Investigation of Steady State Infiltration Rate for Different Constant Head Conditions

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***Abstract*—**This paper aims at determining the soil characteristics that influence the irrigation process of green landscapes and deciding on the optimum amount of water needed for irrigation. The laboratory experiments were conducted using the constant head methodology to determine the soil infiltration rates. The steady state infiltration rate was reached after 10 minutes of infiltration at a rate of 200 mm/hr. The effects of different water heads on infiltration rates were also investigated, and the head of 11 cm was found to be the optimum head for the test. The experimental results showed consistent infiltration results for the range between 11 cm and 15 cm. The study also involved finding the initial moisture content, which ranged between 5% and 25%, and finding the organic content, which occupied 1% to 2% of the soil. These results will be later utilized, using the water balance approach, to estimate the optimum amount of water needed for irrigation for changing weather conditions.

***Keywords*—**Infiltration rate, moisture content, grass type, organic content.

I. Introduction

THE UAE is classified as a hyper-arid-climate country with scarce rainfall [1]. Water resources in UAE are limited. Thus, the implementation of an efficient irrigation system is necessary to conserve water while maintaining the expansion of the green landscapes across the country.

Several case studies in the UAE, conducted over the span of 2014-2016, have noted that the irrigation practices can be further enhanced to prevent inefficient water consumption and water losses due to evaporation or faulty irrigation systems used. The consequence of inefficient practices is not only placing a strain on water resources, but also on the natural grass survival and the financial resources investments on greening the landscapes and maintaining the systems used.

Fig. 1 is a live example of this research study site area, where it clearly shows the inefficient irrigation practices captured on daily basis. Considering that green landscapes cover over 0.44 km^2 in this particular site area, these practices are alarming and warrant further investigation to determine the factors influencing the irrigation practices in order to devise a step-by-step water balance approach for efficient irrigation.

Over irrigation results in: deep percolation, which allows the water to seep through the lower layers of the soil that could possibly reach the ground water levels; leading to contamination of clean water resources. Moreover, when soil reaches saturation level, water starts accumulating on the surface of soil creating a pond. Ponding results in the waste of significant amounts of water through evaporation. Additionally, stagnant water constitutes a perfect environment for various bacterial species to appear and reproduce, making the area susceptible to foul smell. The third detrimental effect of over irrigation is runoff; that is the spread of water over areas surrounding green lands, creating bad view and dispersal of dirt from the green lands. The only approach to avoid such problems is to maintain an irrigation flow rate that would not exceed the infiltration flow rate of the soil in the area of interest [2], [3].

Fig. 1 Inefficient irrigation practices in project site area

II. Literature Review

The definition of the value of the steady-state infiltration rate from infiltration measurements is not standardized. Many studies [4]-[6] have set boundary rules to quantify steady-state infiltration rates in the field and in the laboratory. Vieira [7] determined this value after four days of continuous ponding, Sharma & Hughes [8] determined steady-state infiltration rates after 60 min of infiltration testing, while Kohne et al. [9] determined steady infiltration rates, using tap water at 5-20 minutes for all infiltrations, wherein the final steady-state infiltration rate was calculated as an average of the last five to 10 measurements taken at one minute intervals. Maani et al. [10] determined steady infiltration rates at 45 minutes, taking the last three consecutive samples as the final (steady-state) infiltration rate. The soil characteristics under consideration and the available technical equipment play a main role in

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determining steady state infiltration rates [6], [10], [11].

Steady-state infiltration rates are highly dependent on the initial moisture content and ponding infiltration experiments are a useful source on the soil profile [11]. However, a steady-state infiltration rate is reached which, according to theory, is independent of the initial moisture content and dependent the gravity forces become also important [12], [6]. Bagarello et al. [5] have discussed that how the infiltration rates changes with the technical details of the experimental protocol; such as the number and size of the infiltration cylinders and the depth of insertion into the soil. All effects, such as structure and texture irregularities, air-water interactions, hysteresis, and layering are always combined under field conditions [11]. The challenge remains to trace particular effects.

The ponding infiltration rates were studied by inserting cylinder infiltrometer into the soil to a depth of 15-20 cm [11]. A major finding of this study was that the air entrapped by water films apparently influences the balance between the capillarity-dominated and gravity-dominated parts of total volume of water in the sample [11]. This finding is further supplemented by other studies [13]-[16]. In other studies, measured infiltration rates and saturated hydraulic conductivity interchangeably using constant and falling head infiltration methods on soil samples collected for different soil types [4], [5], [14], [17], [18]. Their results suggest that the influence of measurement methodology on spatial variability estimation is dependent on soil type, sample size, and measurement method to name a few [4], [5], [14], [17], [18].

