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ORIGINAL ARTICLE

The feasibility of using variable rate water application under a central pivot irrigation system

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Abstract The purpose of this paper was to assess the feasibility and significance of applying spatially variable irrigation under a central pivot system at the Federal German Agricultural Research Center, Braunschweig, Germany. The assessment was based on soil moisture holding capacity, soil depth variation and root development. Soil texture analysis was carried out by sampling on a 60 meter grid. The German Agro-Meteorological Model was applied to simulate the water balance in the crop-soil-atmosphere system for the growing season 2003/4. The research findings are presented in terms of six scenarios: 20, 30, 40 mm water application depths per irrigation under both variable rate application and uniform application. The comparison revealed that the loss of water was higher for the uniform application scenarios than that for the variable rate application (VRA) scenarios for the applications of 20 and 30 mm. The VRA scenario of 20 mm water application was found out to be the best option for water conservation.

Keywords Central pivot · Mapping soil variation · Precision irrigation · Variable rate irrigation

1. Introduction

Water is a precious commodity that needs to be rationed and efficiently applied in agriculture which is the biggest consumer of fresh water (UN Report, 2003). According to Buchleiter et al. (1996), over-irrigation wastes natural resources and power and inflicts damage on

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the environment through the leaching of nutrients causing contamination to the ground water. Under-irrigation, on the other hand, can cause water stress and reduction in yield productivity (Nijbroek et al., 2003). Furthermore, as Savabi (2001) observes, insufficient water in the root zone hinders nutrient uptake and ultimately decreases the rate of photosynthesis whereas excessive water in the root zone limits oxygen availability resulting in an anaerobic condition. To cope with these problems, several studies proposed solutions using variable rate application (VRA) and scheduling based on simulation models (Pereira, 1999). Nijbroek (2003) have implemented the site specific management zone techniques to address spatial variability of soil properties that influence soil water holding limits and that is a major source of non-uniformity in crop management. An irrigation system should thus consider several parameters: soil, plant, weather and water delivering equipment. As evident from research in soil spatial variability, soil texture is heterogeneous across the field (Nijbroek 2003). Furthermore, it determines the scope of the available water (Duke 1992).

Irrigation simulation models can help simulate the real world and improve irrigation performance; thus saving water and increasing farm productivity (Clemmens et al., 1999; Dechmi et al., 2003). Boken et al., (2004) demonstrated that these models are also used to integrate knowledge about soil, climate, crops and management for making better management irrigation decisions. Simulation models allow the system operator to run the model several times under specified environmental conditions in order to determine the best method of controlling or managing the irrigation process. According to Sadler et al. (2000), the growth models developed do not have as one of their objectives the process of describing within-field variations. In the context of the present work, the model was operated 21 times in order to incorporate site specific soil texture spatial variations. Few studies have attempted to compare a field under uniform application (UA) with a field under VRA in order to assess the best irrigation management options and the significance of saving water.

Precision irrigation (PI) is defined as the timely and accurate water application in accordance with the spatial and temporal soil properties and in response to the plant demand during the different growth stages. It is a subcomponent of precision agriculture which can be defined as the management of spatial and temporal variability in a subfield to improve economic returns and to reduce the environmental impact. PI requires specific information on mapping the geo-referenced soil variations, the metrological data and the high-tech water application systems that can be adjusted to the specific operation tasks and the accurate positioning systems.

Optimal water application is the application of water to meet the plant requirements which include the optimal plant irrigation depth and the application of water for purposes other than irrigating the plants. The optimal irrigation depth (OID) changes due to changes in the soil moisture holding capacity across the field. Thus, determining the appropriate depth of water application for management purposes minimizes both yield losses and water quality degradation (Duke et al., 1992). The OID is determined by the plant growth stage and the soil type.

The feasibility of applying VRA rather than UA on a specific field at the Federal Germany Research Centre (FAL) was investigated in the present study. The implementation of VRA was carried out via the central pivot (CP) irrigation system. The amount of water and its spatial distribution under the UA was compared with that under VRA in order to assess the best irrigation management option that could promote water conservation, sustain production, maintain natural resources, minimize variation in yields and optimize the input to the farming system.

