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Correlation between TDR and FDR Soil Moisture Measurements at Different Scales to Establish Water Availability at the South of the Yucatan Peninsula

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Additional information is available at the end of the chapter

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Abstract

The advantages that offer new techniques such as remote sensing to estimate soil moisture require local accurate measurements of this variable since these values are key to validate the estimated ones. The chapter analyses the performance to measure soil moisture using different sensors that correspond to different scales at the field. Sensors used were based on reflectometry, time and frequency, which were calibrated with gravimetric measurements. Additionally to have accurate soil moisture values, the idea is to have an operational system in a very complex ecosystem in order to see its influence to maintain the aguadas (small natural lagoons) at the south of the Yucatan Peninsula. These aguadas represent an important source of water in the region because the area presents shortage associated not only with the climate variation but also with high influence due to the type of soils (karst). Results demonstrated that the sensors tested were accurate particularly in the rainy season with some differences in the dry period, and also, the sensitivity of each device was determinant. Results will cover different areas from point to small regions (<4 km), since soil moisture data obtained could be extrapolated to different scales based on the climate, vegetation and type of soil, to compute the real water availability for the communities in the zone.

Keywords: soil moisture, DTR, FDR, aguadas, water availability

1. Introduction

Today, technological advances have favored a better understanding of the circumstances around natural phenomena, being necessary to explain, in order to comprehend the dynamic nature of the climate, all the interrelations of the atmosphere, and the terrestrial surface at determinate time and space. Nicholson [1] described that seasonal time scales define the dynamic predictability, which is explained by atmospheric fluctuations defined by internal and boundary forcing. For the internal forcing, short and medium scales are associated with mechanisms as flow instabilities, non-linear interactions, thermal and orographic forces, fluctuating zonal winds and tropical/extratropical interactions. Whereas boundary forcing could be associated to a lower boundary condition for heat and moisture fluxes related to external factors such as soil moisture, vegetation, sea-surface temperature, among others, this is also for example, soil moisture feedback on precipitation or quantifying the scales of heterogeneity in surface vegetation and soil, and their dependency with other variables as the leaf area distribution, topographical, and meteorological properties. Thus, in order to understand the different interaction process in the hydrological cycle, it will be necessary to establish the behaviour of parameters such as soil moisture at different levels of aggregation [2, 3]. For instance, on a global scale, soil moisture is important because it maintains a series of interactions with the climatic and terrestrial systems, by serving as a source of water for the atmosphere through evapotranspiration and about 60% of the amount of atmospheric water is returned to the Earth's surface in the form of precipitation [4]. As a regulator of the climate, soil moisture is linked to mass and energy cycles, affecting climatic components such as air temperature and precipitation, whose movements and disturbances presented in the atmosphere at different scales interact with the Earth surface generating heat exchange and, in consequence, supporting the stability of the air near the Earth's surface and its temperature [5]. At the basin scale, the soil moisture content is determined by the soil type and topographic configuration, and influences the partition of precipitation into infiltration and runoff and, therefore, exerts direct control over soil erosion and flooding. At the local scale, local patterns of infiltration and water flow in the soil could affect the surface water quality and groundwater [6]. This means, soil moisture is a variable that directly influences parameters such as precipitation, runoff, evapotranspiration, and infiltration since they depend on the water stored in the soil how defines the degree of modification of the water cycle parameters [5]. Under these terms, soil moisture can be understood as a relevant indicator of the alteration suffered by the climate of a given region due to the interactions with soil, vegetation and the atmosphere affecting directly plants water stress. Also, it is linked to other environmental disturbances such as solar radiation, albedo, surface temperature and water vapour gradients, which was mentioned to control the radiative fluxes between the surface and the atmosphere. This makes soil moisture to show a major complexity, since it has a synoptic condition establishing a two-way land-atmospheric interaction defining spatial patterns and temporal dynamics. Also, having information regarding soil moisture is complex due to its spatial and temporal variability; thus, having a continuous and complete database is difficult. In situ, precise measurements can be obtained but when trying to extrapolate them to a major scale, they are not reliable, which generates uncertainty when trying to use them directly to estimated parameters or in the use of hydrological models. The aim of this chapter is to analyse the database generated for SWC in a complex ecosystem using different methods under different latency and spatially in order to answer that (a) shortage periods could redefine water availability and (b) dielectric methods are a real SWC option in an ecosystem highly dynamic.

2. Soil moisture

Arnell [7] defined soil moisture as the amount of water stored in the non-saturated zone, where the soil is made of different layers or horizons (soil profile) each with different properties. These soil properties vary depending on the depth and type of rock that forms it, as well as the time at which the soil has developed and the processes that affect it. As the amount of water present in the soil layers depends on the variation of rainfall intensity and the degree of runoff or infiltration after a storm; areas with rainfall >1800 mm are considered wet, 700–1800 mm are wet-dry and <700 mm are dry. Also, loss of moisture in the soil can be as water vapour by evaporation, extraction of plant roots, transpiration or drainage in deeper layers, being the first two more significant during periods of drought [5, 8]. Within the soil, water presents a dynamic behaviour according to the potential water gradients dominated by hygroscopic and gravity for the saturated moisture content and, by capillarity under drier conditions. The hygroscopic soil moisture is defined as the amount of water that adheres to the surface of the soil particles forming a thin film; this humidity is not available for the root zone. Gravitational moisture is the amount of water that enters from the surface of the soil to the unsaturated zone in a vertical movement. Finally, capillary moisture is the amount of water available to the roots [9].