Shouse et al. [19] noted that after a 30-day ponding period under a constant hydraulic head, infiltration measurements showed that the average infiltration rate decreased with decreasing size of the infiltrometer. Chowdary [6] noted that the infiltration rates were consistent when measured with an infiltrometer of a 10cm diameter and 30cm soil depth. Maani et al., [4] building on the findings of [6], performed laboratory tests which confirmed that infiltration capacities decreased after irrigation by a factor of about 1.4 of those before irrigation until steady state was attained.

The current research is an extension to previous work of [10], [4] and aims to characterize the temporally and spatially varying soil characteristics including infiltration rates and water retention capacity and develop a diagnostic evaluation framework of the effect of several environmental factors on the irrigation. The experimental setups within this study will be devised to provide the duration required for sustainable landscape irrigation; which is the time required to reach the steady state infiltration rate. For this purpose, this research employed several experimental methods to determine moisture contents, infiltration rates, organic content, and root zone depth.

III. Experimental Setup and Procedure

The experiments were conducted between September and early December 2015; during which the highest temperature in respective months reached 36°C and 31°C. The chosen areas for conducting the experiments are the green lands on the American University of Sharjah (AUS) campus.

A. Soil Moisture Content and Vegetation Root-Zone Depth

The moisture content tests were conducted on multiple samples extracted from each location before and after irrigation at 0.02 m, 0.04 m, 0.06 m, 0.08 m, 0.1 m and 0.12 m depths along the vertical direction. The tests were performed in the laboratory complying with the ASTM 2216 standards. Moisture content implies the water-holding capacity of soil, which decides the speed with which infiltration rate drops once irrigation starts. This depends on the amount of voids and moisture content at beginning of irrigation; hence, moisture content tests were performed on samples obtained before irrigation (BI) and after irrigation (AI). A total of 120 soil cylindrical samples were extracted; half of which were obtained before irrigation and the other half after irrigation.

In order to extract the samples, open-ended aluminum cylinders with sharp edges were used; a cylinder's dimensions were 0.2 m in length and 0.075 m in diameter. Each cylinder was hammered into the area of interest using a wooden plate on top to spread the force over a wide area and facilitate the process [8]. Each cylinder was buried to approximately 0.15 m into the soil. The cylindrical soil samples were dissected into smaller samples at increments of 0.02 m until a depth of 0.12 m is reached. Root zone was measured for each division using a ruler to be used later in the organic content test. The next step is oven drying; where 100g of each division of soil were put into a previously-weighed porcelain dish and the overall weight was recorded. Due to the existence of organic matter in the samples the "ASTM D2216" recommendations for oven-drying temperature was altered from 110 °C to 60 °C and the 24-hour duration was prolonged to 48 hours to ensure complete dryness of the sample [20]. The dry weight of the sample is then recorded.

The formula used to calculate the moisture content is:

$$w=[(M_{cws}-M_{cs})/(M_{cs}-M_{c})] \times 100\%$$

where M_{cws} is the weight of container plus the sample before drying, M_{cs} is the weight of the container plus sample after drying and M_c is the weight of the container.

B. Soil Infiltration Rates

The infiltration rates were determined in the laboratory according to the ASTM constant head test standards. Mariam et. al. [10] conducted experimental studies with a constant water level of 150 mm above the soil surface. This study concluded that the constant head of 150 mm might affect the infiltration rate due to higher water pressure. Since the current study is a continuation study of [10]; the lab infiltration test was repeated using different heads of 0.15 m, 0.11 m, 0.08 m, 0.05 m, and 0.02 m in order to decide on the optimum head that will be later used to find the field infiltration rate. The infiltration rates are observed at different times from the starting of the irrigation process, this will help us identify the time when the steady state is reached. This test was performed on 45 samples. When transferring the sample from the aluminum extraction cylinder into the armfield infiltration test apparatus, the soil undergoes disturbance and loses its coherence; thus, creating air voids which rules out the sample as unrepresentative of the soil of interest. Therefore, before starting the constant head test soil underwent compaction to regain its undisturbed-condition coherence. However, in order to achieve the purpose of compaction, the level of compaction should not result in more than 10% difference in soil density between initial undisturbed condition and after compaction condition; otherwise, the sample ought to be discarded.

