayyid. This is the mean of 0.25 mm/day, 0.47 mm/day and 0.50 mm/day which are the average evaporation rates for winter, spring and summer, respectively, as shown in Figure 4.7.

It can be observed that there is significant difference between the mean evaporation rate for winter and that of spring and summer though the difference between the spring and summer mean evaporation rate is marginal. The reason for the significant change in mean evaporation rate between winter and spring could be ascribed to the considerable change in temperature, RH, wind speed and gust speed, coupled with changes in soil moisture content.

While temperature and its corresponding RH for spring ranged between 42.1 °C and 13.5% and 20.6 °C and 59.7%, respectively, temperature and RH for winter ranged between 27.9 °C and 30% and 12.4 °C and 55%. In addition to temperature and RH values, which favor higher evaporation in spring, there were also considerable wind and gust speed to transport the evaporating water vapor away from the surface to enable more evaporation to take place. Further, the results of soil water content shown in Figure 4.11 indicate that the spring season had higher water content in the soil, which facilitates evaporation, compared to values in winter season.

Generally, one would expect significant difference between spring and summer evaporation, but it is not always the case regarding sabkah soil. This is because, in summer, sakha is often characterized with high temperature, though it has high RH, this often happens in the night which leads to relatively high condensation compared to spring. This is validated by the closeness of the result obtained in spring and summer. Though weather data and soil characteristics favored considerable evaporation in summer season, the result obtained showed otherwise. The reason could be attributed to the fact that in sabkha soil, precipitation of salt always accompanies evaporation. The precipitation of salt forms salt crust on the surface of the soil which reduces or shutdowns evaporation when there is high salinity [41]. This is because the energy required to break the bond between the salt crust and the water molecules to release the water molecules to be evaporated may not be available or not completely adequate for the salt crust. This is the reason for similarity of evaporation rate for summer and spring even though most factors favor high evaporation rate in summer compared to spring, as shown in Figure 4.7.

A mean annual evaporation rate of approximately 145 mm was obtained for Sabkha Jayb Uwayyid.

In a related research, an average annual evaporation rate of 69 mm/year was found to be lost from Sabkha Matti in Abu Dhabi, United Arab Emirates [26]. The significant difference between the two average annual evaporation rates could be attributed to the unique characteristics of the different sabkhas, especially regarding the soil solute concentrations.

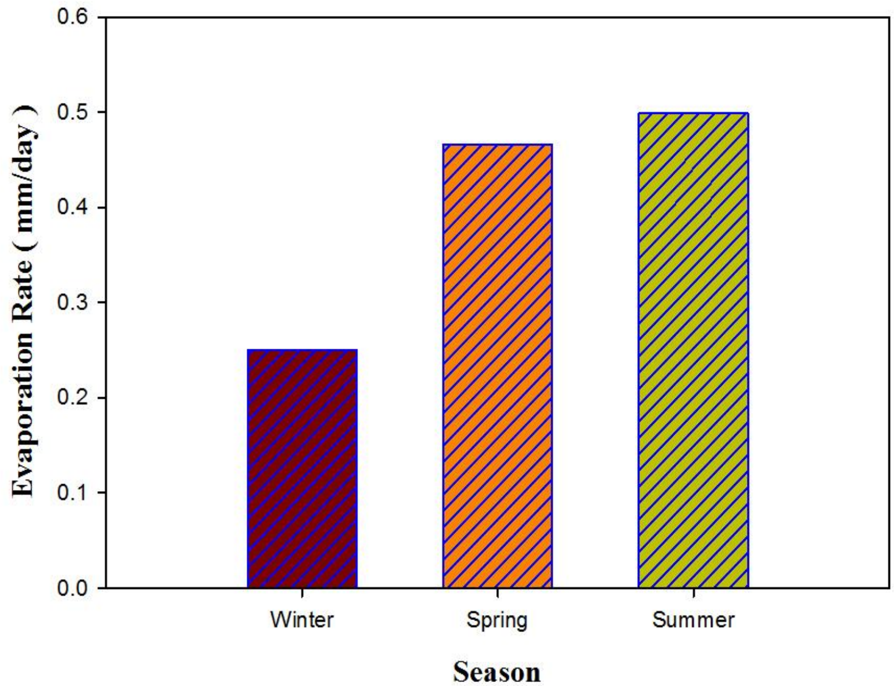


Figure 4.7: A graph of seasonal evaporation rates.

4.2 Grain Size Analysis

Grain size analysis results for Sabkha Jayb Uwayyid are numerically summarized in Table 4.1 and Figure 4.8. Based on these results of the grain size analysis, a grain size plot between % finer by weight on the y-axis and grain diameter or particle size (mm) on the x-axis was plotted as shown in Figure 4.9. From the shape of the curve, it was observed that the sabkha soil was primarily sand. However, the degree of sorting could not be ascertained from the shape of the grain size analysis plot.

Table 4.1: Grain size analysis result for Sabkha Jayb Uwayyid.

Sieve Number	Diameter (mm)	Mass of Soil Retained on Sieve (g)	Percent Retained (%)	Cumulative Retained (%)	Percent Finer (%)
5	4	1.40	0.35	0.35	99.65
10	2	7.90	1.98	2.33	97.67
18	1	13.70	3.43	5.76	94.24
35	0.5	69.60	17.40	23.16	76.84
60	0.25	136.40	34.10	57.26	42.74
120	0.125	134.40	33.60	90.86	9.14
230	0.063	32.00	8.00	98.86	1.14
Pan	< 0.063	4.60	1.15	100.01	0.00
Total		**400**	**100**		

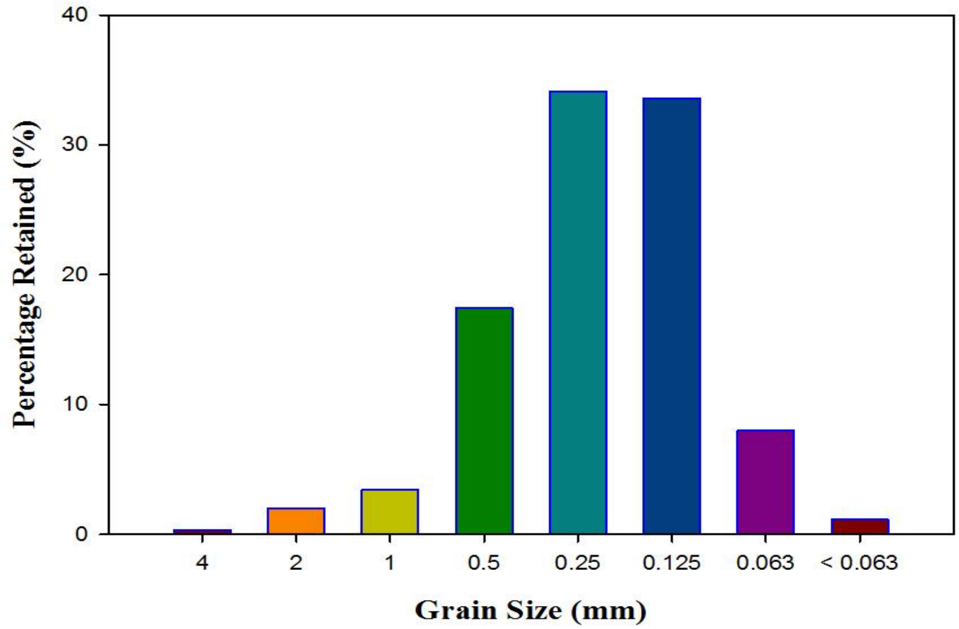


Figure 4.8: Grain size graph for Sabkha Jayb Uwayyid.

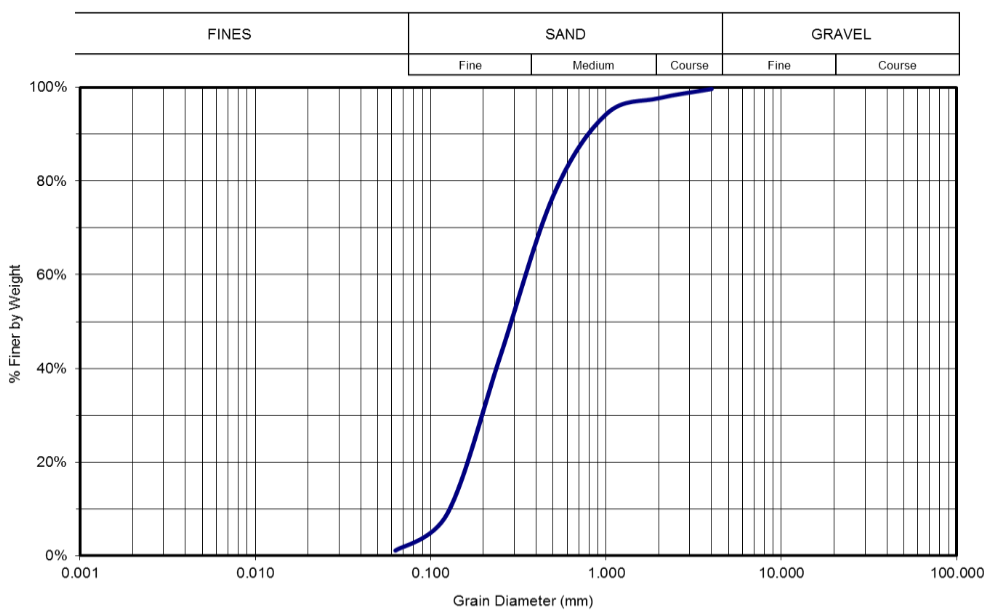


Figure 4.9: Grain size analysis plot for sabkha soil.

For determining the degree of sorting, another graph was plotted between cumulative percent retained on the y-axis and phi size on the x-axis, as shown in Figure 4.10. The phi size was obtained by finding the negative logarithm of the diameter of the sieves used for the soil analysis. From the cumulative curve obtained, phi sizes were determined for phi value at 5% (φ5), 16%, 25%, 50%, 75%, 84% and 95% (where % refers to cumulative percent). The phi sizes obtained were used to calculate the mean, standard deviation, skewness and kurtosis. The statistical parameters help to determine the average sizes of the soil, and the measure of sorting or variation in sizes. The parameters show if the distribution is bell shaped or shifted to one side, and the graph displays if the distribution is bell shaped, very flat or very peaked [42].

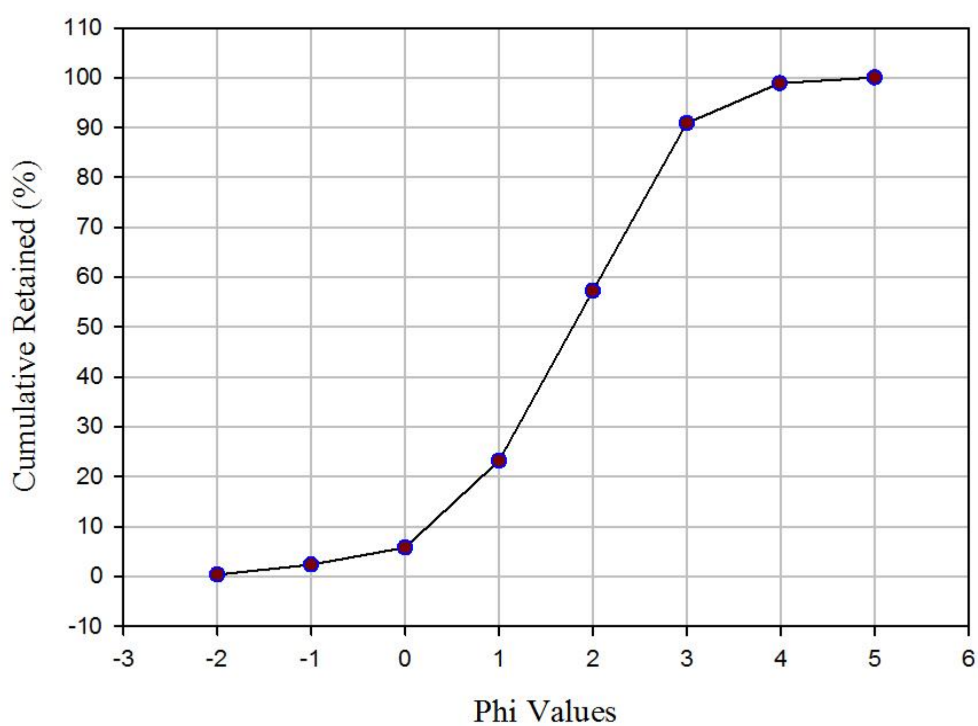


Figure 4.10: Cumulative frequency plot for sabkha soil.

The formulae used for the various calculations and their interpretations, as shown in Table 4.2, were described in references [42] and [43] and are as follows:

Mean, $M = \frac{\varphi 16 + \varphi 50 + \varphi 84}{3}$ (7)

Where $\varphi 16$ is phi at 16%

$\varphi 50$ is phi at 50%

$\varphi 84$ is phi at 84%

Standard deviation, $\sigma = \frac{\varphi 84 - \varphi 16}{4} + \frac{\varphi 95 - \varphi 5}{6.6}$ (8)

Skewness, $S = \frac{\varphi 16 + \varphi 84 - 2\varphi 50}{2(\varphi 84 - \varphi 16)} + \frac{\varphi 5 + \varphi 95 - 2\varphi 50}{2(\varphi 95 - \varphi 5)}$ (9)

Kurtosis, $K = \frac{\varphi 95 - \varphi 5}{2.44(\varphi 75 - \varphi 25)}$ (10)

From the above formulae, a mean value of 1.77 signifying a medium grained soil while a standard deviation of 1.1 indicating a poorly sorted soil were obtained. Similarly, skewness value of -0.07 and a kurtosis of 1.05 representing a symmetrically skewed soil and mesokurtic shape, respectively, were achieved.

Based on these soil characteristics, it can be concluded that the sabkha soils is poorly sorted. Poorly sorted soils are less porous compared to well sorted soil and, hence, transmission of water through the sabkha soil will be slow compared with well sorted soil and this condition has the effect of reducing the rate of evaporation.

Table 4.2: Values for sorting, skewness, kurtosis and their interpretations.

Sorting (σ)	Skewness (S)	Kurtosis (K)
Very well sorted < 0.35	Very fine skewed $^{+}0.3$ to $^{+}1.0$	Very platykurtic < 0.67
Well sorted 0.35 – 050	Fine skewed $^{+}0.3$ to $^{+}0.1$	Platykurtic 0.67 to 0.90
Moderately well sorted 0.5 to 0.7	Symmetrical $^{+}0.1$ to -0.1	Mesokurtic 0.90 – 1.11
Moderately sorted 0.7 to 1.00	Coarse skewed $^{-}0.1$ to -0.3	Leptokurtic 1.11 – 1.50
Poorly sorted 1.00 – 2.00	Very coarse skewed $^{-}0.3$ to $^{-}1.0$	Very leptokurtic 1.50 – 3.00
Very poorly sorted 2.00 – 4.00		Extremely leptokurtic > 3.00
Extremely poorly sorted > 4.00		

4.3 Soil Moisture Content

From the data in Figure 4.11, a soil moisture content of 28% was obtained at a depth of 0.1 m while a water content of 30.3% was obtained at a depth of 0.5 m for winter. In spring, a moisture content of 32.3% was obtained for a depth of 0.1 and 34.4% at a depth of 0.5. Different values were again obtained for summer season. Then 32.8% was obtained at a depth of 0.1 while 37.7% was obtained at a depth of 0.5 m. Volume wetness at saturation in sandy soil is on the order of 40%, it is about 50% in medium-textured soil and it is roughly 60% in clayey soils [44]. Based on this criterion, the sabkha soil is partially to nearly saturated soil.

Generally, the values obtained at both depths show variation over the three seasons considered. The water content at 0.1 m depth ranged from 28% to 32.8%, while at a depth of 0.5 the water content ranged from 30.3% to 37.7%.

Movement of solute is not only via soil water but also within the soil in response to concentration gradients. Some of the factors that influence the movement of solute within the soil are temperature, acidity, composition, concentration of the soil solute, and oxidation-reduction potential within the soil [44]. Based on the result of the soil salinity shown in Figure 4.12, the salinity is highest at the surface of the soil and at decreased levels with depth. Generally, if there is no restriction on flow, water moves from an area of higher water potential to an area of lower water potential but the presence of dissolved salt negates the water potential relative to the pure water reference. With this, the highest salinity obtained at the soil surface negates the water potential at the soil surface compared to the water potential with depth. As a result, together with the poorly sorted nature of the soil, the movement of water through the sabkha soil is from the water table to the soil surface as indicated by the higher water content results obtained at a depth of 0.5 m compared to that at 0.1 m depth [2,43] which is also in agreement with capillarity.

Comparing the water content of the sabkha soil for the three seasons considered in this study, it was observed that the water content increased from winter through spring to summer, as shown in Figure 4.11. A water content of 28.0% and 30.3% were obtained at depths of 0.1 m and 0.5 m, respectively, in winter season. These values increased to 32.3% and 34.4% for the same depths in spring and finally to 32.8% and 37.7% in summer. The reason for the increase in the water content in the soil over the various seasons could be attributed to the increase in the concentration of salinity from a value of 156,250 ppm in winter to 260,800 ppm in spring and to 264,100 ppm in summer [41].