The state of soil moisture could be described in terms of the amount of water and the energy associated with the forces that hold the water in the soil. Both water content and water potential are related to a particular soil by the physical properties such as plant growth, soil temperature, chemical transport and ground water recharge. The amount of water is defined by water content, and the energy state of the water is the water potential. At this, the terrestrial water balance for a surface soil layer, which includes vegetation but not the lateral exchange between adjacent soil volumes, is expressed as:

$$\frac{dS}{dt} = P - E - R_s - R_g \quad (1)$$

where $\frac{dS}{dt}$ is the change of water content within a layer of soil, which considers soil moisture, surface water, ice and groundwater, P is precipitation, E is evapotranspiration, R_s is surface runoff and R_g is underground drainage. As soil moisture is not homogeneously distributed varying vertically and horizontally, it differs based on the soil volume being considered. Following this, the soil water content can be expressed based on its distribution in mass and volume; it is function of the apparent density. In the case of the volumetric water content, it is expressed in units of volume of water per volume of soil [$\text{m}^3 \text{m}^{-3}$], while for the content of gravimetric water, there is a relation between the mass of water per unit mass of dry soil [$\text{kg} \cdot \text{kg}^{-1}$] [4, 10].

Soil moisture (θ) is expressed as the ratio of the total volume of soil that is wet [7]:

$$\theta = \frac{V_w}{V_T} \quad (2)$$

where V_w is the wet volume and V_T is the volume of the soil both measured in cm^3 . In practice, only a fraction of the soil moisture is measured, which refers to a volume of soil. In the case of

the energy balance in a soil layer, the partition of energy between soil and air is influenced by the presence and order of magnitude of soil moisture, and it could be expressed as:

$$\frac{dH}{dt} = R_n - \lambda E - SH - G \quad (3)$$

where $\frac{dH}{dt}$ is the change of energy within a layer of soil, including vegetation, temperature and change of phases associated with aquifers as part of the water balance; R_n is net radiation, which considers the differences between short and long wave solar energy input and output; SH is the sensitive heat flow; and G is the soil energy flow from deep layers of soil to the surface. Here, soil water potential is an expression of the energy state of water in soil and must be known or estimated to describe water fluxes. The last means the movement of water that occurs within the soil profile, between the soil and plant roots, and between the soil and the atmosphere. This movement throughout the soil is dependent on energy gradients, which includes adhesive and cohesive forces. The magnitude of the forces depends on texture and the physical-chemical properties of the soil solid matter. The differences in water potential between different soil positions cause the water to flow in it, moving from the points where the potential is greatest to those where it is least [11]. The saturated zone corresponds to the surface hydrostatic pressure that is equal to the atmospheric pressure. In the unsaturated zone, the volume occupied by the pores is filled with water and air including the area that starts at the surface of the soil and limits with the saturation zone where the water is suspended by capillary forces. As soil moisture is in the unsaturated zone, it is related to parameters such as field capacity (CC), maximum retention, percentage of permanent humidity, hygroscopic coefficient, permanent wilting point (PMP), soil tension, evapotranspiration, among others [12]. The CC is defined as the amount of water that can be retained by the soil against the outside of gravity, whereas the PMP is the amount of moisture that is not enough to stop the wilting of the vegetation.

2.1. Soil moisture measurements

There are different methodologies to measure soil water content (SWC) at the different scales: local, field, basin, and regional and global scale. Also, the transitional zone between each scale could be monitored in terms of having a better description of the condition in the area. However, one restriction related to the SWC measurement in large scales is the installation of the instruments along the study site in contact with the soil, since they need supervision and maintenance. Generally, SWC can be measured directly or indirectly. In the first case, the amount of water in the soil is determined physically, by measuring its weight as a fraction of the total soil weight by a thermalgravimetric method [13]. Some errors (bias), as well as imprecisions (larger variance), could occur when volumetric water content is calculated using an assumed bulk density or one measured elsewhere or at another time [14]. Additionally, to the direct measurement of SWC obtained, other advantages are the simple of the equipment required and that it is used as a standard method useful for the construction of calibration curves for other instruments. The main disadvantage of them is related to its destructive nature since the soil sample is removed from the field, and in consequence, the medium is destroyed and disturbs the soil profile; thus, no repetitive observations should be

made. Consequently, there are very large temporary resolutions for extensive measurement networks. Also, it is a time-consuming and impractical way of measuring SWC in large scales [13, 15]. In the second case, the indirect methods estimate the humidity present in the soil by measuring another variable affected by the SWC; thus, any changes observed for this variable represent a change in SWC [15]. This type of measurement could also be sub-divided as in situ and remote methods. In in situ measurements, the instrument registered the variable affected by SWC in direct contact with the ground, whereas in the remote case, instruments are not in contact with the ground, and in fact, instruments are ported in satellite, aeroplanes, or other aerial equipment. In any case, they need to be calibrated through the generation of calibration curves using as base the gravimetric SWC.

There are several indirect in situ methods to estimate soil moisture; one of them is the volumetric. This method determines the volumetric moisture of the soil, and some examples are neutron moderation, nuclear magnetic resonance (NMR), and dielectric. The last one measures the ability of a substance to hold the charge (dielectric permittivity). The dielectric permittivity or constant of the soil determines the speed with which an electromagnetic signal is propagated within the soil. They are based on the principle of reflectometry in various domains such as time and frequency [16–19]. The dielectric constant of the soil (K_a) is dependent on the moisture content and, to a lesser degree, on the texture, temperature of the soil, bulk soil and electrical conductivity (EC). Thus, it is required to consider this dependency in order to select not only the appropriate sensor to be used, but also, those sensor properties such as geometric and electronic features [19, 20]. The value of the soil dielectric constant (K_a) is characterised by the contribution of each of its components in the soil: water ($K_a \approx 81$), solid ($K_a = 4\text{--}16$) and air ($K_a = 1$), and it can be affected by temperature, salinity, presence of organic matter and shape and size of solid soil particles [21, 22]. These differences make the dielectric permittivity very sensitive to SWC variations [23, 24].