2. Material and methods

2.1. The grids and the soil sampling

The field study was carried out in 2004 in south west Braunschweig Germany on a 7.07 ha field; longitude 10.440 E; latitude 52.300 N (WGS 84) and elevation 79 m. The field slope was mapped to determine the potential of run-off. RTK/GPS readings were taken by using Trimble SSI 4000 for 121 points on a grid of 30 m to generate an altitude map. In order to identify field variation, several site measurements were taken to map the most important features of soil water balance and irrigation requirements. The soil survey included 21 sampling locations. Soil texture analysis was conducted for each sample at two depths: 0–30 and 30–70 cm. On the upper layer, a comprehensive soil texture analysis for the sand, clay and silt was carried out since that layer was the one mostly affected by sprayed irrigation and it accommodated a greater number of the roots whereas on the lower layer, an average of four texture sample measurements (clay 4,3%, silt 20,1% and sand 75,6%) were fed into the model; only the sand percentage was sampled for each of the 21 sampling points. Further soil analyses were conducted for mapping salt and the soil moisture content. Volumetric measurements for soil water content were determined by using gravimetric oven dry samples (105 degree) measurements multiplied by soil bulk density. Variation in the upper layer soil depth and available soil water capacity were noted.

2.2. The simulation model

The AMBAV which is part of a complex agro-meteorological toolbox of the German Weather Service is a dynamic model. It calculates separately soil evaporation, transpiration, effective precipitation (if greater than 2 mm), interception and the soil water balance in the crop-soil-system under 5 phenological development stages during the growing season of the sugar beet. It uses Penman-Monteith equation (Monteith, 1965) for calculating potential evapotranspiration defined as the maximum water losses by evaporation and transpiration. Real evapotranspiration is calculated from reference grass based on a lysometer. The model was designed to produce recommendations on irrigation amounts and scheduling for different soil types based on hourly weather data from the meteorological station network (Löpmeier, 1994; Braden, 1995). The data incorporated in the model consisted of the soil bulk density for the two layers, the soil texture, the seeding date, the harvesting date and the growth stages. The data were based on single measurements for each of the parameters above at each of the 21 sampling locations except for the soil bulk density which was measured at three locations. Soil water dynamics were simulated using a mechanistic model based on the Richards Equation (Richards, 1931). Soil water characteristics and hydraulic conductivity functions are described by pedo-transfer functions using a mathematical model (Vereecken et al., 1989, 1990).

The AMBAV model was used to simulate the sugar beet growth on daily bases for the 21 soil sampling locations. The root development was simulated for each 10 cm layer depth. The soil water balance was also simulated for the 21 soil sampling sites on a hourly basis. The model simulated the water flax for each 10 cm depth. In the field under study, there was no pest infection and the sugar beet was not exposed to any nutrient deficit. Therefore, it was assumed that the plant growth is only limited by the availability of soil moisture.

2.3. Weather conditions

The weather data were obtained from the German Weather Service (DWD) which was located 400 m south to the study site. They included the hourly weather parameters: wind speed, temperature and solar radiation, which were used to define the evapotranspiration (ET) values. Data for the growing season 2003, which was a relatively dry season were fed into the simulation model to limit the uncertainty associated with the prediction of the rainfall amount, timing and other weather variables. Rainfall was a spatially variable parameter. For instance, the historical weather data for the irrigation period −170 to 230 days of the year (DOY)- showed that the precipitation for the years 2000, 2001, 2002 and 2004 was 103 mm, 158 mm, 335 mm and 161 mm respectively whereas it was only 57 mm for the year 2003. The calculated soil water balance (precipitation-evapotranspiration) revealed a deficit of 73 mm, 45 mm, 181 mm and 30 mm for the years 2000, 2001, 2002 and 2004 respectively whereas a deficit of 224 mm was received for the year 2003 for the same irrigation period (170–230) DOY. Since the field had a small area and there was only one weather station available, the rainfall was considered uniform for the entire field. The weather data: precipitation, ET, and water climatic balance for the year 2003 are presented in Figure 1.