The higher salinity concentration obtained over the seasons caused high suction or increased transmittal of groundwater from the water table through the soil profile to the soil surface. This explains the higher water content obtained in various depths in summer compared to spring and winter, respectively.

Higher water content at the surface of the soil exacerbates evaporation rate provided there is enough supply of energy and transport of vapor from the evaporative surface [45]. However, in certain cases, if salinity is high at the surface of the soil, even though the soil surface may be saturated with water, the evaporation rate may reduce as a result of precipitation of salt at the surface [41].

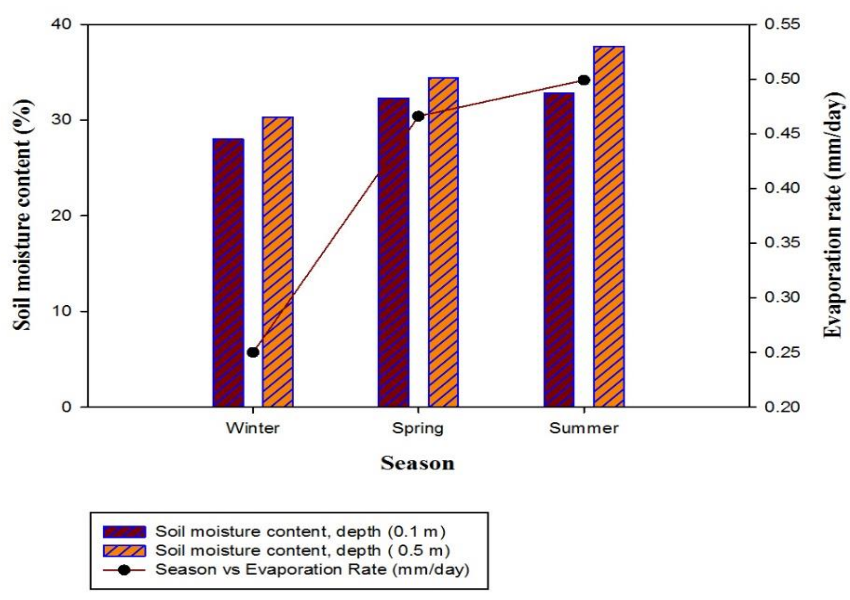


Figure 4.11: Seasonal soil moisture content and evaporation rate for Jayb Uwayyid Sabkha.

4.4 Soil Salinity

The result of soil salinity reported in Table 4.3 was determined from soil samples obtained from a depth of 0.1 m and 0.5 m by measuring the electrical conductivity (EC), in milli-siemens per centimeter (mS/cm). The results obtained were converted to Total Dissolved Solids which is measured in mg per liter (parts per million-ppm). The conversion was carried by multiplying 1.0 mS/cm EC by 500 ppm, which is the American standard [40]. The soil salinity was determined for the three seasons considered in this study. The result of the winter experiment in Figure 4.12 shows that TDS of 112,235 ppm was obtained at a depth of 0.5 m while a TDS of 200,300 ppm was obtained at a depth of 0.1 m. From Table 4.4, TDS ranges from 99,150 to 109,450 ppm in groundwater samples were from the same site.

Table 4.3: Seasonal soil salinity for Jayb Uwayyid Sabkha.

Season	Depth (m)	Total Dissolved Solids, TDS (ppm)	pH
Winter	0.1	200,300.0	8.74
	0.5	112,235.0	8.39
Spring	0.1	380,910.0	8.74
	0.5	140,640.0	8.39
Summer	0.1	414,515.0	8.13
	0.5	113,650.0	8.08

Table 4.4: Well information and brine salinity results obtained in winter season.

Well Name	Depth to water (m)	Total Dissolved Solids TDS (ppm)	pH
PW-01	-0.94	109,450.0	6.58
PW-02	-1.0	107,800.0	6.36
PW-03	-0.95	103,150.0	6.40
PW-04	-1.05	99,150.0	6.20
PW-05	-1.0	101,850.0	6.37

The result of both spring and summer followed similar trends as that of winter. The result of spring (Table 4.3) and Figure 4.12 shows that a TDS of 140,640 ppm and 380,910 ppm were obtained at a depth of 0.5 m and 0.1 m, respectively. Similarly, the soil salinity result for summer which is reported in Table 4.3 and Figure 4.12 indicates that a TDS of 113.650 ppm was obtained at a depth of 0.5 and 414,515 ppm obtained at a depth of 0.1 m.

Observing the results for all the seasons, it was noticed that the salinity concentrations decreased with depth from the surface of the soil through the soil profile to the lower depth. This is probably an indication that as the soil solute is being transmitted from the lower depth of the soil profile to the surface, the solute gets precipitated as it moves up through the soil thereby increasing the salt concentration.

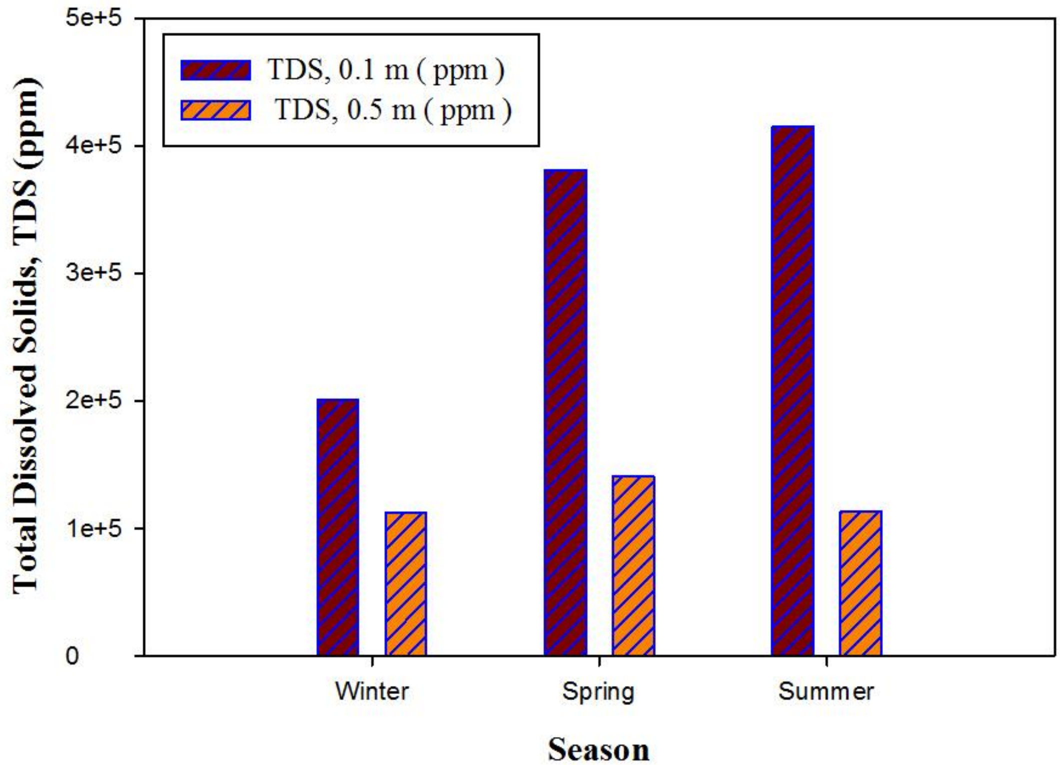


Figure 4.12: Seasonal soil salinity for Jayb Uwayyid Sabkha.

Regarding the variation of soil salinity over seasons, the highest soil salinity was obtained in summer season followed by spring and winter, respectively, as shown in Figure 4.12. The increase in salinity concentration from winter season through spring to summer was as a result of the increase in the rate of evaporation due to changes in climatic factors. Highest temperature of 46.3 $^{\circ}$C and lowest relative humidity of 16.0 were obtained in summer whereas highest temperature of 27.9 $^{\circ}$C and lowest RH of 30.0 were recorded in winter season. The high evaporation causes the precipitation of salt through the various layers of the soil profile and at the surface of the soil. Summary of the results of evaporation rate, soil salinity and soil moisture are shown in Table 4.5.

Salinity has the effect of reducing evaporation rate due to a decreased chemical potential of water or soil [46]. It reduces evaporation as a result of the cohesive forces that exist between the dissolved ions and water as it will make vaporization of water molecules more difficult. Leaney and Christen [33] found evaporation rate to be decreasing exponentially with increasing salinity. According to the research work of Zhang et al [46], salt encrusted soil may reduce evaporation rate by 64.8% on bare soil. Similarly, Innocent-Bernard [41] found that high salinity shuts down evaporation as a result of precipitation of salts on the surface of the soil.

Table 4.5: Summary of Seasonal Variation of Evaporation, Soil Salinity and Soil. Moisture

Season	Evaporation Rate (mm/day)	Depth	Soil Salinity (ppm)	Soil Moisture Content (%)
Winter	0.250	0.1	200,300.0	28.0
		0.5	112,235.0	30.3
Spring	0.466	0.1	380,910.0	32.3
		0.5	140,640.0	34.4
Summer	0.499	0.1	414,515.0	32.8
		0.5	113,650.0	37.7

4.5 Correlation of Evaporation Rate with Weather Data

Pearson correlation coefficient (r) result for evaporation rate and its corresponding weather parameters for winter, spring and summer, respectively are shown in Table 4.6. The guideline for the interpretation of correlation result was adopted from Pallant [38], as shown in Table 4.6.

Table 4.6: Guideline for the interpretation of correlation result.

Classification	Correlation range
Small	r = 0.10 to 0.29
Medium	r = 0.30 to 0.49
Large	r = 0.50 to 1.0

In the winter season, wind and gust speed had a small strength of correlation with evaporation rate on both measurement occasions. A medium strength of correlation was obtained between evaporation rate and temperature on 5th February 2015 with a small strength of correlation obtained on 9th February 2015. The r between evaporation rate and RH was found to have large strength but was negative on 9th February 2015 and that obtained on 5th February 2015 was found to have a small strength of correlation. The negative strength of correlation obtained for RH implies that, as RH increases, evaporation rate decreases and vice versa. The higher the strength of correlation coefficient between evaporation rate and weather parameter, the better the strength of the relationship between them.

The confidence level (listed as Sig. 2 tailed) which shows how much confidence repose in correlation coefficient were determined for the weather parameters and evaporation rate (Table 4.7). A two-tailed test using a significance level of 0.05 was used to find the confidence level for the correlation coefficient. In a two-tailed test, both the null hypothesis *(H0)* and the alternative hypothesis *(H1)* are tested. The *H0* assumes that the population correlation coefficient is zero; implying there is no association between evaporation rate and various weather parameters considered. While the *H1* assumes that the population correlation coefficient is not zero; meaning there is an association between the evaporation rate and various weather parameters. From the Table 4.6, a sig value of 0.48 and 0.41 was obtained for r of evaporation rate and wind speed on 5^{th} and 9^{th} of February 2015. Correlation coefficient obtained for evaporation rate and gust speed on 5th and 9^{th} February 2015 had a sig value of 0.24 and 0.52 while r for evaporation rate and temperature on the same measurement occasions had sig values of 0.02 and 0.30. On the other hand, sig. values of 0.48 and 0.01 for correlation coefficient obtained between evaporation rate and RH were obtained for the same measurement periods. A correlation coefficient value with a sig. value ≤ 0.05 has more confidence or could be more accepted than r value having a sig. value > 0.05. Though, significance of r is affected by the size of the samples, small sample size (e.g. $n = 30$), could have moderate correlations that do not reach statistical significance at the $p < 0.05$ level. Whereas large samples ($n = 100+$) with small correlation coefficient could reach statistical significance [38]. With this in mind, it could be said that the r values obtained for temperature and RH on 5^{th} and 9^{th} February 2015, respectively, have more confidence compared with the remaining r values obtained in the winter season. Temperature and RH were selected to have more confidence because, though wind and gust speed could still have some confidence, their confidence level was found to be lower compared with temperature and RH.

Table 4.7 Seasonal correlation coefficient between evaporation rate and weather data.

Correlation coefficient between evaporation rate and weather data						
Correlation	Winter season		Spring season		Summer	
	05/02/2015	09/02/2015	17/04/2015	28/04/2015	16/08/2015	20/08/2015
Evaporation rate and wind speed	0.15	0.18	0.32	0.10	0.55	0.32
Evaporation rate and gust speed	0.25	0.14	0.44	0.22	0.72	0.39
Evaporation rate and temperature	0.47	0.22	0.82	0.88	0.49	0.53
Evaporation rate and RH	0.15	-0.51	-0.79	-0.85	-0.40	-0.60
Sig. (2-tailed) for evaporation rate and wind speed	0.48	0.41	0.13	0.64	0.01	0.13
Sig. (2-tailed) for evaporation rate and gust speed	0.24	0.52	0.03	0.31	0.00	0.06
Sig. (2-tailed) for evaporation rate and temperature	0.02	0.30	0.00	0.00	0.02	0.01
Sig. (2-tailed) for evaporation rate and RH	0.48	0.01	0.00	0.00	0.05	0.00

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

Contrary to the correlation results of the winter season, spring correlation results between evaporation rate and weather parameters followed a different pattern. Temperature measurement on 17th and 28th April 2015 had a large strength of correlation with evaporation. However, the large strength of correlation with evaporation rate for RH was found to be negative. The strength of correlation coefficient for gust speed and the evaporation rate was found to be medium on the 17th April 2015 while it was found to be small on 28th April 2015. A medium strength of correlation coefficient was obtained for evaporation rate and wind speed on 17th April 2015. On the 28th of April 2015, the correlation was found to be small.

A sig. value of 0.00 was obtained for correlation coefficient values between evaporation-temperature and evaporation rate - RH on both 17th and 28th April 2015, signifying higher confidence repose in the r values obtained. The r values obtained for evaporation rate and wind speed on 17th and 28th April had a sig. values of 0.22 and 0.64 indicating low confidence in the correlation coefficient obtained for the wind speed. A sig. values of 0.03 and 0.31 were obtained for correlation coefficient obtained for evaporation rate and gust speed on 17th April and 28th April 2015 respectively. This is an indication that the correlation coefficient obtained between evaporation rate and gust speed on 17th April 2015 had a high confidence compared to that obtained on 28th April 2015.

The summer season also had its own unique correlation coefficient results with evaporation rate. Wind and gust speed had a large strength of correlation with evaporation rate for the measurement on 16th August 2015. Temperature and RH were found to have a medium strength of correlation with evaporation rate on 16th August 2015. In a similar pattern, temperature and RH had a strong correlation with evaporation on 20th August. The strength of correlation between evaporation rate and wind and gust speed for 20th August 2015 was found to be medium, compared to the large correlation of wind and gust measurement obtained on 16th August 2015 because wind and gust were speedier on 16th August than 20th August 2015.

The correlation obtained between evaporation rate and temperature, and evaporation rate and RH on 16th and 20th August 2015 had sig. values of 0.02, 0.01 and 0.05 and 0.00 which shows a high confidence the in the r values obtained between the evaporation rate and temperature, and evaporation rate and RH. A sig. values of 0.01 and 0.13 were obtained for evaporation rate and wind speed on 16th and 20th August 2015. This implies that while the r value obtained for evaporation rate and wind speed on the 16th had high confidence, the confidence level for the r obtained on 20th August 2015 had low confidence. Similarly, the sig. values obtained for evaporation rate and gust speed on 16th and 20th August 2015 were 0.00 and 0.06. This indication that the correlation coefficient for evaporation rate and gust speed obtained on 16th August 2015 had high confidence when compared with the one obtained on 20th August 2015.

Generally, all the weather data reported in this investigation, such as wind speed, gust speed, temperature and RH, correlate with evaporation rate. Further, while temperature, wind speed and gust speed generally had a positive correlation with evaporation rate, RH showed a negative correlation with evaporation rate. This is an indication that as temperature, wind speed and gust speed increase, evaporation rate increases, whereas, as RH decreases evaporation rate increases. The large and medium strength of correlation were obtained between evaporation rate and RH, temperature, gust speed and wind speed in summer and spring compared to the small strength of correlation obtained in winter.

This was due to increase in temperature, speedy gust and wind together with low RH in summer followed by spring compared to winter.

Moreover, from confidence level obtained, it could be confirmed that RH, gust speed and temperature are more significant in the determination of evaporation rate compared to wind speed.

The correlation result of this study is in agreement with the results obtained by El Bably [47] which found strong and positive correlation between temperature and evapotranspiration while relative humidity showed a negative correlation with ET. Similarly, another study [48] found temperature and wind speed to be positively correlated with reference evapotranspiration (ETo) while relative humidity showed a negative correlation with ETo. The obtained coefficients of correlation for temperature, wind speed and RH were 0.16, 0.95 and -0.03, respectively. Karnataka [49] reported that temperature and wind speed correlate with evaporation with correlation coefficient being 0.45 and 0.13, respectively.