Time domain reflectometry (TDR) determined soil moisture by measuring the transit time of an electromagnetic pulse launched along a parallel metallic probe buried in the soil. It has been shown that the pulse travel time is proportional to the apparent dielectric constant of the soil [25]. Thus, the dissipation signal is proportional to the electrical conductivity of the soil mass; a higher content of water will provide a better propagation velocity [26]. For that water content estimation, once the instrument was calibrated, it can be related to the travel time or to the apparent dielectric permittivity (ϵ_a). The main advantages of this technology are its high accuracy, it can be automated, it provides simple measurements, and it is soil texture-, porosity-, temperature- and salinity independent [25]. For different types of soils, there is a direct relationship between the water content (θ) and the apparent dielectric constant (K_a). Some disadvantages are related to the cost of the equipment to install the sensors and to its limited applicability of the sensor in soils with conditions of high salinity or in soils with highly conductive clays [21].

Frequency domain reflectometry (FDR) provides a continuous measurement of the SWC, by means of an electromagnetic wave that is transmitted along probes and records the frequency of the reflected wave; it presents variations depending on the dielectric properties of the soil measured through the capacitance [13]. This is because the sensors work as part of a capacitor in which the water molecules are polarised and aligned in a dipolar electric field. The capacitor consists of two hollow cylindrical metal electrodes arranged coaxially but separated by

several millimetres with an insulating plastic, and the use of an electronic oscillator produces a sinusoidal waveform [27]. This allow the capacitor to interact with the soil outside of the tube; thus, the capacitance measured will be affected by the soil bulk electrical permittivity and the dipoles respond to the frequency of the electric field, which can determine the capacitance that leads to know the dielectric constant and, therefore, the estimation of SWC. The relationship between the frequency of oscillation and soil water content is inverse.

3. Study case

The Calakmul Biosphere Reserve (CBR) is located at the southeast of Campeche, in the municipality of Calakmul, bordered to the east by the state of Quintana Roo and to the south by the Republic of Guatemala. The natural protected area of Calakmul is characterised by sustaining the ecosystem for different species, as well as being used as a source for water supply for animals and humans. The CBR border coordinates are 19°15'N–90°10'E, 17°45'N–90°10'E, 19°15'N–89°15' and 17°45'N–89°15'E (**Figure 1**) [28, 29].

The CBR has a very particular climatology, edaphology and vegetation, representing a great contribution to the maintenance of the essential ecological processes, such as water and climate regimes and the ecological and evolutionary processes that determine the biodiversity of the area. Most of the land corresponds to a plateau, originated by the erosion of the limestone, little uneven, interrupted by small hills and micro-valleys. Most of the substrate is composed mainly of carbonated rock (CaCO_3) or limestone, and this type of substrate facilitates the filtration and underground transport of water. There are also regions that have more evaporites, rocks formed by the evaporation of marine waters (CaSO_4 mainly in the area), which

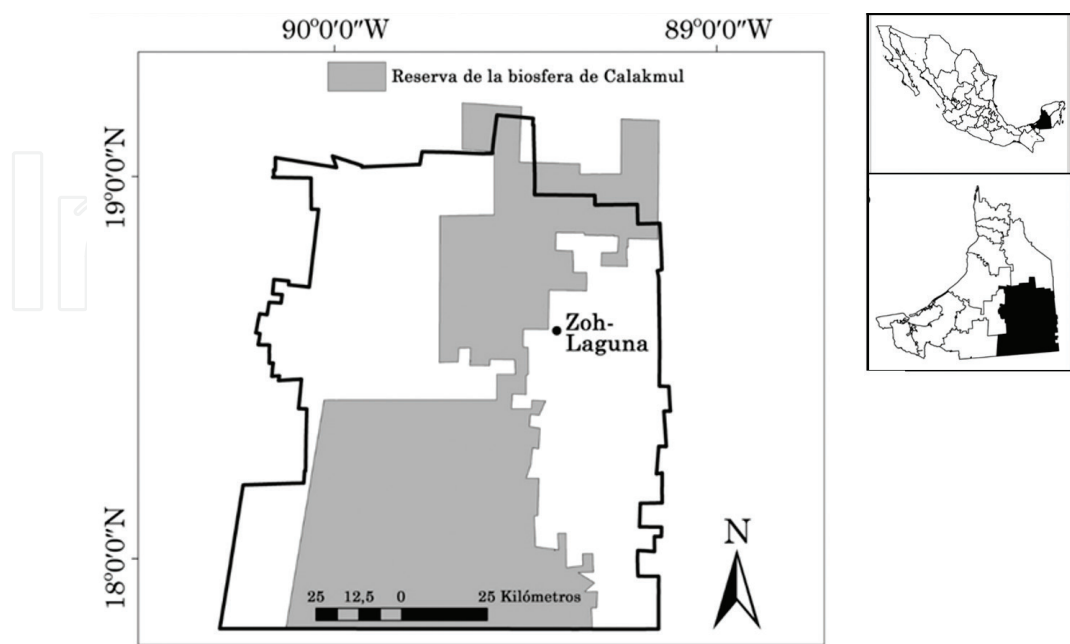


Figure 1. Location of the Calakmul Biosphere Reserve, Campeche. Source [29].

can be dissolved more easily, allowing faster erosion, and alluvium [30]. The composition of the soil allows the development of the karstic system, where water is filtered, dissolving the rock and creating underground tunnels where the liquid finally flows. These tunnels create a drainage system that feeds certain bodies of water located west and northwest of the Yucatan Peninsula, and this process favours the formation of cenotes, aguadas, wetlands, basins, caverns and springs [31].

The biodiversity contains ecosystems characterised by their great diversity, wealth and fragility. Vegetation corresponds to high jungle subperennifolia (25–50% of the trees drop their leaves), medium jungle subperennifolia, medium jungle subcaducifolia (50–75% of the trees lose their leaves), low jungle subperennifolia, savanna, aquatic vegetation and thorny scrub. One important aspect is that roots grow horizontally due to the karstic nature of the area [32–34]. The CBR is allocated in one of the hottest and wettest regions of Mexico. The climate in the CBR is warm and sub-humid with summer rainfall. The average annual precipitation in the region is 1092 mm. Rain is distributed in the months of May to October with 75% of the annual sheet, with an extension of this season until November. The months June to September are the ones observing more abundant precipitation with an average sheet from 135 to 184 mm. The dry season includes the months of December to April, during which the precipitation is less than 50 mm, and the month with the lowest precipitation is February, with an average of 33.9 mm. The average annual temperature is 24–28°C due to the vegetation that regulates it.