2.4. Irrigation threshold parameters

The AMBAV Model was used to calculate the amount of water required for the irrigation season. The simulated irrigation event triggered automatically a sequence of applications applying a definite amount of water 20, 30 or 40 mm in each sequence as a function of the threshold parameters defined by the user of the crop model. The automatic irrigation option added water to raise the soil moisture content to 80% of the depleted plant-available water when the soil moisture content dropped below the value of 50% of the depleted water. Plant available water was defined as the difference between field capacity and welting point. The threshold parameters included the optimal water application depth that was checked daily and the soil moisture balance that was checked hourly. The timing of the irrigation event was specified on the bases of the soil water balance values observed at the sampling locations that required more irrigation sequences than the others to avoid any water stress which might cause reduction in the yields. The quantity and timing of irrigation sequences in each of the 21 sites were calculated to identify differences and similarities between the sites. Based on the

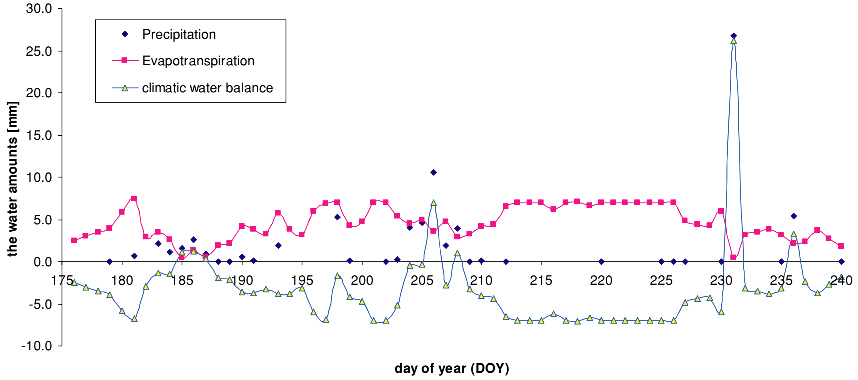

Fig. 1 Climatic data during the irrigation season 2003

results obtained, the field was segmented into management zones that had similar available water holding characteristics.

2.5. Irrigation simulation for the growing season

The model was set to calculate the amount of water required for each optimal irrigation depth (OID) during the plant growing season. A soil water balance sub-model was fed with an estimate of the amount of soil moisture content for the 21 sampling points before the seeding date. A comparison between the measured volumetric soil water content and the simulated soil water content for each layer of 10 cm depth was made to validate the soil water balance simulation throughout the entire growing season. The volumetric soil water content for the upper layer from (0–30) cm is presented in Figure 2. The volumetric soil water content for the lower layer from (30–70) cm is presented in Figure 3. In all irrigation application sequences, water was applied when the soil moisture depletion became less than the allowable soil moisture (50%) and when there was no rainfall predicted within the coming two days in order to avoid plant water stress that might cause decline in the yields. The model was working in conjunction with a weather prediction sub-model updated with metrological data every 15 min. The ground water table was 5–6 m deep; thus it had no effect on the irrigation calculations. The total amount of applied water was then calculated by summing the amount of water applied for each of the 21 points for the entire growing season.

2.6. System efficiency assessment

Water efficiency improvement in irrigated agriculture is a priority for better environmental and economic performance (Bergez et al., 2004). Among the efficiencies that are most frequently utilized in comparing the performance of different water application systems are the application efficiency and the storage efficiency (Wang et al., 1996). In the present study,

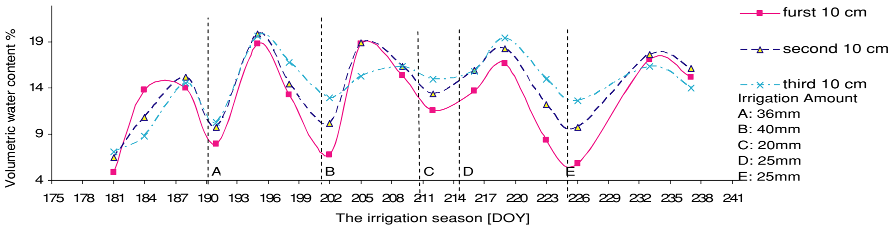

Fig. 2 Soil moisture content for the upper layer at the reference point (A, B, C and D specify the irrigation dates) during the irrigation season 2003