Regression models were constructed to find out the indicators for evaporation rate. The R square (coefficient of determination) was used to assess the combined effect or linear association of RH, temperature, wind and gust speed on evaporation rate. The results from this study show that the four weather data accounted for 64.9% of the variance in evaporation measurement on 5th February 2015 and 54.4% when evaporation was measured on 9th February 2015. In spring, weather parameters contributed to 78.5% of the variance in evaporation rate on 17th April 2015. This same weather parameter accounted for 79.5% of the variance on 28th April 2015. Similarly, in summer, weather data accounted for 72.6% of the variance in evaporation rate obtained on 16th August 2015 and 44.4% on 20th August 2015.

However, there are several factors such as soil moisture content, the level of salinity in the soil, soil texture and structure and other factors that have a significant impact on evaporation rate as indicated by the various coefficient of determination values obtained for all seasons.

Karnataka [49] reported wind speed and solar radiation to contribute 72% in the determination of evaporation rate which is in agreement with the result of this study.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

A portable chamber was successfully constructed to measure evaporation rate on Sabkha Jayb Uwayyid in eastern Saudi Arabia. The evaporation rate was measured in three different seasons and the correlation between evaporation rate and weather data was determined. The effect of soil and water salinity, soil moisture and texture on the evaporation rate was also assessed. Prior to field evaporation measurement, the portable chamber was calibrated to account for the water that would naturally be absorbed by the chamber and data lodger error. Moreover, a weather station was installed at the site and its readings were compared to another weather station installed and monitored by the Centre of Engineering Research at KFUPM for a check on reliability.
Based on the result of the evaporation measurements, evaporation rate of 0.25 mm/day, 0.47 mm/day and 0.50 mm/day were obtained for winter, spring and summer, respectively, with an average of 0.41 mm/day for the study site, giving a mean annual evaporation rate of approximately 145 mm for Sabkha Jayb Uwayyid (as compared with 69 mm for Sabkha Matti in UAE). The seasonal variation of evaporation rate was due to changes in weather data over seasons, coupled with changes in soil properties such as soil water content as well as salinity.

High water content at the soil surface was found to exacerbate the evaporation rate, provided there was supply of energy and transport of vapor from the evaporative surface.

Soil salinity was also found to reduce evaporation rate as a result of the cohesive forces that exist between the dissolved ions and water as it would make vaporization of water molecules more difficult. The highest soil salinity was obtained in summer season followed by spring and winter, respectively. The increase in salinity concentration from winter season through to spring and summer was ascribed to the increase in the rate of evaporation due to changes in climatic factors. The high evaporation causes the precipitation of salt through the various layers of the soil profile and at the surface of the soil.

All the weather data considered in this study (wind speed, gust speed, temperature and RH) were correlated with evaporation rate. However, RH, gust speed and temperature were found to be more significant in the determination of evaporation rate compared to wind speed.

Due to time constraints and other challenges, this research was conducted considering a two-day measurement for each season. Autumn season was not considered in this research.

5.2 Recommendations

From the results of this investigation, the following recommendations could be identified for consideration in future studies in this field:

- Other indirect methods, such as water budget or aerodynamic and energy budget method (combination method) may be used for the evaporation estimation on the same or similar sites.

- This research work could be repeated on a coastal sabkha in order to compare the evaporation rate for Sabkha Jayb Uwayyid (which is an inland sabkha) with the coastal sabkha.
- It would also be interesting to see this study carried out at Al-Hasa (south of the study site) where there are a lot of agricultural activities, so the actual water loss from plants (evapotranspiration) could be estimated to help in formulating good policies for effective irrigational practices.
- This study could be conducted over longer periods and for longer duration including autumn season.
- Extensive soil moisture profile could be measured from the surface to 100% saturation.

References

[1] W. World Meteorological Organization, “Guide to Hydrological Practices, Volume 1,” *Hydrol. Sci. J.*, vol. 56, no. 1, pp. 1–296, Feb. 2008.

[2] C. S. P. . Ojha, R. . Berndtsson, and P. Bhunya, “Engineering hydrology,” *J. Hydrol.*, vol. 27, no. 1–2, p. 440, Oct. 2008.

[3] G. Rana and N. Katerji, “Measurement and Estimation of Actual Evapotranspiration in the Field Under Mediterranean Climate: A Review,” *Eur. J. Agron.*, vol. 13, no. 2–3, pp. 125–153, Jul. 2000.

[4] H. Mughrabi, “Water Evaporation in Areas of High Aridity,” *Jordan J. Civ. Eng.*, vol. 5, no. 3, pp. 322–329, 2011.

[5] H. Tabari, M. E. Grismer, and S. Trajkovic, “Comparative Analysis of 31 Reference Evapotranspiration Methods Under Humid Conditions,” *Irrig. Sci.*, vol. 31, no. 2, pp. 107–117, Jul. 2013.

[6] D. I. Stannard and M. A. Weltz, “Partitioning Evapotranspiration in Sparsely Vegetated Rangeland Using a Portable Chamber,” *Water Resour. Res.*, vol. 42, no. 2, pp. 1–13, 2006.

[7] S. A. Kurc and E. E. Small, “Dynamics of Evapotranspiration in Semiarid Grassland and Shrubland Ecosystems during the Summer Monsoon Season, Central New Mexico,” *Water Resour. Res.*, vol. 40, no. 9, p. n/a–n/a, Sep. 2004.

[8] A. A. Alazba;, H.M Alghobari;, F.S Mohammad;, and A.M Alomran, “Measured and Estimated Crop ET and Kc for Wheat and Barley in Central Saudi Arabia,” *Alex. J. Agric. Res.*, vol. 48, no. 1950, pp. 1–9, 2003.

[9] A. M. Al-Omran, F. S. Mohammad, H. M. Al-Ghobari, and A. A. Alazba, “Determination of Evapotranspiration of Tomato and Squash Using Lysimeters in Central Saudi Arabia,” *Int. Agric. Eng. J.*, vol. 1 & 2, pp. 27–36, 2004.

[10] M. I. Al-Saud, “Reduction of Evaporation from Water Surfaces-Preliminary Assessment for Riyadh Region, Kingdom of Saudi Arabia,” *Research Journal of Soil and Water Management*, vol. 1, no. 1. pp. 5–9, 2010.

[11] S. A. Al-Shalan; and A. M. A. Salih, “Evapotranspiration Estimates in Extremely Arid Areas,” *J. Irrig. Drain. Eng.*, vol. 113, no. 4, pp. 565–574, 1988.

[12] A. Al-Shaibani, “Economic Potential of Brines of Sabkha Jayb Uwayyid, Eastern Saudi Arabia,” *Arab. J. Geosci.*, vol. 6, pp. 2607–2618, 2013.

[13] E. A. Hasenmueller and R. E. Criss, “Water Balance Estimates of Evapotranspiration Rates in Areas with Varying Land Use,” pp. 1–22, 2013.

[14] D. C. Reicosky, “Comparison of Alfalfa Evapotranspiration Measured by a Weighing Lysimeter and a Portable Chamber,” *Agric. Meteorol.*, vol. 28, pp. 205–211, 1983.

[15] S. Reth, M. Göckede, and E. Falge, “CO2 efflux from agricultural soils in Eastern Germany - Comparison of a Closed Chamber System with Eddy Covariance Measurements,” *Theor. Appl. Climatol.*, vol. 80, pp. 105–120, 2005.

[16] D. D. Baldocchi, “Assessing the Eddy Covariance Technique for Evaluating Carbon Dioxide Exchange Rates of Ecosystems: Past, Present and Future,” *Glob. Chang. Biol.*, vol. 9, no. 4, pp. 479–492, 2003.

[17] A. Grau, “A Closed Chamber Technique for Field Measurement of Gas Exchange of Forage Canopies,” *New Zeal. J. Agric. Res.*, vol. 38, no. December, pp. 71–77, 1995.

[18] D. L. Mcjannet;, R. A. Vertessy;, N. J. Tapper;, S. K. O. Sullivan;, J. Beringer;, and H. Cleugh, “Soil and Litter Evaporation Beneath Re-Growth and Old-Growth Mountain Ash Forest,” 1996.

[19] R. F. Angell, T. Svejcar, J. Bates, N. Z. Saliendra, and D. a Johnson, “Bowen Ratio and Closed Chamber Carbon Dioxide Flux Measurements Over Sagebrush Steppe Vegetation,” *Agric. For. Meteorol.*, vol. 108, no. 2, pp. 153–161, Jun. 2001.

[20] N. Pickering, J. . Jones, and K. . Boote, “Evaluation of the Portable Chamber Technique for Measuring Canopy Gas Exchange by Crops,” *Agric. For. Meteorol.*, vol. 63, no. 3–4, pp. 239–254, Mar. 1993.

[21] O. T. Denmead and D. C. Reicosky, “Tillage Induced Gas Fluxes comparison of Meteoroligical and Large Chamber Techniques,” *Interanational Soil Tillage Res. Organ. Conf.*, pp. 357–363, 2003.

[22] W. A. Dugas, L. J. Fritschen, L. W. Gay, A. a. Held, A. D. Matthias, D. C. Reicosky, P. Steduto, and J. L. Steiner, “Bowen Ratio, Eddy correlation, and Portable Chamber Measurements of Sensible and Latent Heat Flux Over Irrigated Spring Wheat,” *Agric. For. Meteorol.*, vol. 56, pp. 1–20, 1991.

[23] M. K. McLeod, H. Daniel, R. Faulkner, and R. Murison, “Evaluation of an Enclosed Portable Chamber to Measure Crop and Pasture Actual Evapotranspiration at Small Scale,” *Agric. Water Manag.*, vol. 67, no. 1, pp. 15–34, Jun. 2004.

[24] D. I. Stannard, “Use of a Hemispherical Chamber for Measurement of Evapotranspiration,” *U.S. Geol. Surv. Open File Rep., 88-452.*, p. 18, 1988.

[25] S. Matsuura, A. Mori, M. Hojito, T. Kanno, and H. Sasaki, “Evaluation of a Portable Chamber System for Soil CO2 Efflux Measurement and the Potential Errors Caused by Internal Compensation and Water Vapor Dilution,” *Agric. Meteorol.*, vol. 67, no. 3, pp. 127–137, 2011.

[26] W. Sanford and W. Wood, “Hydrology of the Coastal Sabkhas of Abu Dhabi, United Arab Emirates,” *Hydrogeol. J.*, vol. 9, no. 4, pp. 358–366, Aug. 2001.

[27] A. Garcia, M. J. J. J. Andraski, K. J. Halford, and C. J. Mayers, “Portable Chamber Measurements of Evapotranspiration at the Amargosa Desert Research Site near Beatty , Nye County , Nevada , 2003 – 06,” *Report*, p. 18, 2008.

[28] A. A. Al-Shuhail and A. M. Al-Shaibani, “Characterization of Sabkha Jayb

Uwayyid, Eastern Saudi Arabi Using Seismic Refraction Profiling," *Arab. J. Geosci.*, vol. 6, no. 3, pp. 845–855, Jul. 2011.

[29] N. A. Alsaaran, "Origin and Geochemical Reaction Paths of Sabkha Brines: Sabkha Jayb Uwayyid, Eastern Saudi Arabia," *Arab. J. Geosci.*, vol. 1, no. 1, pp. 63–74, Jun. 2008.

[30] O. S. B. Al-amoudi, "Studies on Soil-foundation Interaction in the Sabkha Environment of Eastern Province of Saudi Arabia," no. September, 1992.

[31] J. K. Warren, *Evaporites: Sediments, Resources and Hydrocarbons*. Germany: Springer Science and Business Media, 2006.

[32] C. W. Fetter, *Applied Hydrogeology*, 4th ed. Upper Saddle River, New Jersey 07458: Prenctice-Hall, Inc., 2001.

[33] P. Dama-fakir and A. Toerien, "The Effect of Salinity on Evaporation Rates of Brines Resulting from the Treatment of Mine Water," 2000.

[34] US Department of Agriculture, "Determination of the Properties of Saline and Alkali Soils," *Agric. Handb. US Dep. Agric.*, vol. 60, pp. 7–33, 2007.

[35] L. J. Fritschen; and L. W. Gay, *Environmental Instrumentation*. Berlin: Springer-Verlag, 1979.

[36] M. S. D. Groselj, "WMO CIMO Training Workshop on Metrology for the English-speaking Countries of Region V (South-West Pacific)-Relative Humidity," Melbourne, 2011.

[37] D. I. Stannard, "Use of Chamber for Measurement of Evapotranspiration," Denver, Colorado, 1988.

[38] J. Pallant, *SPSS Survival Manual*, 4th Editio. Mc Graw Hill, 2010.

[39] C. Henschke, "Fact Sheet: Testing for Soil and Water Salinity," 2007.

[40] M. Botanix, "'Online grow Mag.'" [Online]. Available: http://www.manicbotanix.com/hydroponic-grow-guide/ec-to-ppm-conversion-chart.html. [Accessed: 08-Dec-2015].

[41] T. Innocent-Bernard, "Evaporation, Cracking, and Salinity in a Thickened Oil Sands Tailings," Carleton University, 2013.

[42] S. J. Blott; and K. Pye, "Technical Communication Gradistat : A Grain Size Distribution and Statistics Package for the Analysis of Unconsolidated Sediments," *Earth Surf. Process. Landforms*, vol. 26, pp. 1237–1248, 2001.

[43] R. Folk and W. Ward, "Brazos River Bar: A Study in the Significance of Grain Size Parameters," *SEPM J. Sediment. Res.*, vol. Vol. 27, no. 1, pp. 3–26, 1957.

[44] D. Hillel, *Environmental Soil Physics*, 1st ed. Academic Press, 1998.

[45] V. Te Chow, D. R. Maidment, and L. W. Mays, *Applied hydrology*, First Edit., vol. 6, no. 2. New York: McGraw-Hill. Inc., 1988.

[46] J. G. Zhang, X. W. Xu, J. Q. Lei, S. Y. Li, R. L. Hill, and Y. Zhao, "The Effects of Soil Salt Crusts on Soil Evaporation and Chemical Changes in Different Ages of Taklimakan Desert Shelterbelts," *J. Soil Sci. Plant Nutr.*, vol. 13, no. 4, pp. 1019–1028, 2013.

[47] A.Z El Bably, "Estimation of Evapotranspiration Using Statistical Model," *Delta*, vol. 449, pp. 441–449, 2011.

[48] B.C Isikwue;, M.O Audu;, and E.J Eweh, "Correlation of Evapotranspiration with Climatic Parameters in Some Selected Cities in Nigeria," *J. Earth Sci. Geotech. Eng.*, vol. 5, no. 4, pp. 103–115, 2015.

[49] Karnataka, "Estimation of Evaporation Based on Meteorological Parameters," *J. Agric. Sci.*, vol. 11, no. 1, pp. 272–273, 1998.