García et al. [35] indicated that as two slopes divide the Yucatan Peninsula: the Gulf of Mexico and the Caribbean, and the CBR is allocated in the intermedium area being subject to high scarcity. In addition, there are real water pressure in the surrounding area to use water for social development, which is manifested in the constant colonisation of the area and therefore in the opening of new crop and livestock sites. Virtually, all the rainwater infiltrates, which produces little or no runoff and the local rainfall is concentrated in small superficial storage called “aguadas,” which hardly maintain the liquid until the following rainy season. Although legally human activities are restricted in the CBR to a tolerant zone, it is being severely affected by irregular human settlements that eliminate the forest to induce changes in land use.

3.1. Selection of point measured sites

The total region was analysed applying first a regular 500 × 500-m grid resulting in systematic 50 sites distributed within the whole area. Then, a zigzag statistical method was used reducing the sample to 18 sites. The priority was to allocate an aguada with or without human impact and within a town to guarantee its maintenance, thus at the field, as some of them were inaccessible, the final sites were nine. The sites were distributed as: three in the northern zone (Refugio, Flores Magón and Modesto Ángel), three in the southern zone (Carlos A. Madrazo—two sites: La Ceiba and Corosal, and Ley de Fomento) and three in the archaeological zone (Ramonal, Bonfil and Heliport) of the CBR. In the case of Carlos A Madrazo, La Ceiba aguada was only analysed since Corosal presented eutrophication.

3.2. Instruments

A monitoring station was installed in the north of the Calakmul Biosphere Reserve in the town Modesto Angel (MA) and at the South close to Ley de Fomento town was an Automatic Weather Station [36]. Soil moisture was measured using the direct gravimetric method and also continuously using indirect methods based on reflectometry: time domain (TDR) and frequency domain (FDR). Additionally, other measured variables at this station were physical characteristics of the soil, rainfall, air temperature, and relative humidity.

TDR sensors used in this study are CS616 (CS) from Campbell placed at 2.5, 5, 10, 20 and 30 cm with a latency of every 20 min. The calibration of the CS616 sensors was done according to the manufacturer (ref). In particular, these sensors use linear or quadratic equations to estimate the volumetric water content, depending on the expected range of water content and accuracy requirements. The accuracy reported for these probes is ± 2.5 volumetric water content. Measurements of CS sensors are stored in a Campbell CR800 datalogger, which records the data and can then be accessed via peripheral communications using a software interface provided by the company.

FDR sensors tested were Decagon EC-5 and Diviner 2000. Decagon EC-5 (DEC) sensors measure the dielectric constant operates at 70 MHz minimising salinity and texture effects. An advantage is that they provide an accurate sensor reading in almost any soil. Factory calibrations are provided for mineral soils, potting soil and others. The design and measurement frequency allows measurement of volumetric water content (VWC) [37]. The EC-5 sensors were connected by a 3.5-mm stereo jack plug to the Generation I THHINK datalogger collecting data every 20 min [38]. Diviner 2000 [39] is a multi-sensor capacitance probe used to determine soil water content by measuring the frequency change induced by the changing permittivity of the soil permeated by the fringing fields of the capacitor sensor. The probe consists of multiple sensors located at various depths installed in specific access tubes. A high-frequency electric field is created around each sensor (sphere of influence). The sphere of influence is every 10 cm, thus readings are taken in 10 cm depth intervals in the access tube; this allows the sphere of influence for each reading to sample a separate soil horizon. Volumetric soils water measurements are done in real time and the readings are converted to soil moisture using a calibration equation. This universal calibration equation is independent of soil temperature but could be affected by salinity. One advantage is that the access tube is installed with minimum disruption to the soil profile. The accuracy level is better than 99% of the volumetric soil water content (θ_v) that is taken instantaneously with excellent repeatability. An access tube was allocated at each of the nine test sites into the soil to different depths until 150 cm, and in some cases just above the water table. Readings were registered every 3 days the first weeks and then every 15 days. Results were used applying the calibration equation in order to have volumetric water content and to compare with the gravimetric, TDR, and FDR (Decagon) methods.

3.3. Soil moisture measurement procedure

Field campaigns were performed in September 2012, February and August 2013, May and September-October 2014 and June 2015. Dates correspond to the rainy and dry periods, to

collect representative data of each of them and in this way observe the distribution of soil moisture in different climatic regimes. The rainy season occurs between the months of June and July, until October and the dry season between December and April or May. During the visits to the study area, the physical condition of the equipment and the environment was recorded.

Fieldwork consisted of the installation of equipment, acquisition of soil moisture, vegetation, and meteorological data, which was done every fortnight, period corresponding to the data collection with the diviner sensor. Soil samples were taken for the measurement of gravimetric humidity. Soil samples were of approximately 300 g and obtained in each of the eight sites, and the following data were obtained: soil moisture and physical properties (textural fraction, bulk density, permanent wilting point (PMP), field capacity (CC), electrical conductivity and pH). Subsequently, samples of 100 g were taken every 10 cm in the soil profile to perform the gravimetric procedure and define the amount of gravimetric water content of each of the study sites. The physical characteristics of the soil samples such as bulk density, PWP and CC, electrical conductivity and pH were carried out in the National Forestry, Agriculture and Livestock Research Institute (INIFAP) and in the Soils and Plants Laboratory of the Academic Division of Agricultural Sciences of the Autonomous Juarez University of Tabasco. Once the humidity values of the indirect measurements in situ have been validated, the analysis of their spatial and temporal distribution is carried out making use of geographic information systems and other computer programs for the graphic modelling of the data.