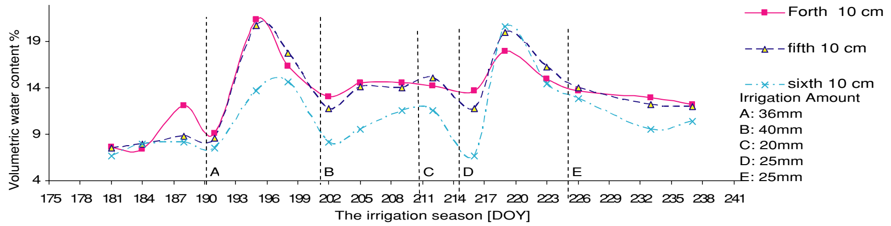

Fig. 3 Soil moisture content for the lower layer at the reference point (A, B, C and D specify the irrigation dates) during the irrigation season 2003

these efficiencies were used to compare water use under normal application with that under variable rate application. The efficiencies utilized were: application efficiency equals water stored in the soil root zone/water delivered to the field and storage efficiency equals water requirement in the root zone stored in the soil root zone/water stored in the soil profile

3. Results and discussion

A summary of the weather conditions observed during the irrigation season of 2003 is presented in Figure 1. For the entire year, the rainfall was 504 mm, the evapotranspiration was 733 mm and the climatic water balance was −229 mm. For the irrigation season (from DOY 176 to DOY 240), the rainfall was 74 mm. The evapotranspiration was 296 mm and the climatic water balance was −222 mm. The summer season was relatively dry the rainfall was less than the annual average. The parameters for the entire growing season were measured. These parameters include the soil texture and the soil moisture content for each 10 cm depth, the irrigation scheduling (time and amount) and the available plant water for the reference point. Soil texture maps for the silt and clay for the upper layer are presented in Figure 4. Soil texture maps for the sand at both the upper and lower layers are presented in Figure 5.

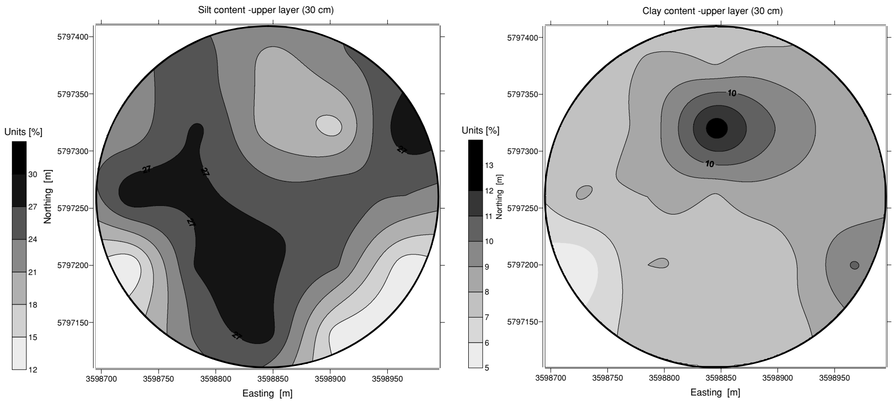

Fig. 4 The percentage of silt (left) and clay (right) at the upper layer for the entire field