Appendix 1 – Measurement Data

Measurement Data for 05/02/2015								
Time (hours)	Evaporation rate at location 2 (mm/day)	Evaporation rate at location 1 (mm/day)	Average Evaporation Rate/hour (mm/day)	Wind Speed, m/s	Gust Speed, m/s	Wind Direction, ø	Temp, °C	RH, %
11	1.404	1.118	1.261	5.200	8.530	231.600	23.472	55.0
12	0.852	0.971	0.912	5.200	8.350	233.100	25.841	49.4
13	0.538	0.405	0.472	5.380	8.720	226.000	25.963	43.1
14	0.496	0.440	0.468	7.980	9.460	9.800	24.508	40.7
15	-0.021	0.035	0.007	8.350	10.580	11.200	24.944	38.2
16	0.160	0.112	0.136	8.910	11.130	9.800	23.857	31.4
17	-0.021	-0.049	-0.035	7.790	11.320	9.800	21.939	35.8
18	-0.070	0.056	-0.007	5.750	7.610	8.400	20.913	40.2
19	-0.063	-0.098	-0.081	5.570	7.610	11.200	20.031	45.9
20	0.196	-0.119	0.039	4.640	6.490	19.700	18.628	52.4
21	0.000	0.084	0.042	2.780	4.820	42.100	18.247	51.6
22	0.014	-0.035	-0.011	3.150	4.270	15.400	16.915	49.5
23	0.077	0.063	0.070	2.230	3.150	35.100	15.676	54.2
24	0.035	0.098	0.067	1.480	2.410	57.600	14.673	52.3
1	0.070	0.056	0.063	1.670	2.410	60.400	13.594	51.9
2	0.035	0.084	0.060	1.110	1.860	99.700	13.546	52.4
3	0.105	0.063	0.084	0.560	1.300	9.800	12.847	55.7
4	0.070	0.161	0.116	2.410	5.200	193.700	15.318	50.1

5	-0.056	0.028	-0.014	4.270	6.490	188.100	13.906	48.1
6	0.077	0.007	0.042	2.970	4.640	178.300	12.703	56.9
7	0.314	0.210	0.262	2.040	2.970	157.200	12.389	61.3
8	0.196	0.482	0.339	2.780	4.820	172.700	15.796	52.9
9	0.258	0.468	0.363	4.080	5.380	182.500	18.224	47.1
10	0.203	0.307	0.255	3.530	5.940	200.800	21.175	51.0

Measurement data for 9/02/2015								
Time (hours)	Evaporation rate at location 2 (mm/day)	Evaporation rate at location 1 (mm/day)	Average Evaporation Rate/hour (mm/day)	Wind Speed, m/s	Gust Speed, m/s	Wind Direction, ø	Temp, °C	RH, %
11	1.425	1.467	1.446	7.420	9.650	265.300	24.968	31.800
12	0.803	0.782	0.793	7.980	10.580	262.500	26.158	30.100
13	0.460	0.363	0.412	7.980	10.580	256.900	26.818	32.100
14	0.580	0.496	0.538	7.790	11.320	248.500	27.087	31.000
15	0.342	0.384	0.363	7.980	9.650	244.300	27.875	30.000
16	0.186	0.300	0.243	7.980	10.390	247.100	27.727	29.400
17	0.063	0.175	0.119	6.860	9.460	245.700	26.329	32.000
18	0.042	0.105	0.073	5.750	9.830	233.100	25.428	35.500
19	-0.063	-0.063	-0.063	8.350	10.580	226.000	23.472	48.400
20	-0.056	-0.001	-0.028	9.460	12.250	234.500	22.465	53.500
21	-0.007	0.042	0.017	8.720	12.620	238.700	21.700	59.600
22	-0.028	-0.007	-0.017	8.160	10.580	240.100	21.079	62.700

23	-0.084	0.000	-0.042	7.240	9.280	240.100	20.531	67.300
24	-0.140	0.049	-0.046	5.010	6.680	233.100	19.770	69.700
1	-0.182	-0.035	-0.108	4.270	6.120	233.100	19.341	70.000
2	-0.147	-0.049	-0.098	3.710	4.820	228.800	19.008	71.100
3	0.175	0.433	0.304	4.270	5.570	234.500	18.747	67.000
4	0.196	0.314	0.255	5.010	6.120	242.900	18.224	63.800
5	0.056	0.224	0.140	5.200	6.680	247.100	17.962	64.200
6	0.531	0.573	0.552	4.270	5.380	259.700	17.415	59.700
7	0.915	0.754	0.835	6.490	8.350	255.500	18.533	51.000
8	0.775	0.573	0.674	7.980	10.580	262.500	21.175	44.800
9	0.217	0.789	0.503	9.090	11.870	290.600	23.184	40.500
10	0.112	0.335	0.224	6.860	8.530	268.100	23.160	32.200

Measurement Data for 17/05/2015								
Time (hours)	Evaporation rate at location 1 (mm/day)	Evaporation rate at location 2 (mm/day)	Average Evaporation Rate/hour (mm/day)	Wind Speed, m/s	Gust Speed, m/s	Wind Direction, ø	Temp, °C	RH, %
13	0.915	1.188	1.052	3.150	6.120	240.100	35.182	22.100
14	0.936	1.027	0.982	2.600	5.200	251.300	35.636	21.400
15	0.685	0.915	0.800	4.080	6.680	231.600	35.102	21.700
16	0.251	0.559	0.405	4.820	7.420	241.500	33.521	23.900
17	0.342	0.201	0.272	5.010	6.680	223.200	31.996	27.100
18	-0.098	-0.112	-0.105	6.860	8.530	195.100	28.270	39.600

19	0.105	0.042	0.074	6.310	9.090	200.800	26.451	43.600
20	0.105	0.132	0.119	5.940	7.610	192.300	25.793	40.700
21	0.091	0.049	0.070	5.750	7.610	198.000	25.428	40.100
22	0.053	0.084	0.069	6.310	8.530	206.400	25.113	40.600
23	0.070	0.133	0.102	3.710	5.380	190.900	24.895	42.000
24	0.042	-0.035	0.004	2.230	3.530	183.900	23.905	46.600
1	-0.003	-0.063	-0.033	0.190	2.040	133.400	22.944	51.300
2	-0.035	-0.035	-0.035	2.780	3.900	154.400	21.939	57.000
3	0.014	0.000	0.007	3.900	5.570	165.700	22.345	56.100
4	0.161	0.028	0.095	3.340	4.640	150.200	21.270	53.800
5	-0.006	0.105	0.050	2.970	3.900	160.000	20.627	59.700
6	0.196	0.196	0.196	2.780	4.270	154.400	21.819	54.800
7	0.391	0.398	0.395	7.050	10.580	185.300	26.036	45.600
8	0.300	0.279	0.290	10.020	13.730	188.100	29.090	35.500
9	0.999	0.782	0.891	14.100	22.820	195.100	30.142	30.700
10	1.041	0.741	0.891	13.920	28.020	190.900	30.824	28.100
11	1.083	0.710	0.897	12.800	24.490	186.700	31.816	26.800
12	1.355	1.495	1.425	3.150	5.750	252.700	34.598	23.400

Measurement Data for 28/05/2015								
Time (hours)	Evaporation rate at location 1 (mm/day)	Evaporation rate at location 2(mm/day)	Average Evaporation Rate/hour (mm/day)	Temp, °C	RH, %	Wind Speed, m/s	Gust Speed, m/s	Wind Direction, ø
13	1.984	1.998	1.991	42.100	13.507	3.920	5.120	239.300
14	1.327	1.097	1.212	41.646	12.807	4.220	4.830	221.400
15	1.530	1.020	1.275	41.112	13.077	4.800	5.930	211.700
16	0.663	1.446	1.055	38.531	15.027	6.260	6.320	226.500
17	0.517	0.461	0.489	35.222	17.154	5.630	5.930	213.500
18	0.265	0.265	0.265	31.189	19.551	5.320	6.850	195.100
19	0.272	0.182	0.227	29.895	20.365	5.310	7.920	210.200
20	0.231	0.224	0.228	28.661	21.330	5.980	6.120	165.400
21	0.286	0.063	0.175	28.545	22.462	6.310	6.540	199.130
22	0.224	0.140	0.182	26.058	23.157	4.820	5.230	186.400
23	0.147	0.049	0.098	26.289	23.323	4.080	4.450	197.200
24	0.161	0.105	0.133	24.652	26.140	2.520	3.650	185.300
1	0.105	0.147	0.126	24.223	28.258	3.500	3.790	141.600
2	0.189	0.112	0.151	23.512	26.586	3.410	3.850	101.500
3	0.189	0.154	0.172	24.011	23.657	2.630	4.970	123.400
4	0.140	0.077	0.109	22.570	28.997	3.080	4.890	167.300
5	0.133	0.084	0.109	23.106	28.714	4.071	4.730	142.200
6	0.293	0.265	0.279	24.653	23.285	5.820	6.560	124.700
7	0.468	0.433	0.451	26.691	22.836	7.240	8.560	168.500
8	0.699	0.727	0.713	29.745	20.352	8.950	6.960	174.300
9	0.761	0.678	0.720	33.379	16.113	11.210	8.740	183.300

10	0.831	0.720	0.776	35.778	16.171	10.780	12.720	168.600
11	0.943	0.943	0.943	39.434	15.280	6.680	8.130	176.200
12	1.509	1.628	1.569	35.996	14.578	2.510	6.640	198.300

Measurement Data for 16/08/2015								
Time (hours)	Evaporation rate at location 1 (mm/day)	Evaporation rate at location 2 (mm/day)	Average Evaporation Rate/hour (mm/day)	Wind Speed, m/s	Gust Speed, m/s	Wind Direction, ø	Temp, °C	RH, %
7	2.662	1.684	2.173	3.900	7.420	226.000	31.919	68.600
8	1.181	1.321	1.251	1.300	3.710	32.300	34.334	67.600
9	0.866	1.013	0.940	3.900	5.750	39.300	37.480	55.900
10	1.431	1.600	1.516	3.340	5.750	40.700	39.318	43.100
11	1.886	1.914	1.900	4.080	7.050	26.700	39.943	41.500
12	0.803	0.860	0.832	4.080	6.860	29.500	41.972	30.400
13	1.530	1.502	1.516	5.940	8.910	33.700	41.736	30.700
14	1.327	1.243	1.285	5.940	7.790	32.300	42.953	22.800
15	0.965	0.942	0.954	4.640	6.860	28.100	43.586	21.200
16	0.720	0.715	0.718	4.450	6.680	28.100	43.314	21.300
17	0.601	0.608	0.605	4.820	7.240	25.300	42.624	20.200
18	0.349	0.321	0.335	3.710	4.820	23.900	41.007	21.000
19	-0.281	-0.307	-0.294	3.900	5.200	1.400	38.672	25.200
20	-0.664	-0.803	-0.734	3.900	5.010	349.600	35.716	56.200
21	-0.251	-0.342	-0.297	3.340	4.270	0.000	34.995	63.900

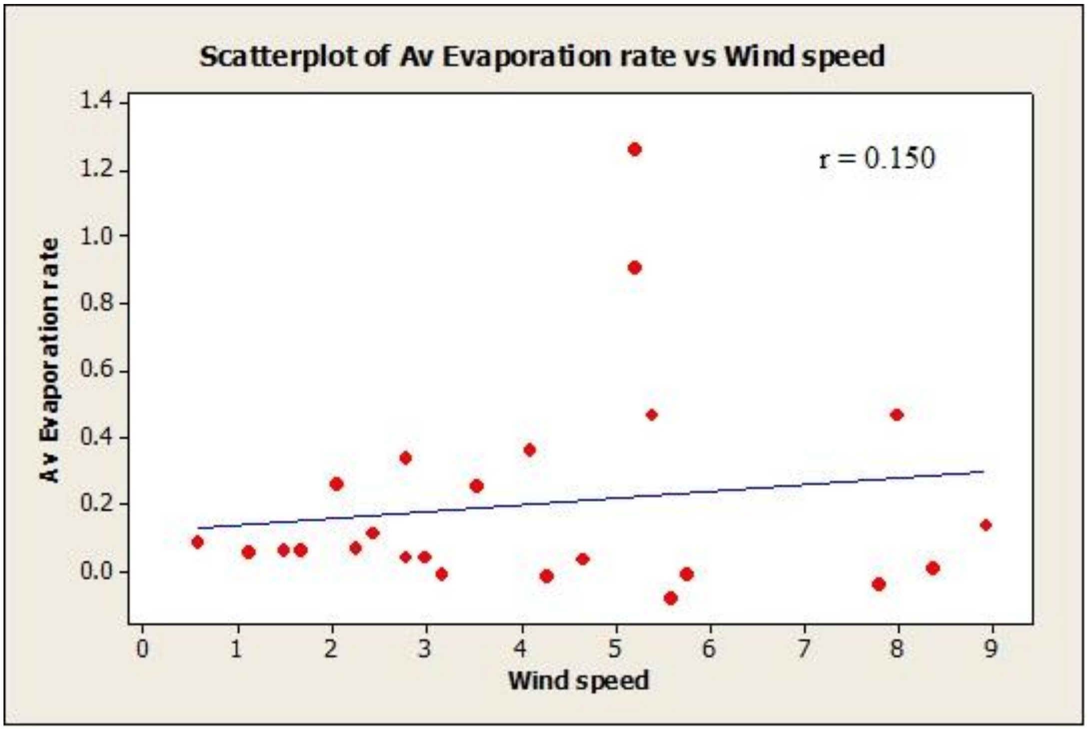
22	-0.035	-0.307	-0.171	2.230	3.530	2.800	34.651	63.700
23	-0.014	-0.112	-0.063	0.740	2.040	33.700	33.157	65.100
24	-0.119	-0.224	-0.172	1.480	2.600	40.700	32.175	68.900
1	-0.160	-0.328	-0.244	1.480	3.340	80.000	30.950	71.100
2	-0.203	-0.189	-0.196	0.740	2.970	80.000	30.217	78.800
3	-0.210	-0.196	-0.203	1.110	2.040	87.000	29.916	79.800
4	-0.342	-0.100	-0.221	0.740	2.040	78.600	29.389	79.800
5	-0.077	-0.084	-0.081	0.740	1.860	40.700	29.015	80.200
6	0.258	0.238	0.248	1.110	1.860	311.700	30.016	76.700

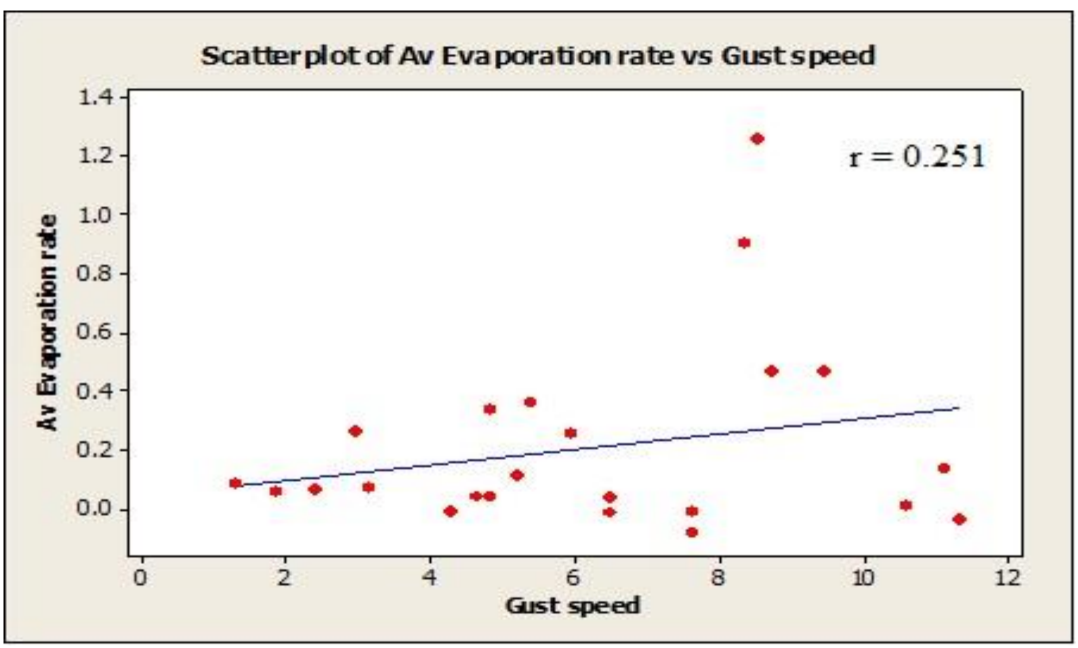
Measurement Data for 20/08/2015								
Time (hours)	Evaporation rate at location 1 (mm/day)	Evaporation rate at location 2(mm/day)	Average Evaporation Rate/hour (mm/day)	Temp, °C	RH , %	Wind Speed, m/s	Gust Speed, m/s	Wind Direction, ø
7	1.698	1.446	1.572	31.970	76.800	1.860	2.410	279.400
8	3.549	2.676	3.113	36.389	39.700	2.410	3.530	205.000
9	1.774	1.621	1.698	39.149	34.400	2.600	4.080	251.300
10	1.628	1.726	1.677	42.297	25.200	4.820	7.980	278.000
11	1.495	2.319	1.907	45.687	16.000	1.860	4.080	351.000
12	1.383	2.047	1.715	46.035	14.300	3.340	6.490	64.600
13	1.027	1.495	1.261	46.194	15.700	3.900	7.240	56.200
14	0.964	1.118	1.041	46.321	18.600	2.970	5.940	75.800
15	0.632	0.517	0.575	43.982	28.800	5.570	8.910	124.900