Once the density of the sample was verified, the constant head test was performed. Multiple constant heads were experimented, in order to decide on the optimum head that results in minimal variance between infiltration rates of the samples. The heads compared were: 0.15 m, 0.11 m, 0.08 m, 0.05 m, and 0.02 m. The readings of the head were recorded after 1 min, 2 min, 4 min, 8 min, 10 min, 20 min, 30 min and every 30 min thereafter, until three exact same readings were recorded; that is when steady state is reached.

C. Soil Organic Content

The ASTM 2974 soil organic content test is performed on samples obtained from different locations along the vertical depth of soil; 0.02 m, 0.4 m, 0.06 m, 0.08 m, 0.1 m and 0.12 m depths. The presence of organic content affects the properties of soil, including water-holding capacity and decreases the water-infiltration rates infiltration rate. Additionally, the effective root zone depth was measured to evaluate the effective water depth required for irrigation. The organic content test was measured for 38 samples using ASTM 2216 standards.

Each soil sample represents one of the five depths of a cylindrical soil sample-discussed previously in the moisture content test-, specifically the top 2-4 cm sample as it contains the highest concentration of grass roots. Samples were put in dishes marked with the depth from which the sample was taken. The samples were weighed and the dishes were placed in the furnace for an hour at 440 °C.

IV. Results and Discussion

A. Moisture Content

The tests were performed on samples from the top 12-15 cm layers of soil, in accordance with the studies carried out by [4], [10] on root-zone depth of landscape areas of the same study site. The average of the moisture content for each depth tested was calculated for both case scenarios BI and AI, and the results are demonstrated in Table I.

TABLE I
AVERAGE AMC ACROSS THE SOIL DEPTH FOR BI AND AI CASES

Range (cm)	AMC BI (%)	AMC AI (%)
2 - 4	16.66	19.49
4 - 6	13.73	16.31
6 - 8	11.63	13.74
8 - 10	10.21	12.43

Table I shows that the increase in moisture content is largest closer to the surface. As anticipated, the moisture content AI is higher than BI and this will affect the magnitude of IR. However, the increase was at most (by 4.4%) in the 2-4 cm range; that is the root zone with highest concentration of observed roots. The BI, as well as the AI, moisture contents show a continuous drop until reaching the end of the root zone. It is significant to note that the before irrigation moisture content is an indication of the approximately-24-hour (since last time it was irrigated) water-holding capacity of soil which will be very useful to determine the optimum infiltration rate. The top 2-4 cm of soil showed a 16.7% 24-hour-post-irrigation retention of water according to the moisture content of the BI cases. A 16.7% of AMC allows for further investigation to determine the actual irrigation demand using the water balance approach as appose to the current irrigation supply.

B. Infiltration Test

In the laboratory test, the steady state infiltration rates were recorded and plotted for each sample (Fig. 2). The figure presents infiltration rates of different samples at different heads ranging between 2 cm and 15 cm; this was done to decide on the optimum head that would minimize the effect of head height on the results.

Several different water heads were tested to determine the optimum head for the test. The experimental results showed consistent infiltration results for the range between 11cm and 15 cm. However, due to the less fluctuation on results the lowest head (11 cm) was used as a baseline for the tests as shown in Fig. 3.

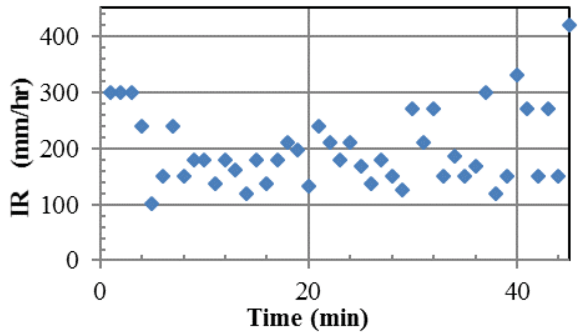

Fig. 2 Infiltration rates for all samples

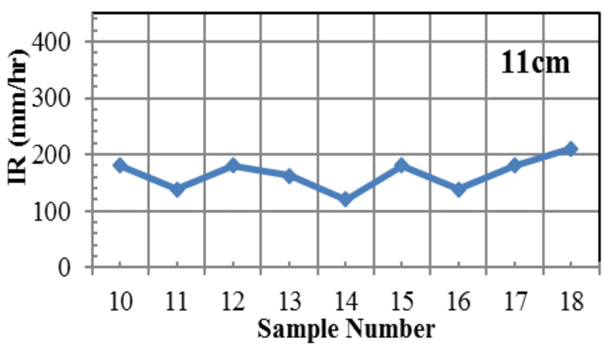

Fig. 3 Infiltration rates for 11cm head

During the infiltration test in the laboratory, the infiltration rates between pre-determined intervals were recorded and plotted against time (Fig. 4). The steady state was reached after 10 min of the start of irrigation regardless of head tested; as can be seen in Fig. 4. This notes an improvement from the experimental testing by [10], will result in a faster attainment of steady-state infiltration rate. This is highly attributed to the consistent consolidation methodology carried out to replicate field conditions in the laboratory. The steady-state duration conforms to the works of [9], wherein the duration to attain steady-state was determined at the range of 5 min to 20 min.