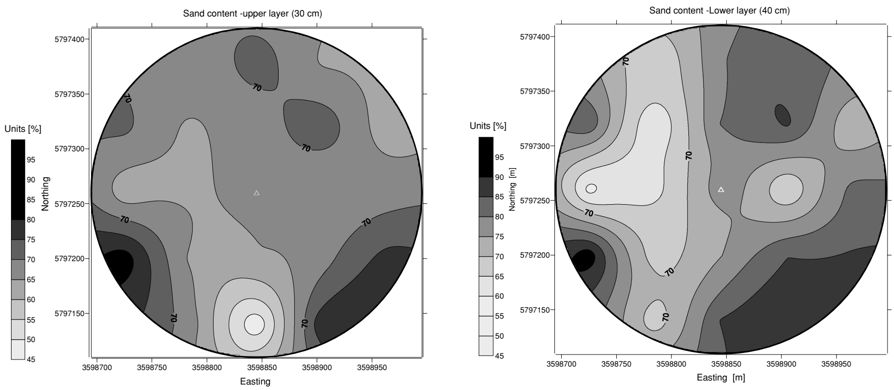

Fig. 5 The percentage of sand (left) for the upper layer and sand (right) for the lower layer for the entire field

3.1. Irrigation simulation out put

Simulated volumetric soil water content for the root depth was represented by layers of 10 cm depth each for the 21 sampling points. The model responded very well to the individual rainfall events and water applications as shown by the changes in the soil moisture content for each of the depth layers at the reference point Figures 3 and 4. Generally, the model simulated the soil water content reasonably well for the different soil texture samples in comparison with the measured volumetric soil water content for the individual soil layers at the reference point. The analysis of the AMBAV model results revealed that the soil water balance was highly sensitive to both soil texture and irrigation volume.

3.2. Irrigation scheduling scenarios

Scenario 1, VRA under 20 mm water application, resulted in segmenting the field into three zones: zone A which was 4.1 ha received 10 irrigation sequences: the total amount of water was 8291.8 m^3, zone B which was 2.3 ha received 11 irrigation sequences: the total amount of water was 5059 m^3 and zone C which was 0.6 ha received 12 irrigation sequences: the total amount of water was 1396 m^3. The resulted total amount of irrigation required for the entire season was 14746 m^3. The spatial distribution of water is illustrated in Figure 6.

Scenario 2, UA under 20 mm water application: the entire field received 12 irrigation sequences. The resulted total amount of irrigation required for the entire season was 16865 m^3. Irrigation was set in response to the areas that had the lowest soil water holding capacity as represented in zone C in Figure 7. By comparing the two scenarios: VRA and UA, it became evident that zone C received the optimal water application, zone A received two irrigation sequences more than the optimal water requirement and zone B received one irrigation sequence more than the optimal water application.

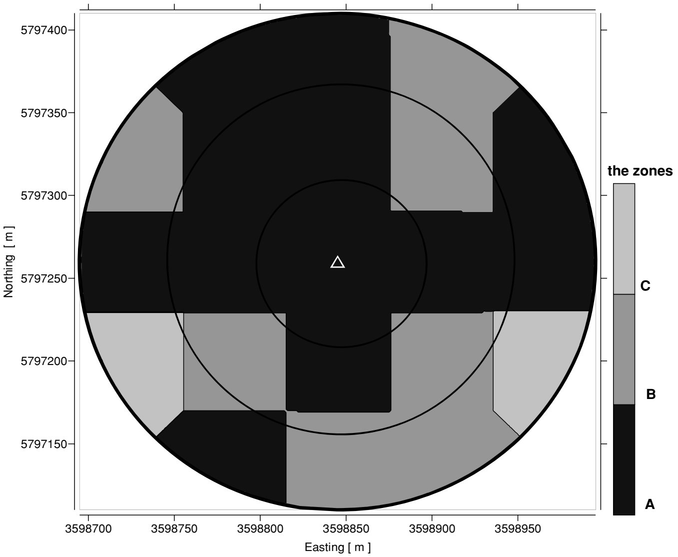

Fig. 6 Management zone for 20 mm spatial water distribution.