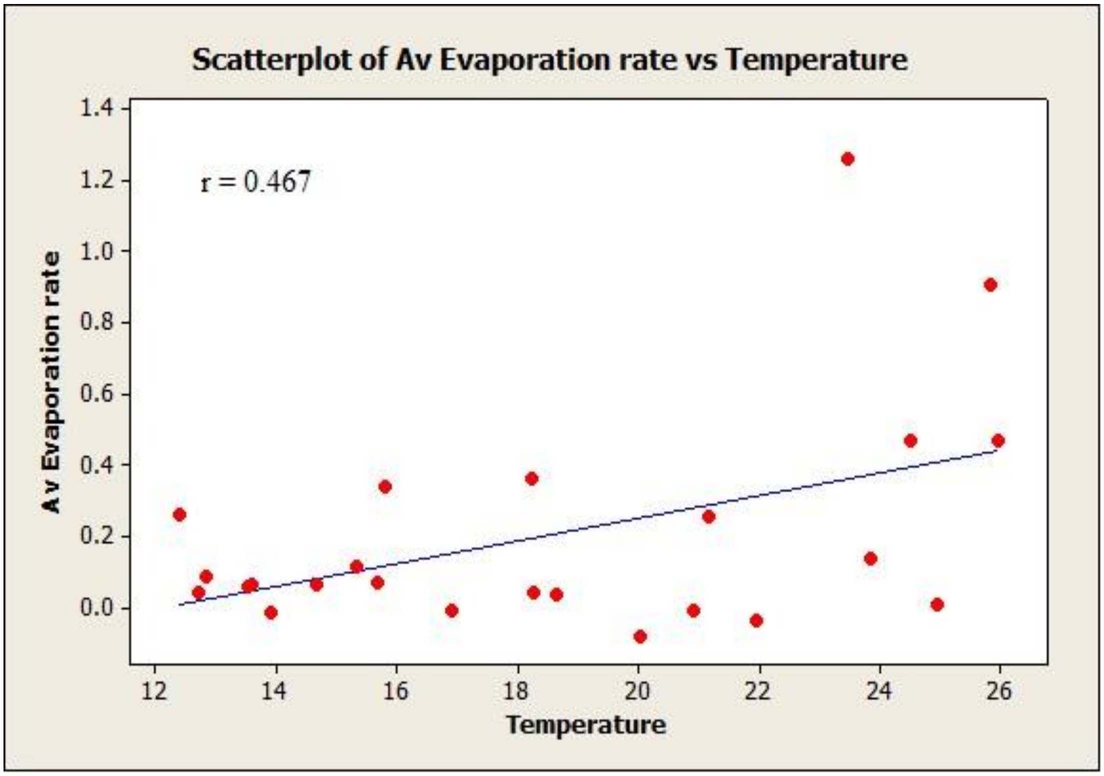
16	0.582	0.492	0.537	43.133	31.600	5.750	7.610	109.500
17	0.517	0.349	0.433	42.386	29.100	5.940	7.980	109.500
18	-0.251	-0.251	-0.251	40.142	34.700	5.380	6.680	122.100
19	-0.098	0.014	-0.042	37.728	43.300	3.710	5.570	148.800
20	-0.161	-0.363	-0.262	36.579	47.700	2.230	3.150	169.900
21	-0.447	-0.426	-0.437	35.262	54.600	1.480	2.410	226.000
22	-0.112	-0.265	-0.189	33.914	63.100	1.110	2.230	261.100
23	-0.091	-0.335	-0.213	32.949	66.900	0.930	2.040	248.500
24	-0.154	-0.272	-0.213	33.001	68.700	0.740	2.410	130.600
1	-0.349	-0.566	-0.458	32.330	71.600	0.740	1.860	269.600
2	-0.503	-0.377	-0.440	31.663	76.300	0.930	1.670	269.600
3	-0.391	-0.622	-0.507	31.637	79.100	0.560	1.480	269.600
4	0.098	-0.189	-0.046	30.976	75.600	0.370	1.480	311.700
5	0.168	-0.524	-0.178	29.916	77.100	0.000	0.560	259.700
6	0.182	-0.077	0.053	30.217	81.200	0.930	1.670	262.500

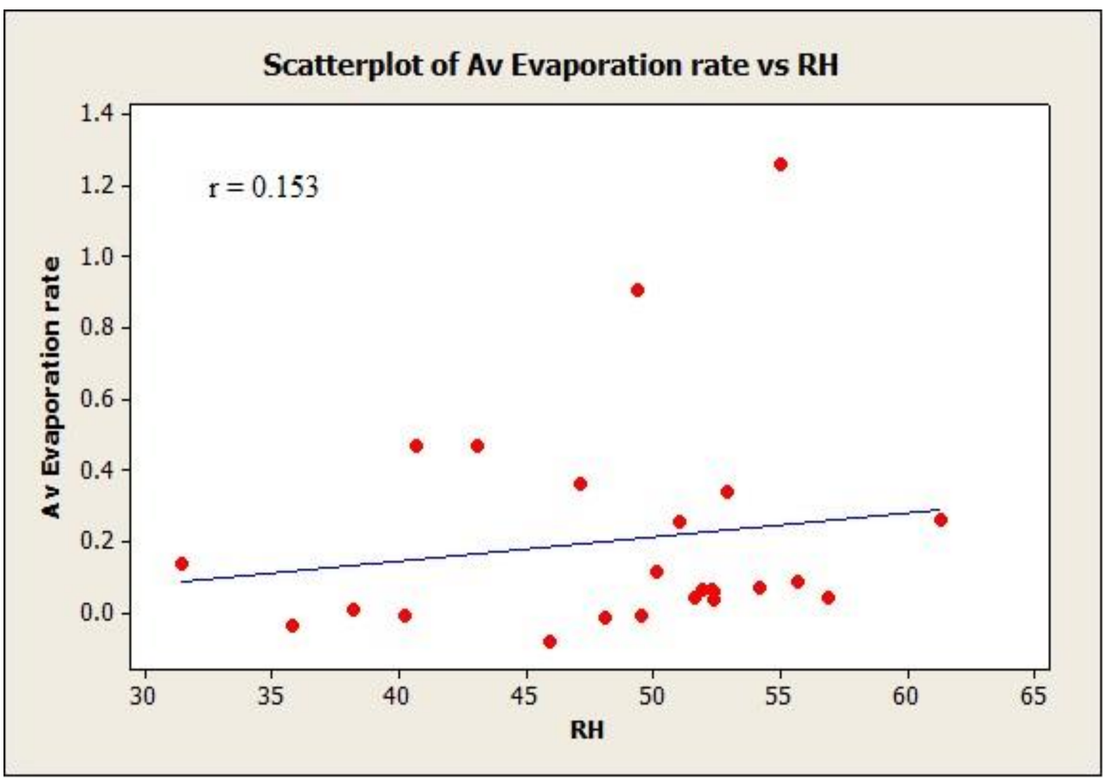
Appendix 2: Scatter Plots for Evaporation Rate with Weather Parameters over Seasonal Variations

Winter season: 5/02/2015

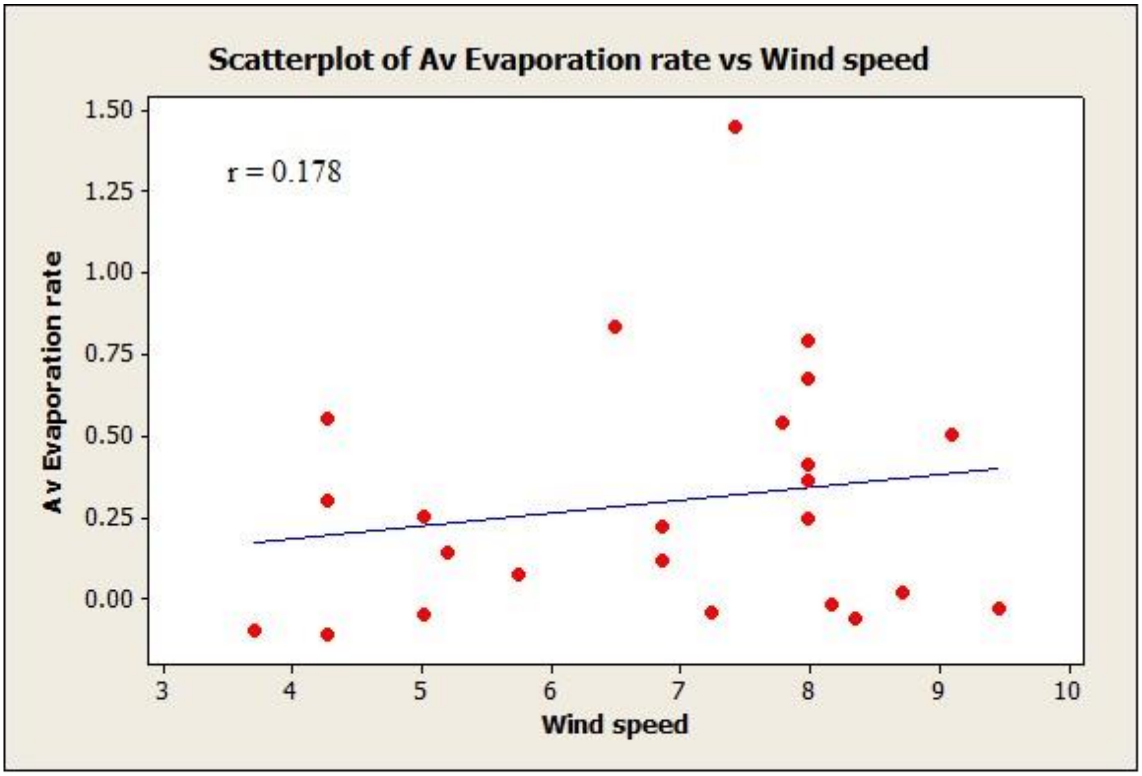


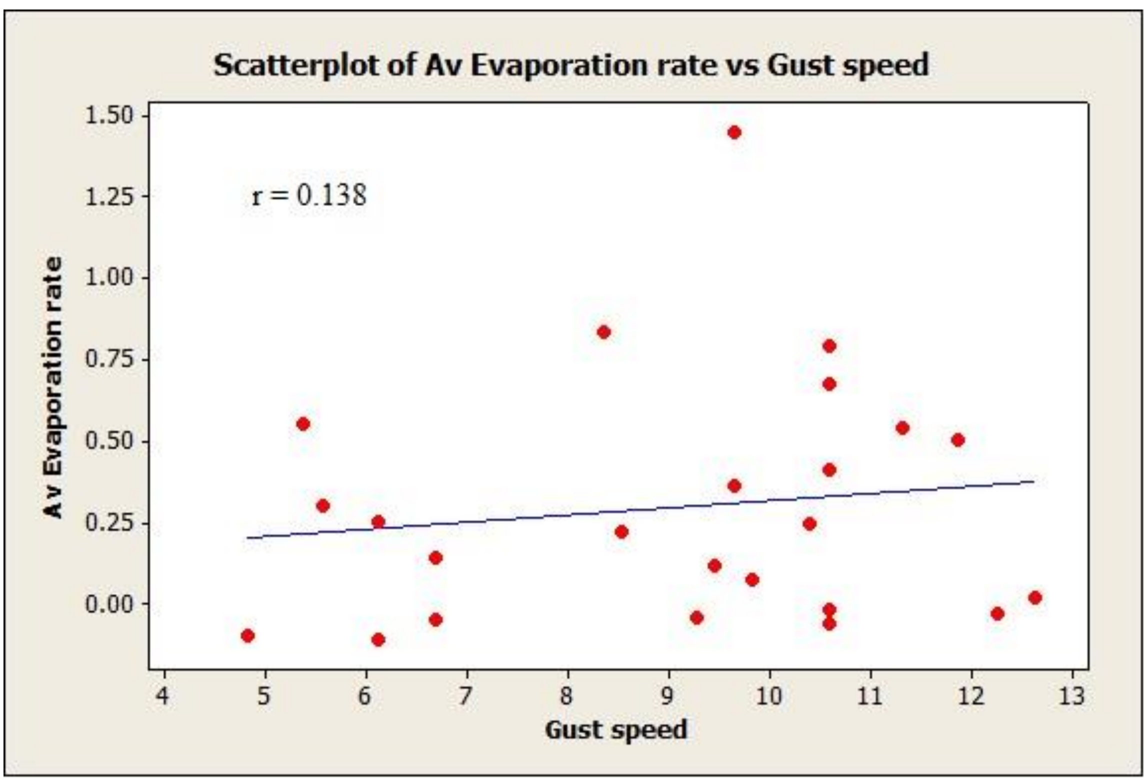


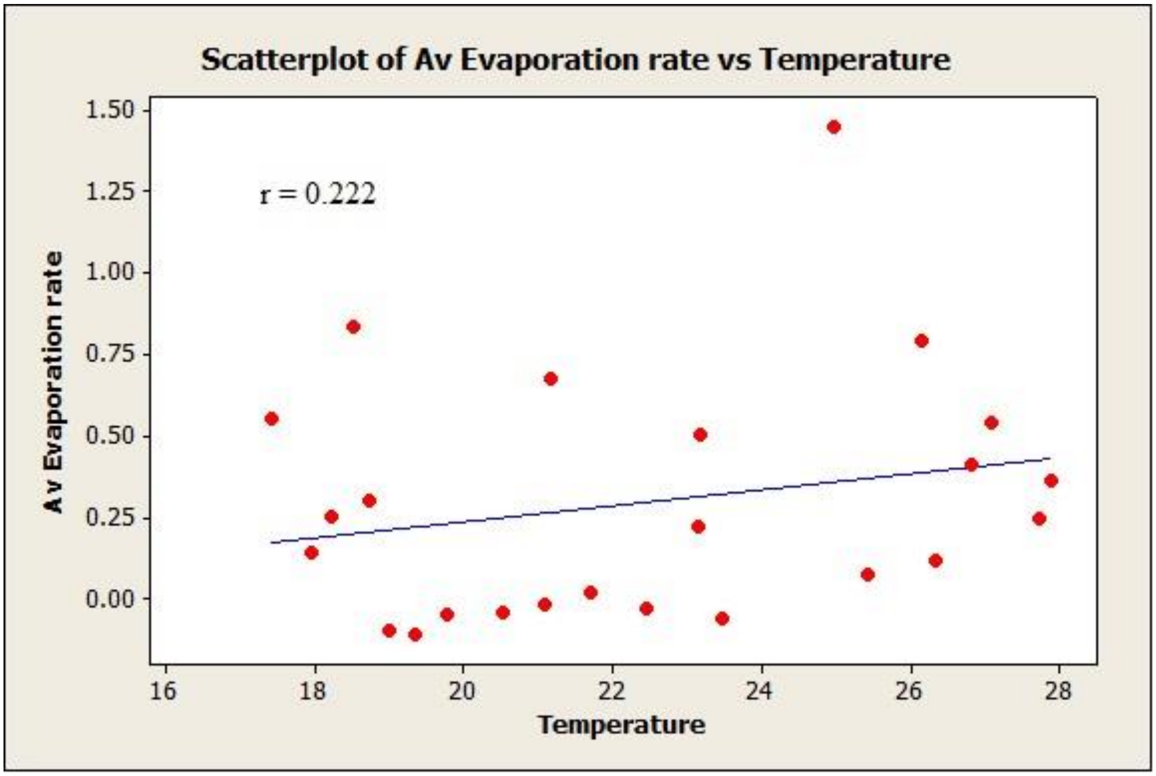

Scatterplot of Av Evaporation rate vs Temperature
r = 0.467
Av Evaporation rate
Temperature
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
12
14
16
18
20
22
24
26

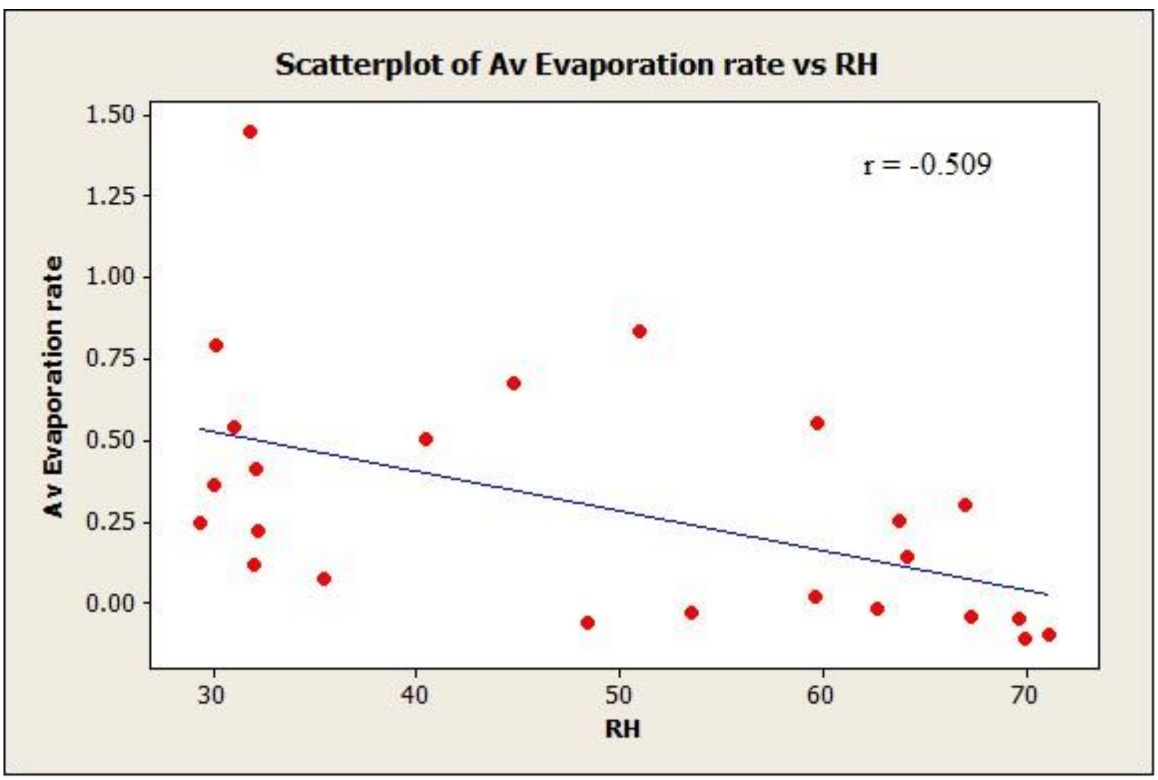

Scatterplot of Av Evaporation rate vs RH
r = 0.153
Av Evaporation rate
RH
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
30
35
40
45
50
55
60
65