The vertical analysis allows the visualisation of the fluctuation of soil moisture for each site, taking into account the relationship with the textural fraction of the soil. The results of this analysis permit the understanding of the mechanism of infiltration, drainage and saturation in the first meters of the soil layer. The temporal resolution to obtain one measurement varies for each technique. The highest temporal resolution can be provided by the TDR and FDR-Decagon (FDR_Dec) with one observation for every 20 min, the FDR-Diviner 2000 (FDR-Div) can record one measurement for every week, and the gravimetric method can be used for every 4 months. This indicates that one can have more frequent TDR and FDR-Dec observations than the other FDR techniques.

Once measurements with sufficient support at the local scale are obtained and the spatial and temporal stability are established, they can be scaled. Scaling up soil moisture is divided into two categories: small scale or less than 20 km², affected by variations in soil characteristics, heterogeneity and changes in soil cover; and regional scale, from 50 to 400 km², impacted by meteorological and climatological effects such as precipitation or solar radiation [3]. In this paper, a small scale is presented since the radius of influence is less than 50 km.

3.4. Soil moisture comparison

In order to estimate the accuracy between the three soil moisture methods, a comparison analysis was performed. Statistical indicators such as the coefficient of determination (R^2), the root mean square error (RMSE), relative error, mean bias error (MBE) and normalised root mean square error (NRMSE) were applied [40].

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^N (D_i - Obs_i)^2} \quad (4)$$

where subscripts D_i is the output of the devices (FDR and TDR readings) and Obs_i is the observed gravimetric soil moisture. $RMSE$ minimum value is zero under the hypothetical situation that the model is capable of perfect (long-term) readings of the system, and there are no data errors being small values desirable. Mean bias error (MBE) measures the average magnitude of the errors in a set of readings. It is the average over the test sample of the absolute differences between prediction and actual observations having the differences an equal weight. According to [41] an acceptable value for volumetric soil moisture is $0.04 \text{ m}^3 \text{ m}^{-3}$.

4. Results and discussion

The results present the climatic variations of the studied area that make it a complex system to analyse the variability of soil moisture in the sampling sites. The test of the TDR and FDR systems can offer more than the evaluation of the accuracy of each system if they are used as well as a complementary study. Also, a datalogger was tested to work in a complex environment in order to guarantee a constant data register in order to monitor water requirements and its supply for the different uses in the area.

4.1. Climatic data

As it was mentioned, the climate that predominates in the region is warm humid and warm sub-humid, with an average maximum temperature of 36°C during the months of May and June and average minimum temperature of 18°C during January. However, in some occasions during August, the so-called *dog days* is presented, which is the year period where heat

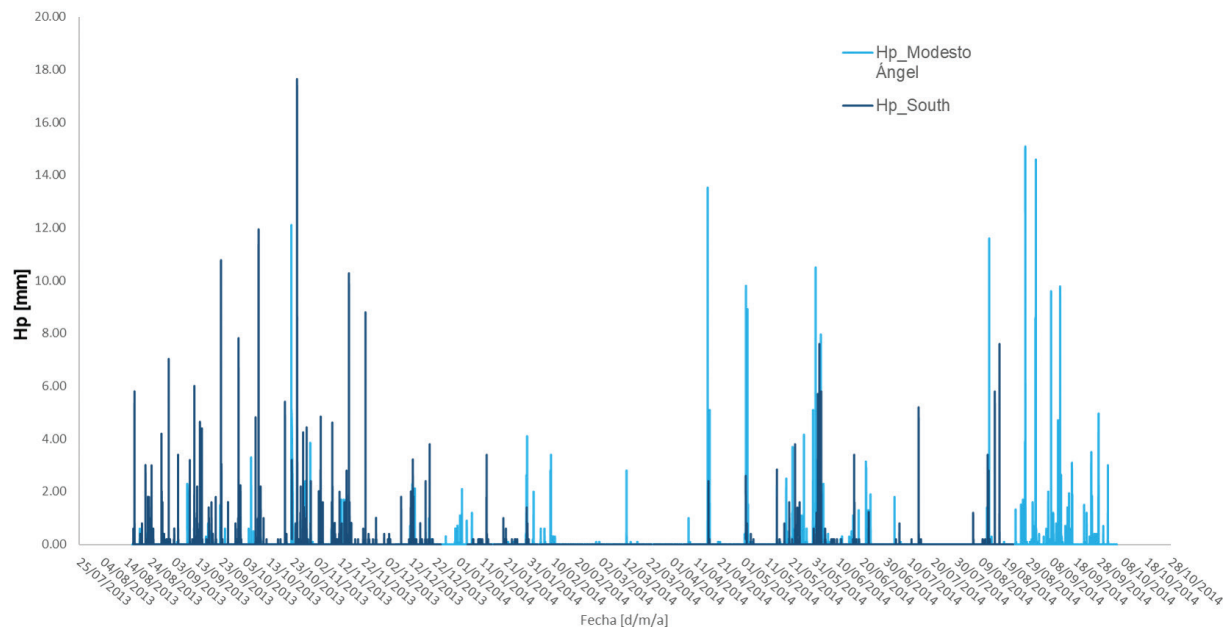


Figure 2. Distribution of head of precipitation recorded from August 2013 to October 2014 in the Modesto Ángel station and the Automatic Weather Station (EMA)-CONANP station at the north and south of the study of the CBR, respectively.

is severe and drought is taking place. According to [30], the rainy season occurs during the middle of summer until autumn, although it was observed in **Figure 2** that occurs from July to February. During the winter, the tropical storms have influence on the generation of precipitations and also they cause a decrease of the temperature until reaching 10°C [30].

Figure 2 shows the rainfall distribution in the study area. Although the north area seems more affected by the winter rainfall, there is more rain in the south part of the CBR. Besides, in the dry season from April to July, there was some rainfall at the north area. This variability favoured the presence of humidity maintaining the diversity of vegetation species in both areas. The archaeological zone is considered at the south.