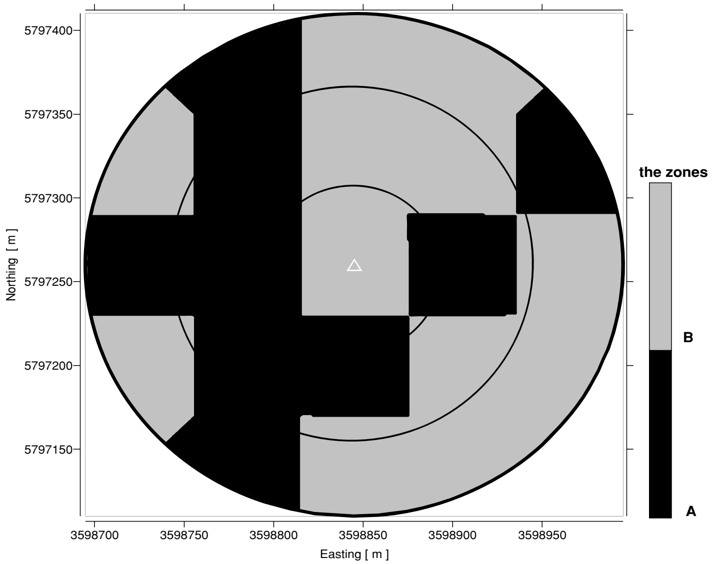

Fig. 7 A management zone for 30 m spatial water distribution

Scenario 3, VRA under 30 mm water application, resulted in segmenting the field into two zones: zone A which was 3.1 ha received 7 irrigation sequences: the total amount of water was 6510.6 m^3 and zone B which was 3.9 ha received 8 irrigation sequences, the total amount of water was 9424 m^3. The resulted total amount of irrigation required for the entire season was 15934.6 m^3. The spatial distribution of water is illustrated in Figure 6.

In scenario 4, UA under 30 mm water application**,** the entire field received 8 irrigation sequences. Irrigation was also set in response to the areas that had the lowest soil water holding capacity: zone B as represented in Figure 7. The resulted total amount of irrigation required for the entire season was 16865 m^3.

By comparing the two scenarios: VRA and UA for 30 mm application, it became evident that zone B received the optimal water application and that zone A received one irrigation sequence more than the optimal water application.

In scenario 5, VRA under 40 mm water application, one management zone received 6 irrigation sequences: the total amount of water required for the entire season was 16865 m^3. Since the whole field was a one management zone, both VRA and UA under 40 mm water application resulted in 6 irrigation sequences. With this amount of application, there was no variation between the two irrigation strategies: VRA and UA.

The model also specified the timing for each irrigation sequence of each the scenarios (the time tables are not presented in this paper). By comparing the water application maps with the soil texture maps, it became apparent that the south eastern and south western parts of the field demanded more irrigation than the rest of the field due to the high content of sand in both specified layers.

Comparing the two scenarios of VRA and UA under 20 mm water application resulted in water saving of 2118 m^3 (for the VRA). Comparing the two scenarios of UA and VRA under 30 mm water application resulted in water saving of 930 m^3 (for the VRA). For the application of 40 mm, the water Percolation losses were greater compared with the losses in the previous scenarios 20 mm and 30 mm because the applied amount of water exceeded the root zone capacity. For the same reason, there was no difference between the UA and the VRA. Applying less amount of water more frequently would enhance water conservation but it would on the other hand require more frequent operation of the central pivot. An energy input analysis will thus be essential before implementing such system.

The water stored in the soil root zone was considered a fixed parameter that depends on the soil hydraulic properties. The application efficiency and the storage efficiency yield the highest values with the application of 20 mm under VRA, which secured the saving of 1188 m^3 water compared with the VRA under 30 mm. Most of the root growth happened in the early growth stages. During the irrigation season, there was no significant development in the root depth because of the growth stage of the sugar beet.

The drainage that occurred as a result of applying 40 mm and 30 mm water was more than that occurred by applying 20 mm. This explains why more water was lost as a result of applying greater amount of water than that lost by applying less quantity more frequently. Drainage also occurred as a result of the rainfall which exceeded the upper drain level of the soil capacity at the root depth. That amount of water lost in this type of drainage was not calculated. The run off on the field was not calculated accurately because of the difficulties involved in simulating the water dynamic movement over three dimensional surfaces. However, the study showed that the rainfall rather than the irrigation was the main source of the run off.