Winter season: 9/02/2015

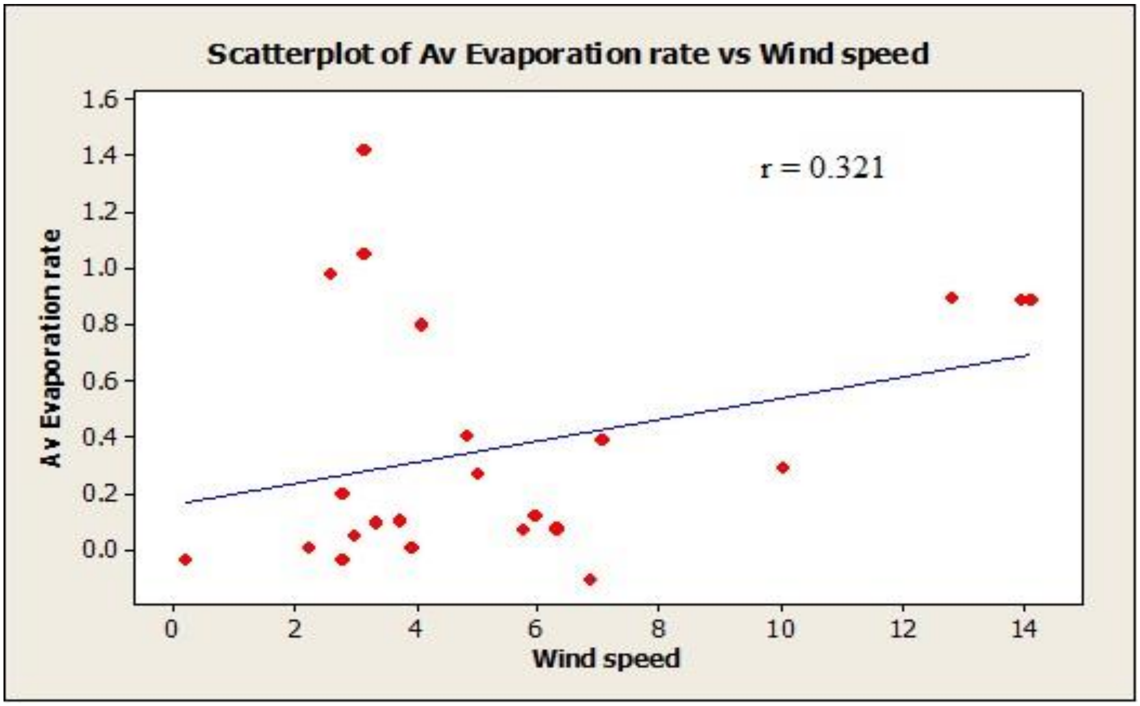


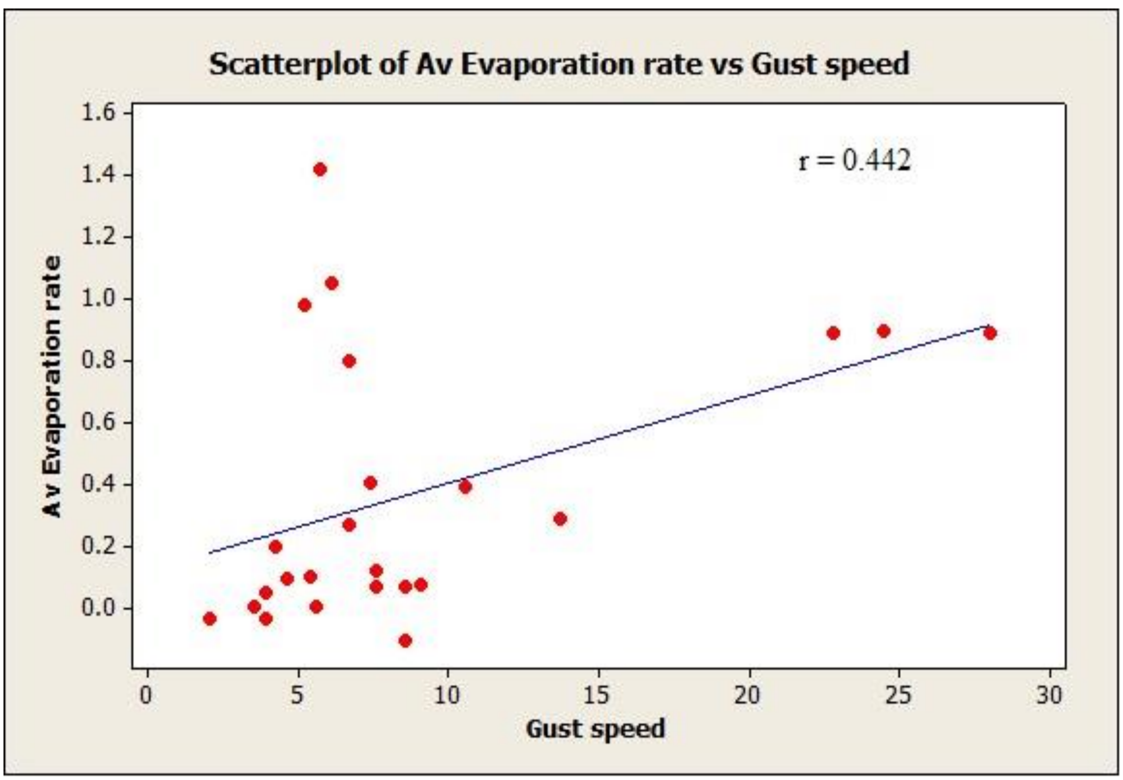


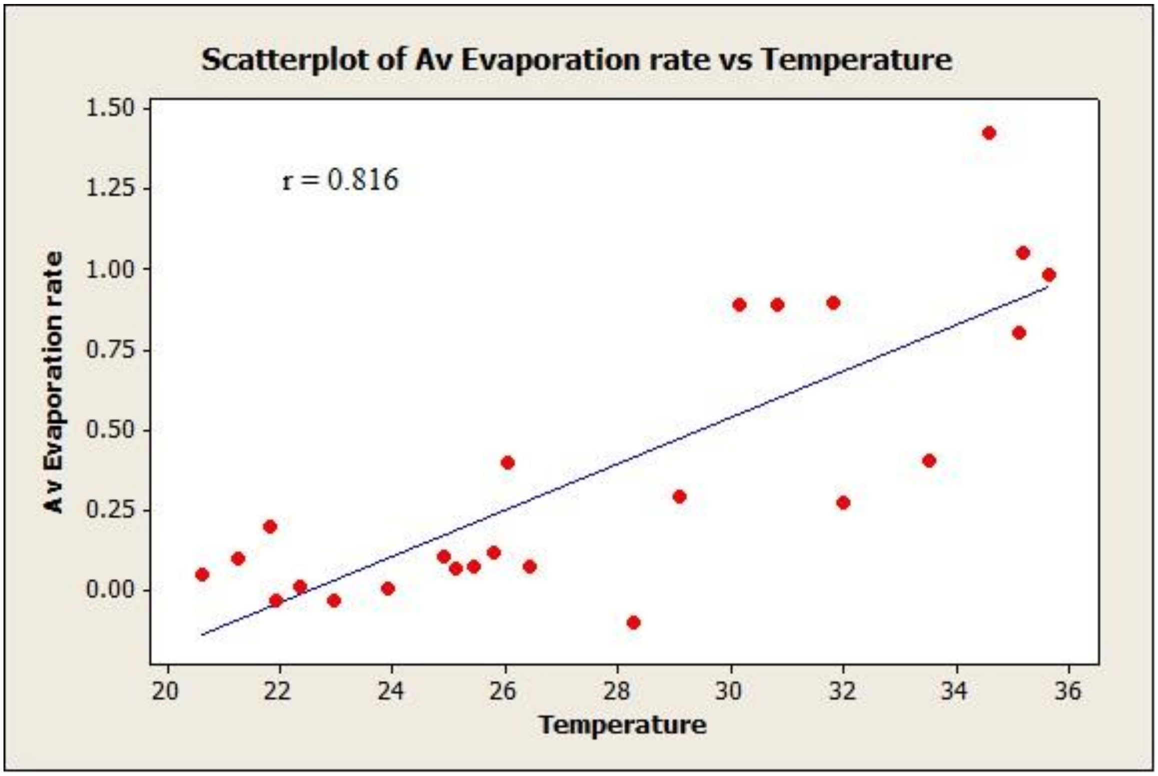

Scatterplot of Av Evaporation rate vs Temperature
r = 0.222
Av Evaporation rate
1.50
1.25
1.00
0.75
0.50
0.25
0.00
16
18
20
22
24
26
28
Temperature

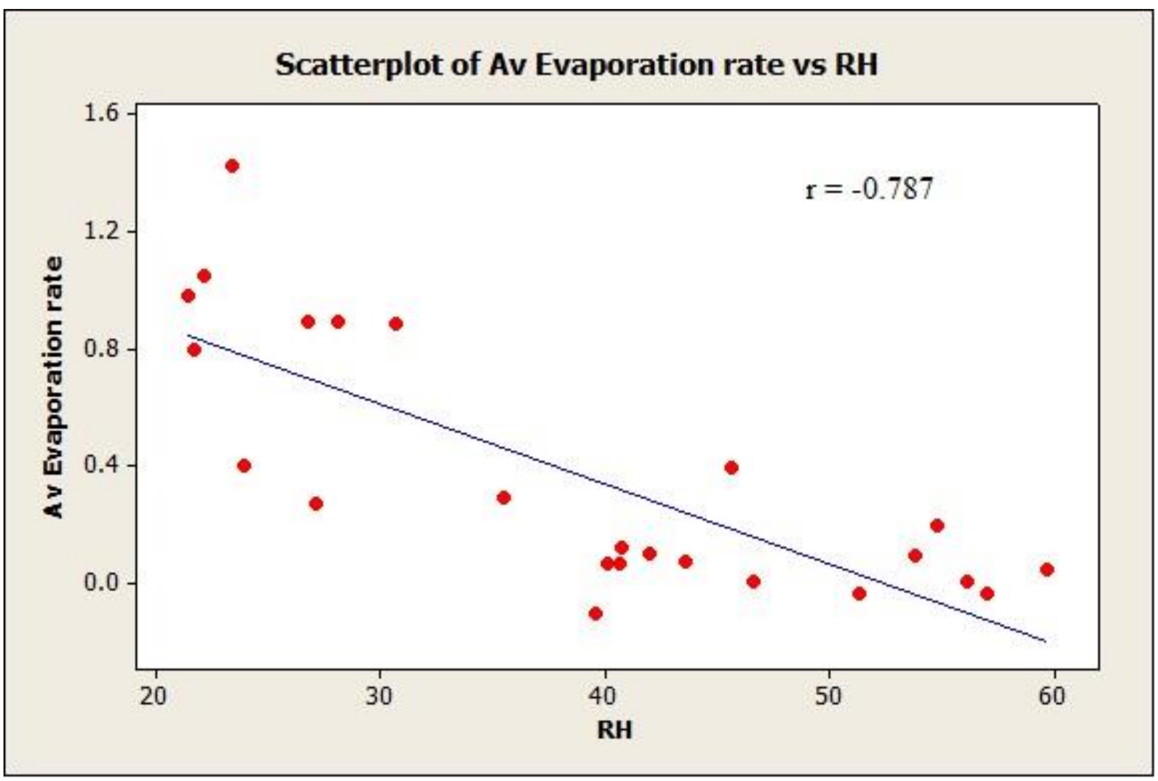

Scatterplot of Av Evaporation rate vs RH
r = -0.509
Av Evaporation rate
1.50
1.25
1.00
0.75
0.50
0.25
0.00
30
40
50
60
70
RH