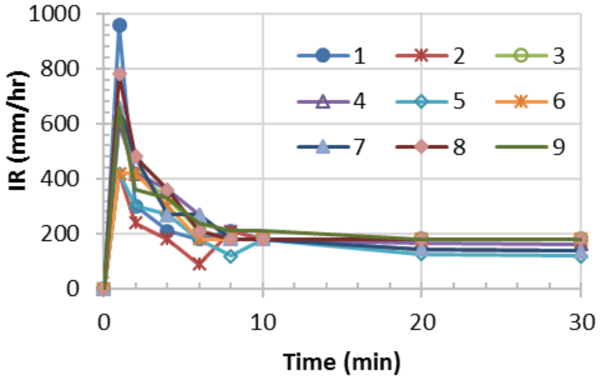

Fig. 4 Attainment of steady-state infiltration rates

All the nine samples gave a similar infiltration rate pattern, starting very high then dropping sharply until reaching the steady flow equal to 200 mm/hr at almost exactly the same time.

C. Soil Organic Conte

The organic content test was performed on the top 2-4 cm of the soil due to the high concentration of roots in that area. As can be seen from Fig. 5, the minimum and maximum observed organic contents were 0.97% and 1.73%, respectively. This is noted to be a typical value for soil covered with natural grass.

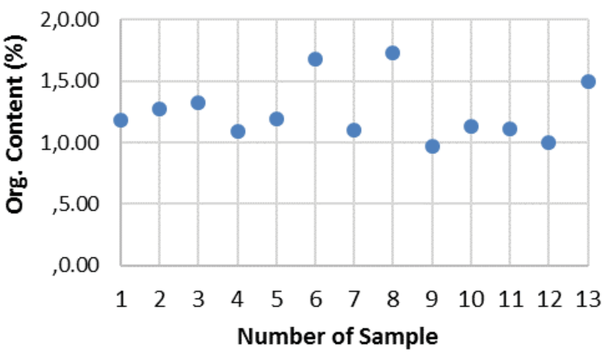

Fig. 5 Organic Content in Depths 2-4 cm

Fig. 6 explains how the root concentration (organic content) decreases with depth; hence, the water-holding capacity of soil decreases. These values verify the previously noted moisture contents of all five depth ranges.

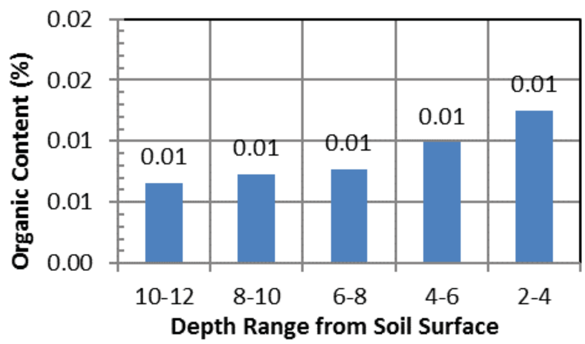

Fig. 6 Average Organic Content for entire depth

V. Summary and Conclusions

This study successfully showed that the irrigation conditions in AUS, Sharjah are very inefficient. The following conclusions can be drawn from this parametric study:

- A 20 min irrigation period with an unknown irrigation flow rate is the main causes of huge water losses characterized in ponding, runoff and deep percolation.
- The optimum time to attain steady-state infiltration was found to be 10 min at a steady flow rate of 200mm/hr. However, it should also be noted that this will be further investigated with different climate conditions.
- The experimental results showed consistent infiltration results for the range between 11 cm and 15 cm, and as such, the lowest head (11 cm) was used as a baseline for the tests.
- The moisture content test concluded that the water-holding capacity of soil after approximately 24 hours of irrigation reaches a maximum of 16.7% in the top high-root-concentration zone, whereas, the AI moisture content reaches 19.5%.
- The root zone measurements showed a high concentration of roots in the top 2-4 cm, extending until 12 cm depth. Utilizing organic content procedure, the highest concentration of roots in the top 2-4 cm resulted in 1-2% organic matter, which decreases with depth until the end of grass root zone.

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