4.2. Soil characteristics

The characterisation of the soil is based on the measurement of its texture on the surface and some physical parameters such as electric conductivity, pH, soil moisture, % of saturation, field capacity (CC) and permanent wilt point (PWP) (see **Table 1**). CC is the largest amount of water that this type of soil will retain under conditions of complete humidity $CC = (\% \text{clay}) * a + (\% \text{silt}) * b + (\% \text{sand}) * c$, and the PWP is the minimum water content where the plants usually die; for each of the sampling soils $PWP = \frac{CC}{1.84}$, the coefficients a, b and c are determined for each region and type of floor, and in this case, the coefficients used are $a = 0.555$, $b = 0.187$ and $c = 0.027$ [42].

Modesto Ángel where the three techniques were implemented has a more constant type of soil: the first 5 cm is a sandy soil, from 10 to 80 cm is Frank and more than 90 cm is loamy clay. In all the other sites, soil type varies as the depth increases.

Site	Sand	Clay	Silt	Type of soil	% Humidity	% Saturation	CC	PWP	pH	Electric conductivity
Flores Magón	53.28	15.08	31.64	Sandy loam	37.04	60.0	45.0	23.6	7.38	0.291
Refugio	12.00	58.56	29.44	Clayish	37.04	104.0	78.0	41.0	6.42	0.251
Modesto Ángel	31.84	31.80	36.36	Frank	30.77	102.2	76.7	40.2	7.23	0.361
Ley Fomento	26.20	42.16	31.64	Clay	38.34	107.0	80.3	42.1	6.57	0.551
La Ceiba	31.84	27.80	40.36	Frank	39.13	120.0	90.0	47.3	7.93	1.101
Ramonal	74.40	7.24	18.36	Sandy loam	35.71	65.8	49.4	25.9	6.80	0.797
Bonfil	30.76	31.24	38.00	loamy sandy	37.93	125.0	93.8	49.2	6.84	0.564
Helipuerto	32.20	25.80	42.00	loamy sandy	32.38	120.2	90.2	47.3	5.43	0.024

Table 1. Soil characteristics measured at 10 cm depth in the sites.

4.3. Soil moisture analysis

Soil moisture instruments tested report changes in time or frequency related indirectly to the dielectric permittivity to the volumetric water contents. Results are presented per site and per type of technique, and this means that TDR were analysed with Campbell sensors (TDR_Campbell), FDR using the Decagon sensors (FDR_Dec) and FDR using Diviner 2000 (FDR_Div). A specific analysis for the field conditions under the different operating sensors was not necessary since there were the same conditions at the sites (Modesto Ángel with three methods and the other two sites). Individual calibrations per depth offer equations that improve the sensor performance. Then all together were compared in order to know the sensitivity of each one.

4.3.1. FDR and TDR devices at the Modesto Ángel station

In the Modesto Ángel station, the three devices to measure soil moisture were installed: TDR_CS, FDR_Dec and FDR_Div. TDR_CS calibration process includes a first analysis using data collected from the datalogger with the default equations of the device. Both lineal and quadratic equations were tested founding that the lineal equation offered better results than the quadratic one with RE of 0.22 and 0.41, respectively. Secondly, the calibration using the gravimetric data measured at the field was done in terms of volumetric water moisture, θ_{gv} . The gravimetric measurements were 10 samples per site from 2012 to 2013 years, at 2.4, 5, 10, 20 30 cm depth. Six more gravimetric samples per site were measured during 2014–2015 to confirm the reliability of the calibration for a different weather, soil and vegetation conditions. The TDR_CS provides a R^2 of 0.96, with RMSE, MBE and RE values of $0.101 \text{ cm}^3 \text{ cm}^{-3}$, $0.107 \text{ cm}^3 \text{ cm}^{-3}$ and 0.12, respectively. The major deviation was observed at the 2.5 and 5 cm, this is because the place where the sensors were installed was not disturbed but the place where the sample was taken, even if it was close to the area of the station, was more susceptible to the surface soil conditions at this specific time. In the case of the FDR_Dec, R^2 once calibrated the readings was 0.90 with RMSE, MBE and RE values of $0.18 \text{ cm}^3 \text{ cm}^{-3}$, $0.407 \text{ cm}^3 \text{ cm}^{-3}$ and 0.083, respectively. For FDR_Div, results showed that the first 30 cm have the same texture; thus, a calibration equation was obtained for it with an R^2 of 0.86, RMSE $0.086 \text{ cm}^3 \text{ cm}^{-3}$, MBE $0.079 \text{ cm}^3 \text{ cm}^{-3}$ and RE 0.069. FDR_Div was the best device, but it is important to mention that only three depths were tested at 10, 20 and 30 cm. Between TDR_CS and FDR_Dec, it is quite difficult to analyse since results are not conclusive, but TDR_CS could be expected to provide a more consistent value. This is because Decagon devices demonstrated to be more sensible to the weather (see temperature and precipitation results) and to soil conditions at the time of the sampling. However, the RE is major for TDR_CS. Despite the previous results, the calibration equations were applied to 400 daily θ_s records with a latency of 20 min for the 2012–2015 period for both TDR_CS and FDR_Dec. **Figure 3** plots the behaviour of the devices at a 10 cm depth for 2013–2014.