Spring season: 17/04/2015

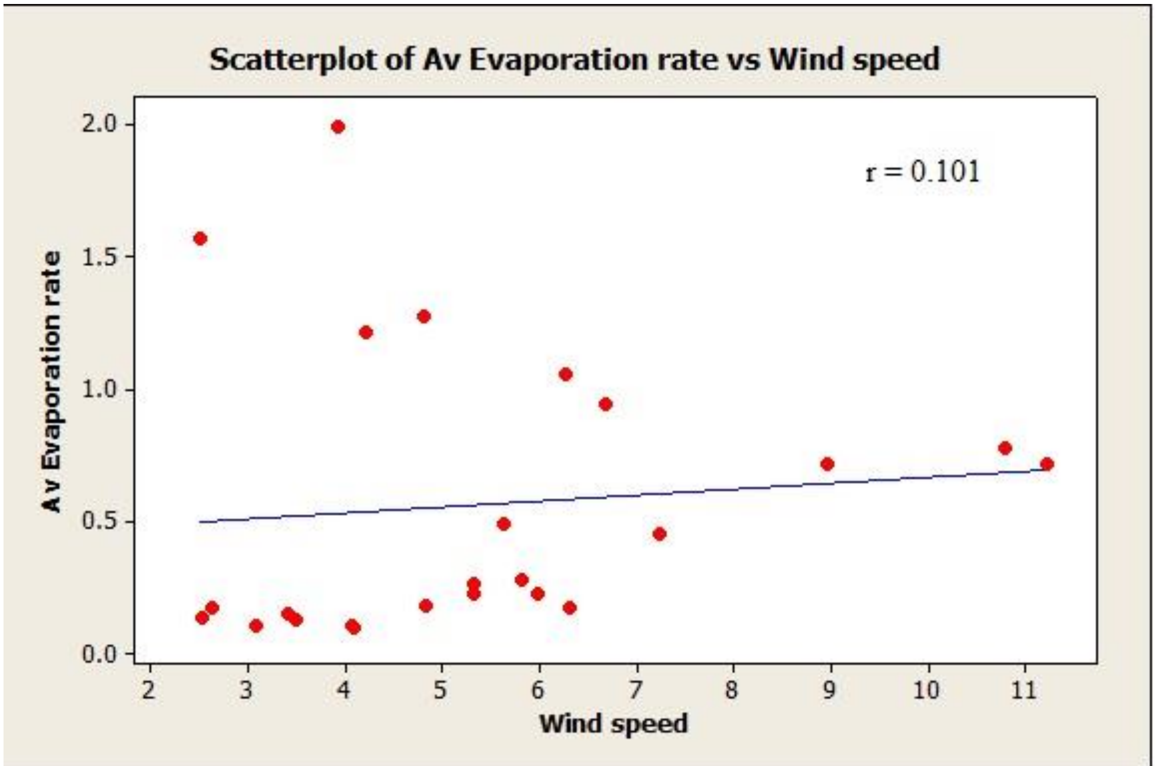


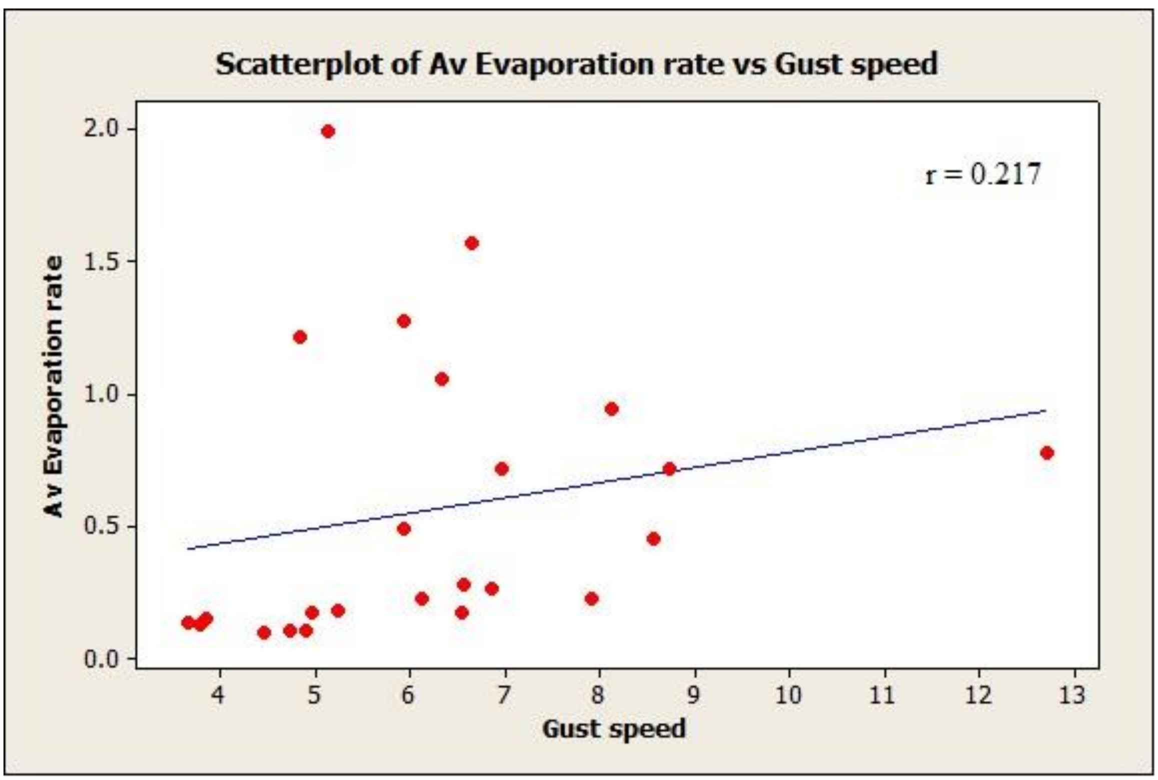


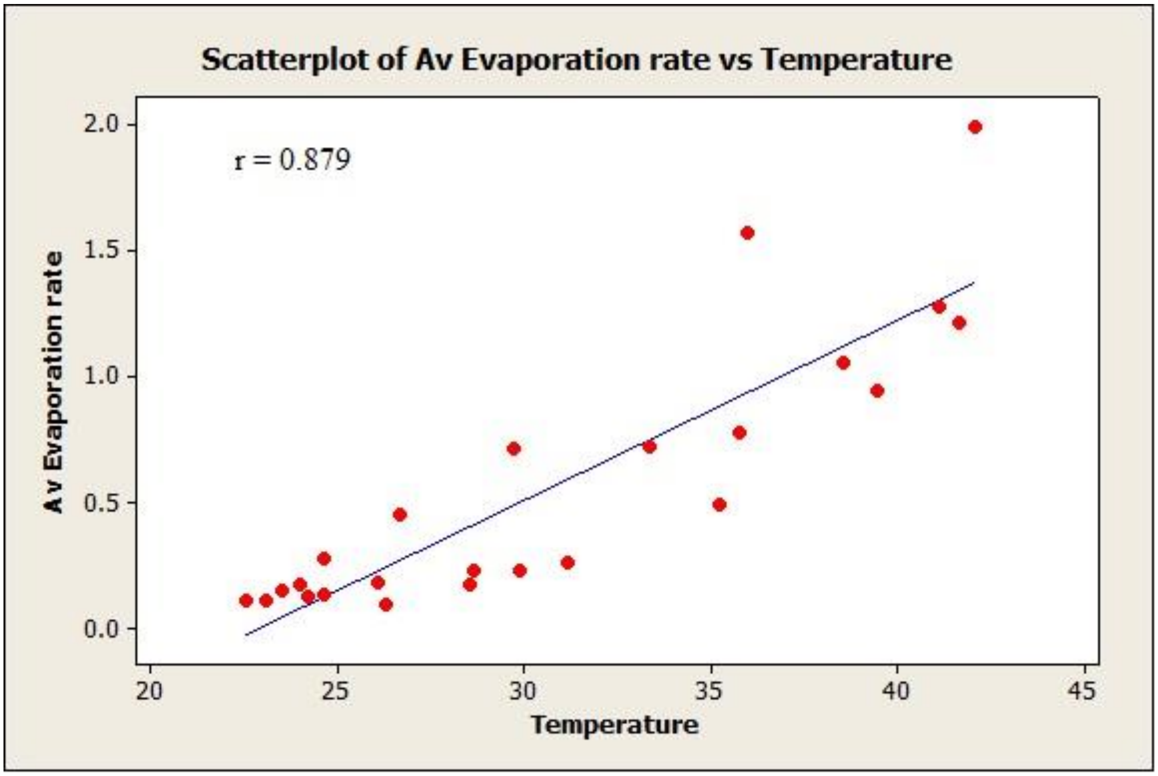

Scatterplot of Av Evaporation rate vs Temperature
r = 0.816
Av Evaporation rate
1.50
1.25
1.00
0.75
0.50
0.25
0.00
20
22
24
26
28
30
32
34
36
Temperature

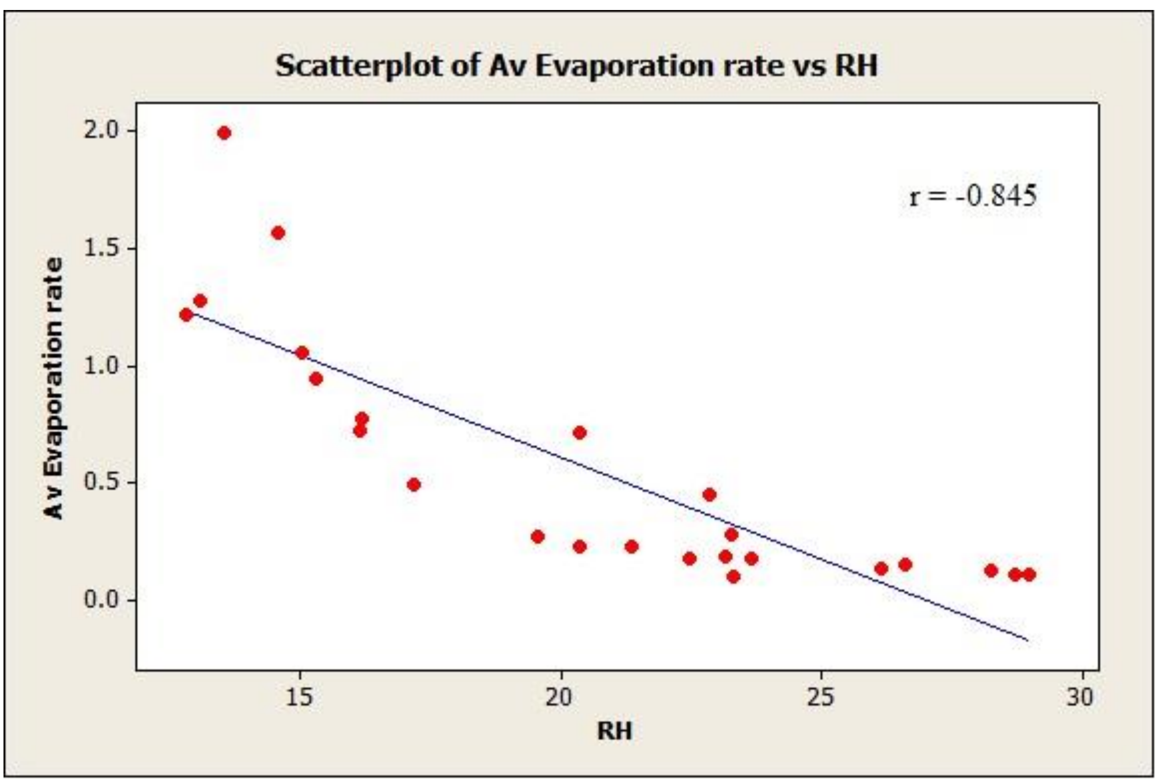

Scatterplot of Av Evaporation rate vs RH
r = -0.787
Av Evaporation rate
1.6
1.2
0.8
0.4
0.0
20
30
40
50
60
RH

Spring season: 28/04/2015

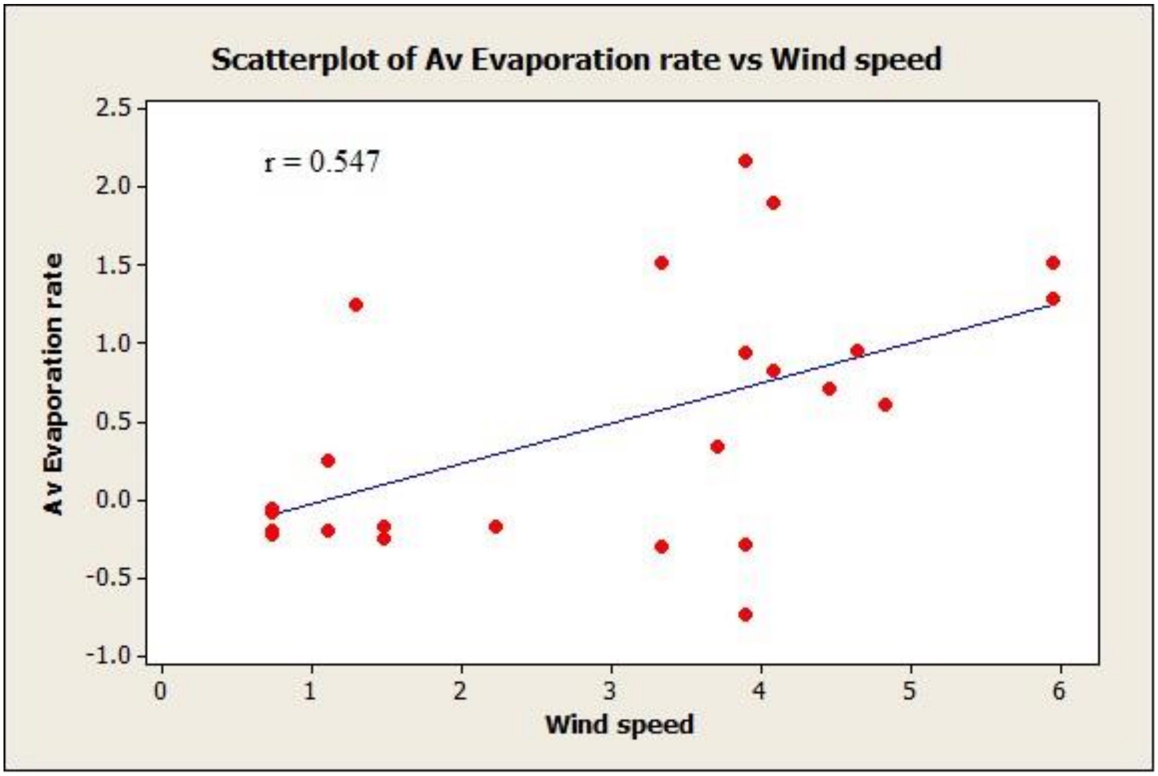


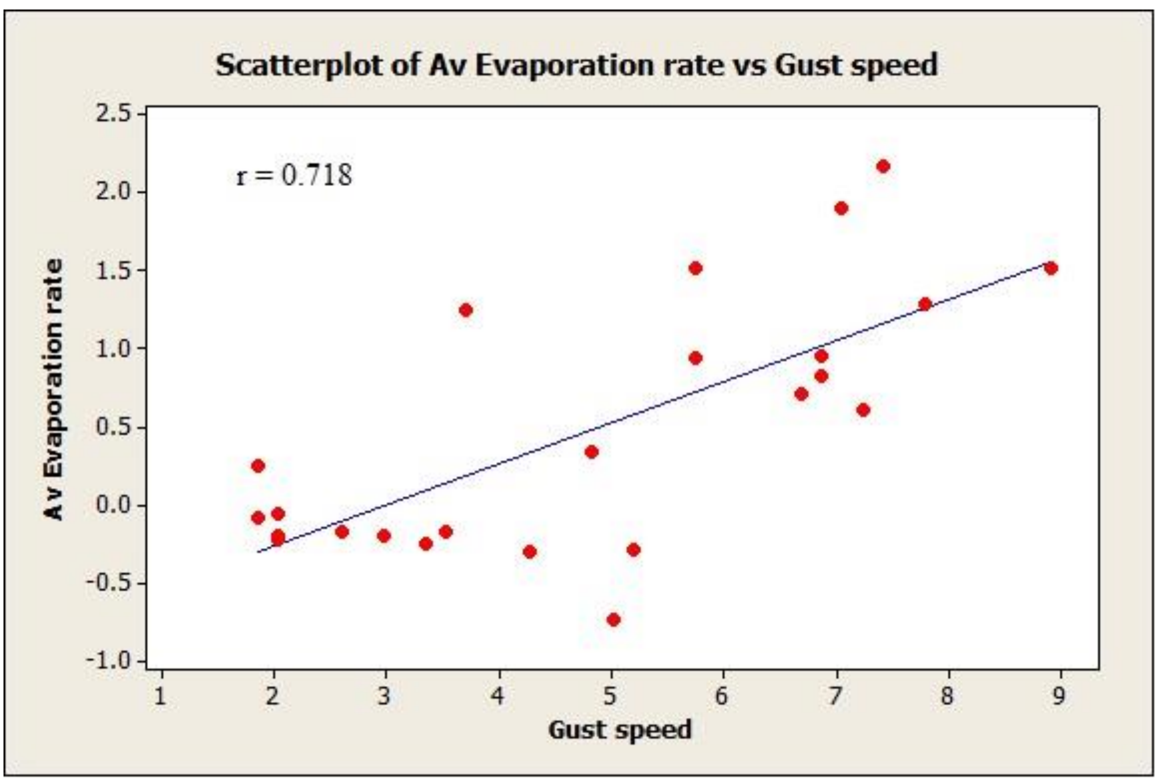


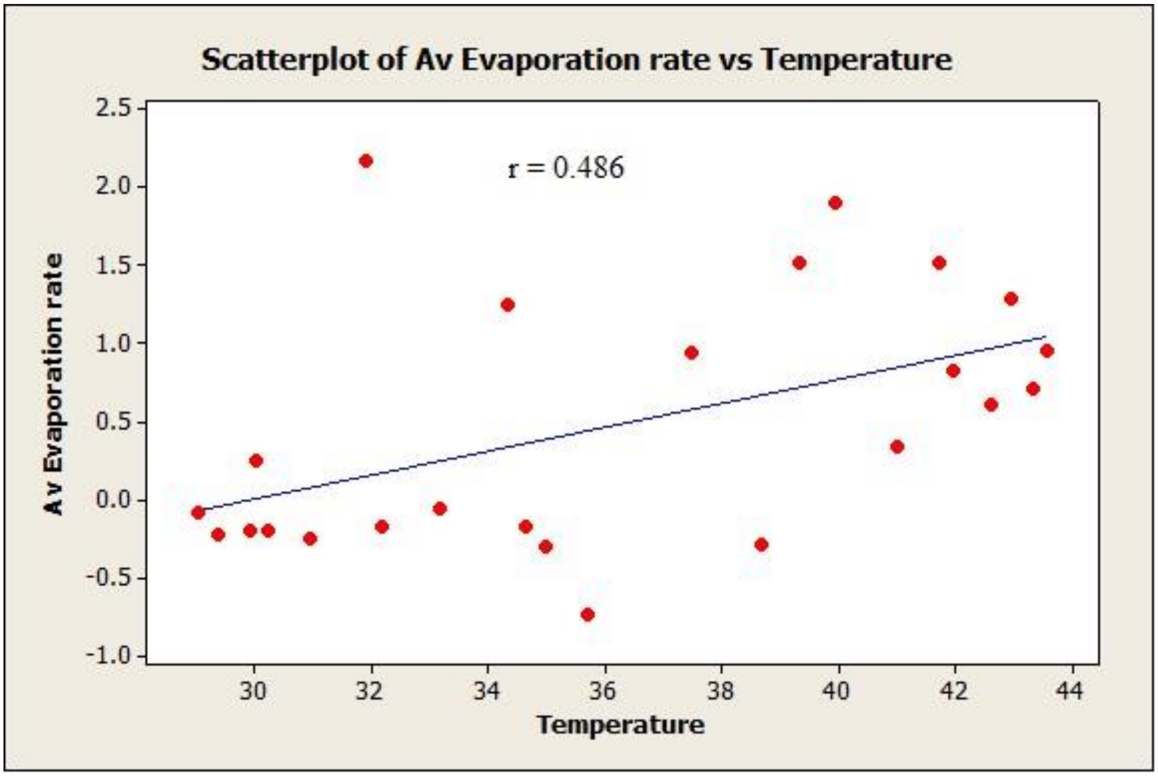

Scatterplot of Av Evaporation rate vs Temperature
r = 0.879
Av Evaporation rate
2.0
1.5
1.0
0.5
0.0
20
25
30
35
40
45
Temperature