3.3. The field soil moisture variation

George et al. (2001) observed that the increasing demand on water could be met either through the development of new water resources or by using the existing water resources more efficiently. The efficient use of the existing water resources (rationing water use) requires less investment in time, effort and expenses than developing new water resources. Irrigation requirements used to be calculated by taking the measurements of soil water content in a certain location on the field. This method disregards the variation across the field. The soil is heterogeneous both vertically and horizontally as evident from mapping soil moisture content and soil texture. Thus, such sampling method is not representative of the entire field since the water that is held in the root zone varies from one soil to another and from one soil horizon to another. “Soil profiles are heterogeneous owing to texture, mineralogical and structural changes with depth, which in turn affect hydrologic conductivity, erodibility and water retention” (Savabi, 2001:59).

The 21 salinity measurement results revealed a low level of salt content in the field; thus there was no need to apply irrigation for reasons other than meeting the plant water requirement. The slope measurements showed a difference of 3.8 m between the highest and lowest points. The comparison of the soil moisture content (SMC) at the upper 0–30 cm with that at the lower 30–70 cm Figure 8 under no irrigation condition revealed that there was higher moisture content at the upper 30 cm (mean value 13,5) than that at the lower 40 cm (mean value 9,6). At the same layer the sand content percentage was 10% higher than that at the upper layer.

The hydraulic system of the field was disturbed by a cement layer that could perch the water above it. The layer was 100–130 cm deep from the soil surface. It could prevent or slow down the water penetration through the profile causing the build up of high moisture content that was stored there during the rain season and that could last for the dry season. Therefore, there is a need to understand the hydraulic behavior of such soil (capillarity and infiltration) especially during the dry season.

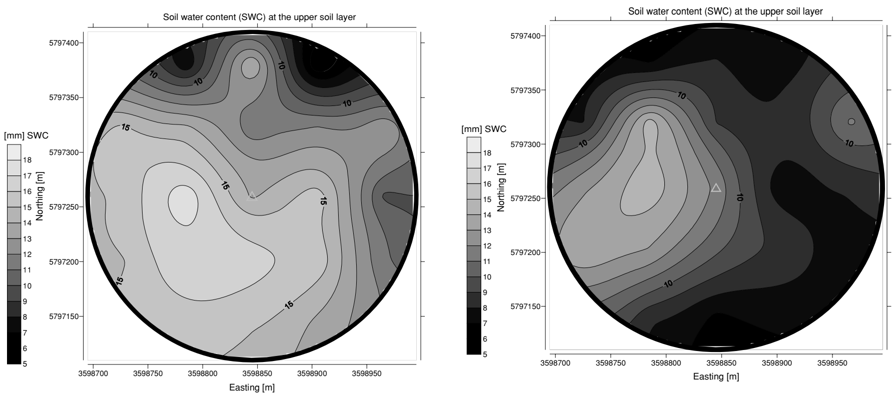

Fig. 8 Spatial soil moisture content variation under natural (no irrigation) condition

4. Conclusion

It can be concluded that the utilization of variable rate application as an irrigation strategy can save a significant amount of water and can be less labour intensive since it does not require daily sampling of data to calculate the soil water content. Three scenarios for VRA under 20 mm, 30 mm and 40 mm water applications were compared with three scenarios for UA under 20 mm, 30 mm and 40 mm. The comparison revealed that the loss of water was higher for the UA scenarios than that for the VRA scenarios. For the 40 mm application scenarios, there was no difference in the water requirements between the UA and the VRA scenarios because the applied amount of water exceeded the root zone capacity.

The loss of water under 20 mm application was less than that under 30 mm application for the VRA due to dividing the field into three zones instead of two and to reducing water application amount in each irrigation sequence. On the other hand, there would be an increase in the energy utilized due to the additional rotation times required. With the amount of 40 mm water application, under both VRA and UA, results reveled that there was no variation in water consumption between the two irrigation strategies.The study also identified the areas the farm manager could neglect in case of water scarcity throughout the season. Under uniform application, the area of the field that received the largest amount of water and that had the lowest available water holding capacity compared to other areas in the field contributed to the largest amount of deep percolation losses. Running the model under different conditions improved our understanding of the optimal plant water requirements.

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