As one can observe, there is a good agreement between TDR_CS and FDR_Dec, following a similar pattern taking into account the accuracy of each device. However, there is a major response of the Decagon sensor when rain is presented, being evident an increase in some

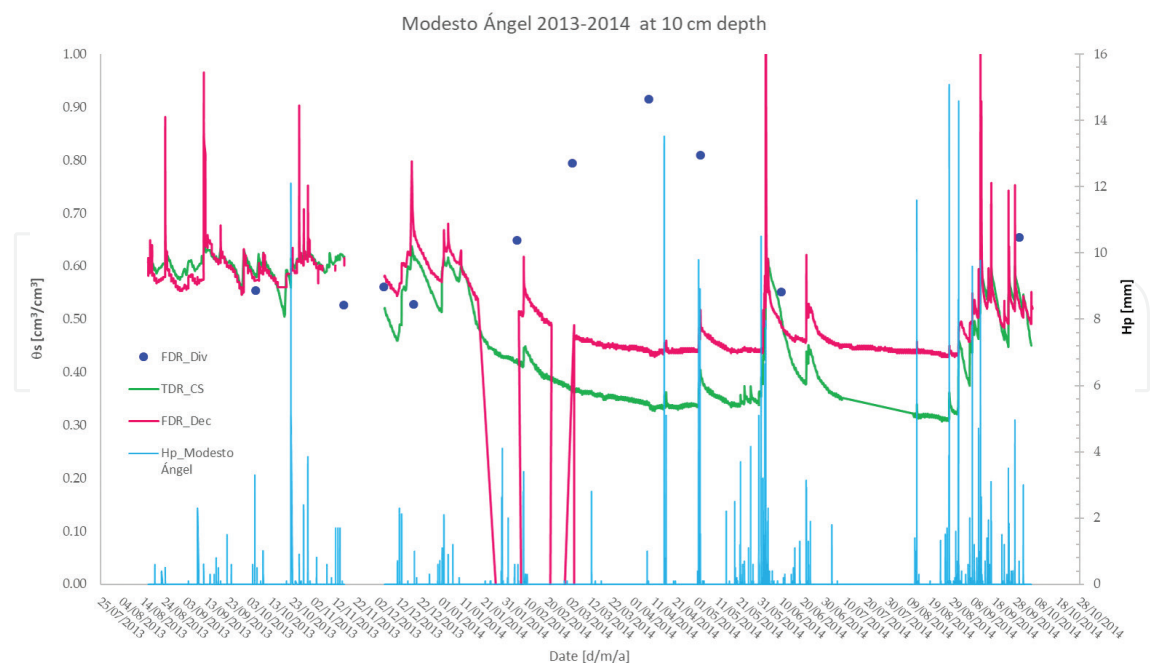


Figure 3. 10 cm depth soil moisture values from July 2013 to October 2014 at the Modesto Ángel station.

cases until reaching almost 1.0 of water content. The maximum difference perceived from January to August 2014 was close to 30%. Looking at the FDR system, it is a major agreement for both Decagon and Diviner 2000, although during the dry period, FDR_Div overestimated more than 50% the soil moisture. The gravimetric measurements for October 31, 2013 and May 05, 2014 were also included in the plot demonstrating that TDR_CS is closer than FDR_Dec.

The life of the experimental THINNK datalogger without change of battery was from 2013 to 2015. In the case of the Campbell datalogger, it was required to change the battery since the extreme conditions at the field lowered its energy every 6 or 8 months. Also, it was necessary to protect the battery of the Campbell datalogger, whereas in the THINNK, one could be attached to a tree without more protection.

4.3.2. FDR diviner for the other sampling sites

The Diviner 2000 allows monitoring different areas once the accessed pipe in each site was installed. Thus, eight aguadas were monitored; Carlos A Madrazo was analysed at the La Ceiba site only. More than 30 readings were registered in the period of 2012–2015, as well as several gravimetric analyses were performed a less two per year. As soil moisture is function of the texture along the profile, this implicates different water aggregation and, in consequence, a different behaviour. For that, along the profile, one could have more than one calibration equations in order to represent what actually happened to soil moisture in the profile. For each site, a graph was developed as shown in **Figure 4** for the Modesto Ángel site with 120 cm depth. For this place, three equations were established:

(a) 10–30 cm: $y = 425.6 x^{-0.597}; R^2 = 0.93$ (5)

(b) 40–80 cm: $y = 37.33 x^{0.123}; R^2 = 0.02$ (6)

(c) 90–110 cm: $y = 136.8 x^{0.308}; R^2 = 0.35$ (7)

The equation proposals agree with the findings of [43] who defined two equations according to the texture: one group for fields with heavier soils where clay content was >40% and other group with coarser textured fields with clay content <40%. Looking at Eq. (6) for the second

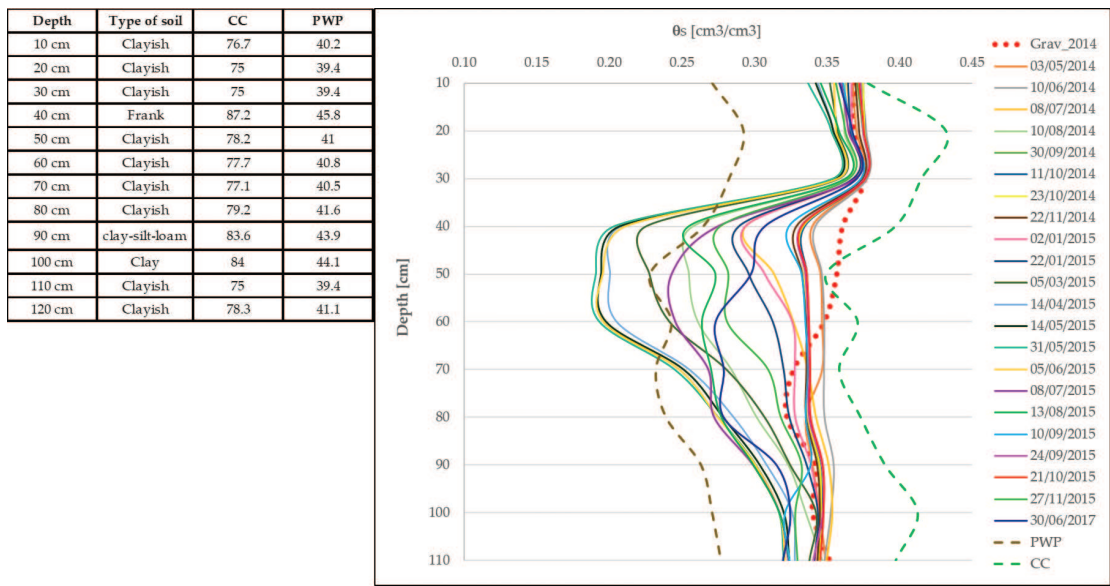


Figure 4. The texture and field capacity (CC) and permanent wilt point (PWP) through the profile of the Modesto Ángel site.