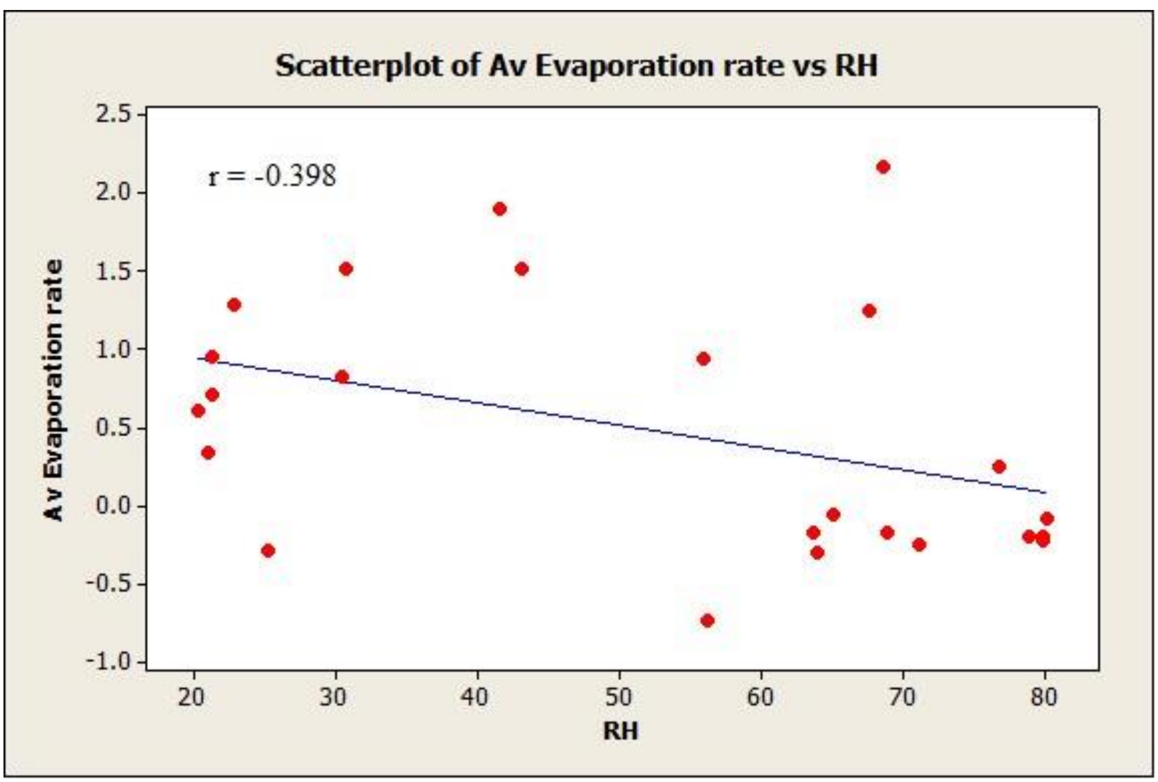

Scatterplot of Av Evaporation rate vs RH
r = -0.845
Av Evaporation rate
2.0
1.5
1.0
0.5
0.0
15
20
25
30
RH

Summer season: 16/08/2015

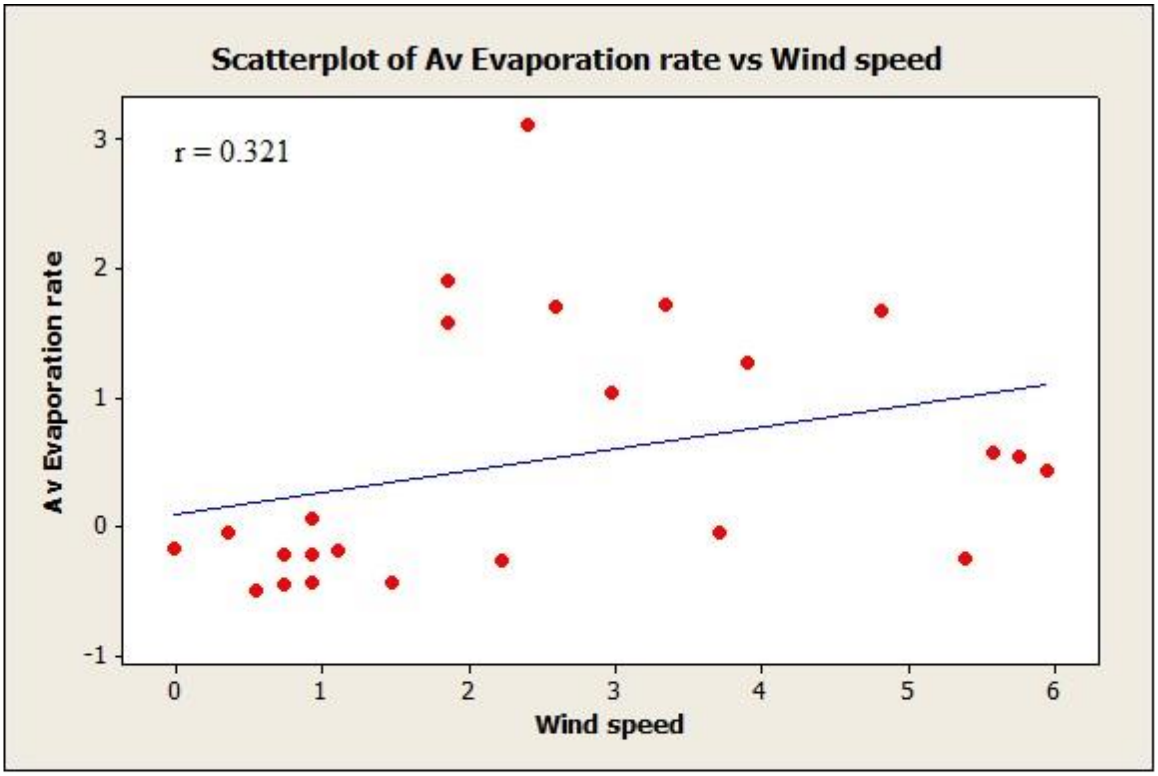


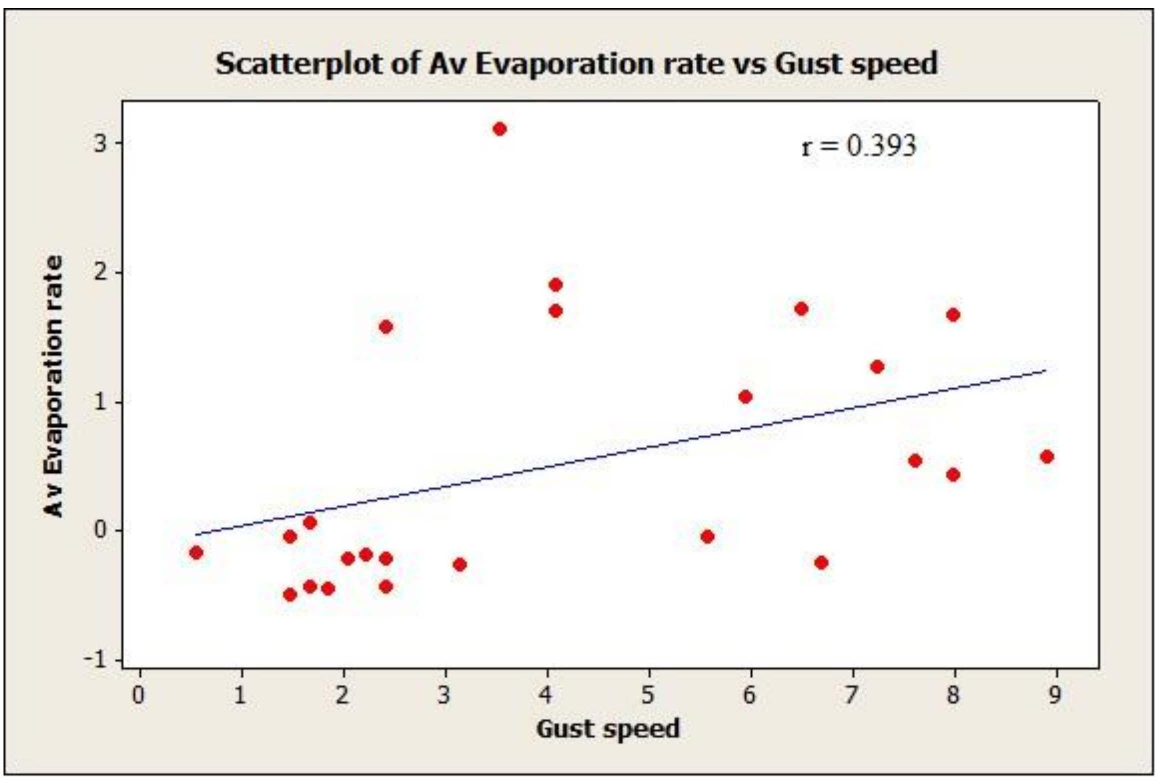


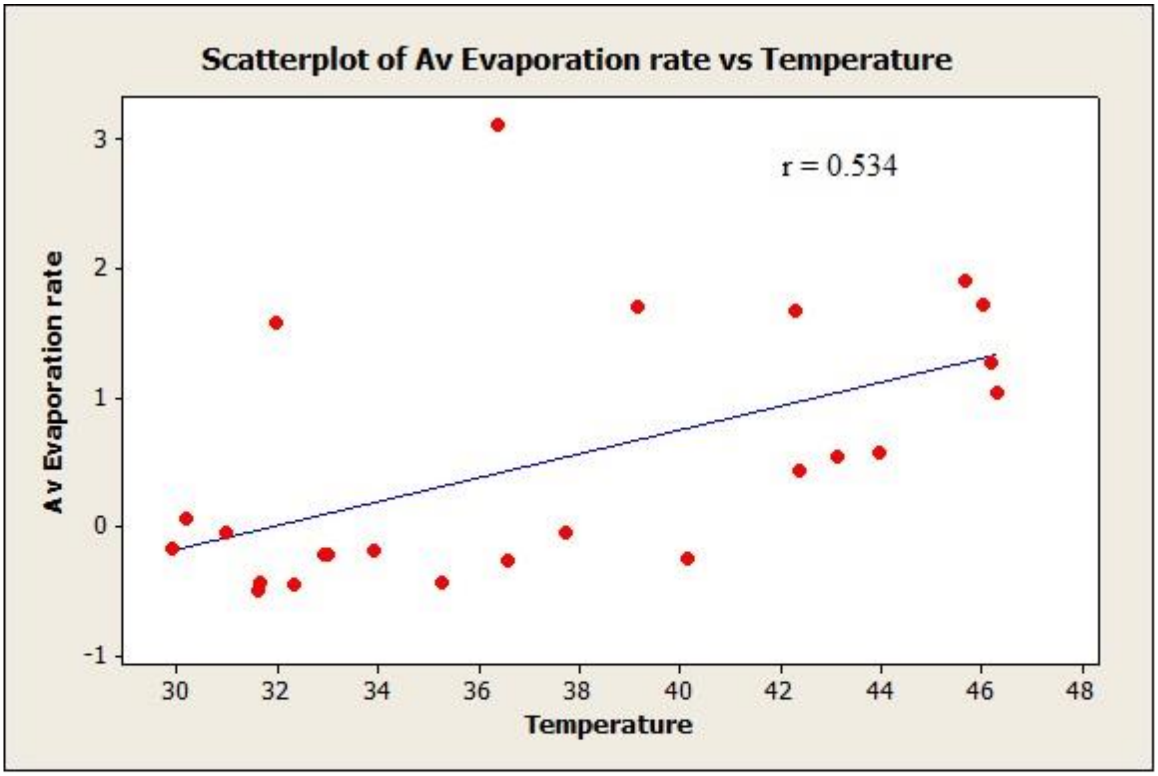

Scatterplot of Av Evaporation rate vs Temperature
r = 0.486
Av Evaporation rate
Temperature
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
30
32
34
36
38
40
42
44

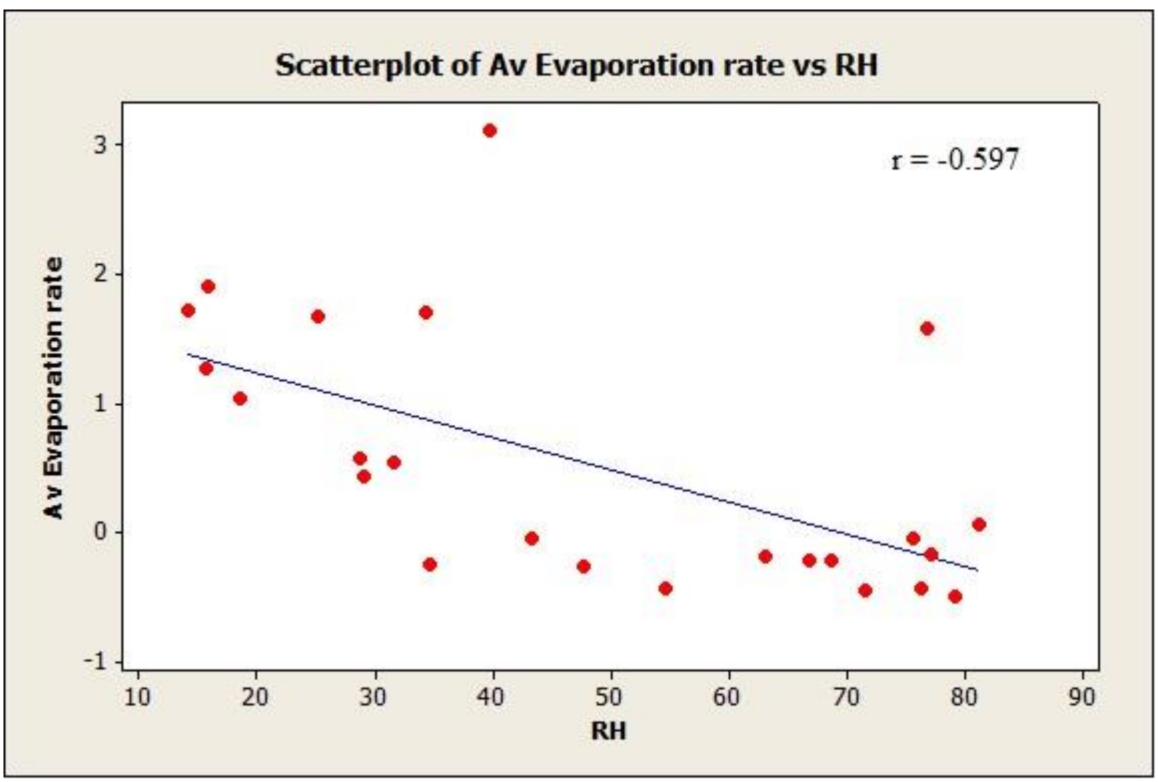

Scatterplot of Av Evaporation rate vs RH
r = -0.398
Av Evaporation rate
RH
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
20
30
40
50
60
70
80

Summer season: 28/08/2015






Scatterplot of Av Evaporation rate vs Temperature
r = 0.534
Av Evaporation rate
Temperature
3
2
1
0
-1
30
32
34
36
38
40
42
44
46
48


Scatterplot of Av Evaporation rate vs RH
r = -0.597
Av Evaporation rate
RH
3
2
1
0
-1
10
20
30
40
50
60
70
80
90

Curriculum Vitae

Full Name : Matthew Armoh

Nationality : Ghana

Email : m.armoh@yahoo.co.uk

Address : P O Box GP20055 Accra, Ghana West Africa

Education and Qualification

2013 to 2015 **Master of Science: Environmental Science**

King Fahd University of Petroleum and Minerals (KFUPM) - Dhahran, Saudi Arabia

Title of thesis: Determination of Evaporation Rate in a Sabkha in the Eastern Province, Saudi Arabia

2008 to 2011 **Bachelor of Science: Environmental and Natural Resources Management**

Presbyterian University College - Abetifi-kwehu, Eastern Region, Ghana

- Dissertation thesis on the topic solid waste management and awareness of recycling among the inhabitants of Darkuman, Accra – Ghana

2011 **Certificate in Foundation Course in MS Project**

Techy Consult, Ghana

2001 to 2004 **Higher National Diploma (HND): Civil Engineering**

Cape Coast Polytechnic - Cape Coast, Central Region, Ghana

- Dissertation thesis on the topic solid waste management: a case study of Asankrangwa Town-Ghana

Workshop and Conferences

February 2014 **International Conference**

- Petro-Environment in Saudi Arabia

March 2007 **Workshop**

- Reduction of failure costs, Risk management and lessons learned by Koen Benders (Engineer) and Alex Velzen (Estimator) from Netherland

ACCOMPLISHMENT

Strategic Management

- Supervised and directed over 100 employees on 8100 m^2 parking plant for Wilmar Africa that was worth over 10 million US dollars in Accra-Ghana in 2012.
- Successfully completed a three number ten storey residential building complex worth over 30 million dollars as an engineer.

Work History

11/2014 to 11/2015	**Part time Job at Center for Environment & Water, Research Institute of KFUPM.** Sorting of benthic organisms and grain size analysis
02/2013 to 08/2013	**Acting Resident Engineer for Civil Works** Adamus Resources Limited (Australia Mining Company in Ghana) Teleku Bokazo Partial Resettlement Construction Project
01/2012 to 01/2013	**Project Manager** Atlantis Structures (Designing and Construction of Steel Structures) 8100 m^2 Parking Plant for Wilmar Africa in Tema Harbour.

03/2011 to 12/2012	**Site Engineer** PW Ghana Limited (Irish company) Polo Heights
01/2010 to 02/2011	**Works Engineer** Rom Consult Limited (Ghanaian company) Rehabilitation of Feeder Roads in the Akuapim South District.
11/2008 to 6/2009	**Project Engineer** J. Adom Ltd (Ghanaian company) LOT/PSI/ONSI/01: Site Clearing and Land Preparation, Internal Roads, On-site Drains and Associated Works
02/2006 to 11/2008	**Engineer** Interbeton BV (Netherlands Company) Rehabilitation of 50 km Sefwi-Wiawso- Benkyema Junction Road
01/2005 to 12/2005	**National Service Person** **P.W** Ghana Ltd **(Irish company)** Rehabilitation of 80 km Abuakwa-Bibiani Road Project

Publications

- Direct Determination of Evaporation Rate in Eastern Saudi Arabia (submitted to journal of soil and water conservation for publication)
- Correlation of evaporation with weather parameters in Eastern Saudi Arabia (submitted to journal of soil and water conservation for publication)