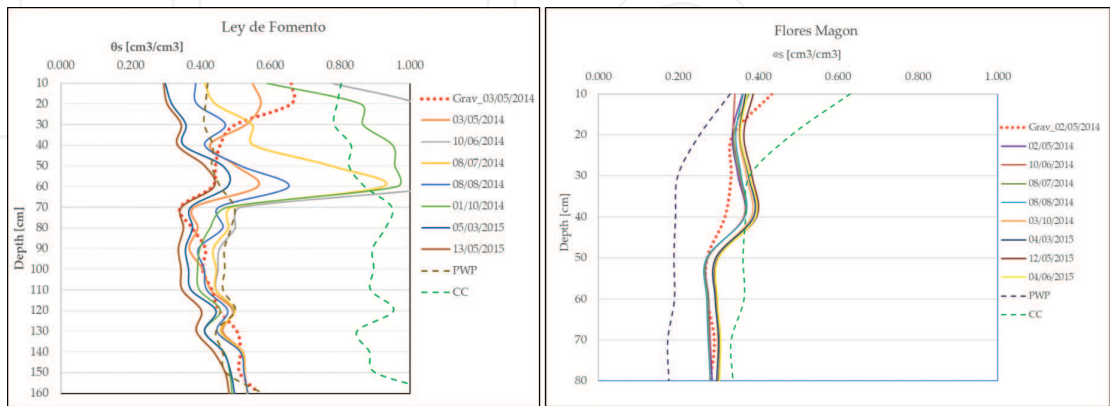


Figure 5. Soil moisture profile for Ley the Fomento and Flores Magón sites.

group shows a very poor correlation, there is a tendency towards the PWP, and in some cases, it seems that water was not available from the 40–80 cm depth. For these specific cases, FDR_Div values correspond to late March to mid-June of 2015 where a drought also took place. In addition, the drop between these depths was evident in the gravimetric measurements, although it was not in such an accentuated way. This could be interpreted as a combined effect of soil properties in these strata, the horizontal development of vegetation root systems and the dielectrical methods characteristics in that range of soil moisture. However, this requires a further research.

One interesting factor resulted from the analysis at the sites of Flores Magón and Ley de Fomento was that both FDR_Div and the gravimetric carried out the same day with less than 30 min of difference had not been similitude within the first 50 cm depth (**Figure 5**). In these cases, it was assumed that the disturbing at the moment of sampling in the gravimetric method was significant to obtain different values. Also, in these sites, the aguadas were extended and the types of soil were clayish in Ley de Fomento, and frank and clay in Flores Magón, conditions that change the water content in the soil.

4.4. Water availability

Although one knows from [35] that the approximated number of the aguadas in the CBR was 1353 and the majority was in the North with 868 and 485 in the South, with an approximate density of 1.87 aguadas per hectare. One does not know the rate of increment in the number of aguadas, in particular for the artificial ones since they are the only source of water during the dry season. Also, the area of the aguadas is variable from some small as one observed in La Ceiba at Carlos A Madrazo to many hectares such as Flores Magón. In terms of estimation of the water availability, it can be considered that the aguadas are generically of the same size; thus, the contribution area (basin) of each aguada can be calculated within the CBR as the relation between the total area of 724,000 ha and the total aguadas (1353), so here are 535 ha of contribution per aguada.

To estimate the water availability based on the real soil moisture during the year, it is necessary to review the distribution in the horizontal line at the different profile. Thus still, there is work to do. Until now, the work done has established the variation along the profile finding some constant values after the 50 cm depth that could be related to the water table that keep water in some aguadas during the year although at its minimum value, in particular those less impacted by humans.

One already knows the average rainfall, and the evapotranspiration could also be estimated moreover if one consider that practically all the water infiltrates (probably 92.7%), which results in little runoff (7.3%) that is concentrated in natural aguadas. However, these data are not enough since soil moisture needs to be considered as the water storage capacity that can be removed by evapotranspiration is the function of the type of vegetation and the depth of the root zone. But, in the study area, root depths are quite smaller growing horizontally rather than vertically. This demands a major study in the horizontal line in order to compute reliable water balances.

5. Conclusions

Over the studied period, the soil moisture values at the soil profile varied in all the sites sampled. There are some similitudes grouping the areas in those sites in the north, south and in the archaeological zone. However, there are not only different soil conditions, but also vegetation, climate and topography differences. Vegetation varies from low to middle jungle with roots growing horizontally. Climate varies dividing the area in quadrants with important temperature and precipitation variations.

Soil moisture result using TDR_CS and FDR_Dec sensor in a datalogger systems was more similar after 10 cm depth. At 2.5 and 5 cm, there is a high variability mainly associated to the actual conditions in the soil surface. However, the seasonal effect under soil moisture demonstrated that FDR_Dec was very sensitive in periods of high rainfall and overestimated soil moisture during the dry season. Something similar happened using the FDR_Div sensors, which overestimated significantly in the dry season. The best result was provided by the CS616 Campbell sensors for over the whole study period. Looking at the soil moisture values along the depth profile, it was effectively probed that when it has a heterogeneous soil in the unsaturated zone, texture is determinant. If one did not consider these, a wrong calibration could be obtained and soil moisture values would have nonsense. Another important aspect to be considered is the possible disturbance of the soil at the moment of the sampling for the gravimetric method. Also, raw values from the different devices need to be calibrated; otherwise, any soil moisture value could be obtained. Even if the calibration was not appropriate under dry conditions, it is necessary to consider the karstic nature of the soil in the area; thus, infiltration could occur at different deep levels.

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