INFILTROMETER TESTS IN AD-DAHNA SAND DUNES

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الخلاصـــة :

أُجريت مجموعتان من اختبارات تسرب (ترشيح) المياه في الكثبان الرملية في الدهناء . وقد اشتملت المجموعة الأولى منها على خمسة اختبارات تسرب في مواقع مختلفة من الدهناء ، بينما احتوت المجموعة الثانية على اختبارات عند موقع واحد ولكن بنسب رطوبة ابتدائية مختلفة . وقد طُبِّـقت طريقة (جرين وآمبت) على المجموعة الأولى من الاختبارات وقُورنت نتائج هذه الطريقة مع النتائج الحقلية . لقد أظهرت نتائج هذه الدراسة أن الكثبان الرملية متجانسة في نسب الرطوبة الابتدائية مع بداية فصل الأمطار ، وكذلك في نسب الرطوبة النهائية بعد اختبارات التسرب ، وفي التوصيل الهيدروليكي للتربة ، كما بيَّـنت الاختبارات أن نسبة الرطوبة النهائية في الكثبان الرملية أصغر بكثير من المسامية الكاملة كما تبيَّـن أن نسبة الرطوبة تتناقص بشكل كبير بعد اختيار التسرب مباشرة حتى تصل إلى نسبة الرطوبة المتبقية وبعد ذلك يقل معدل التناقص في الرطوبة بشكل ملحوظ .

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ABSTRACT

Two sets of infiltrometer tests were conducted in Ad-Dahna sand dune area. The first set consisted of five infiltration experiments that were performed at different locations in Ad-Dahna. The other set involved test at one location but with different initial moisture contents. Green and Ampt approach was used to predict first set field values. Predictions of Green and Ampt method were compared with field results. Experiments have shown uniformity of dune sand in terms of initial moisture content at the beginning of the season, final moisture content after wetting and hydraulic conductivity. Final moisture content in sand dunes was found to be significantly smaller than total porosity. Moisture content dropped rapidly after wetting until residual moisture is reached. After that, the decrease in moisture content seems to slow down substantially.

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INTRODUCTION

Vast areas of the Kingdom of Saudi Arabia are covered with sand dunes and it is suspected that the aquifers below receive substantial amounts of recharge from the sand dune areas above. Examples of these areas are Al-Ruba Al-Khali, Ad-Dahna, and Al-Nafud areas. Part of the Saq aquifer occurs beneath Al-Nafud dunes while Al-Wasia aquifer extends below Ad-Dahna [1, 2].

There are quite a few studies on modeling infiltration and recharge in sand dunes and the factors that affect the recharge process. One of the past researches in the sand dune area is the work of Prill [3]. He conducted his study in the sand-dune area of southwestern Kansas for a period of one year when precipitation was nearly the highest on record. He estimated the build-up of moisture under sagebrush–grass and under grass communities. Amounts of water depletion from soil were also evaluated. Similar work was done by Frank [4] on the Clatsop plains in Oregon. He estimated the annual groundwater flow at different locations of the dune that have different permeabilities. A study on recharge through dunes in the Ad-Dahna area was done by Dincer, *et al.* [5]. The study showed that a significant portion of the annual rainfall of about 80 mm infiltrates through the dunes and can be a source of major recharge to the aquifer formation outcrops covered by the dunes. The study was performed by the observations of the temperature gradient, moisture content, size distribution of the sand, tritium, deuterium and oxygen-18 content of the moisture in the dunes. Allison *et al.* [6] investigated the rates and mechanisms of local recharge in a semi-arid environment beneath two major landscape settings overlain by dunes in South Australia. It has been estimated that annual recharge was about 100 mm. A study of the effect of groundwater recharge on the configuration of the water table beneath dunes has been done by Winter [7]. The study was done by the analysis of water-level fluctuations in about 30 observation wells and 5 lakes in the sandhills of Nebraska. It indicated that water-table configuration beneath dunes in that area varied considerably, depending on the configuration of the topography of the dunes. The recharge beneath dunes was also affected by the dune configuration.

OBJECTIVES

The first process when the dunes receive precipitation is the infiltration of water into the dunes. Several equations, some empirical and others physically based, have been proposed to describe the infiltration of water as a function of time. Empirical formulas were developed to analyze the results of infiltrometer tests and the resulting equations were applied to describe a rate of infiltration decreasing from an initial maximum to a final minimum rate. The most famous empirical equations of infiltration include those proposed by Kostiakov [8], Horton [9, 10], and Holtan [11]. Empirical equations possess some serious limitations. Their parameters have little or no physical meaning and they cannot be determined or estimated from knowledge of the soil. The most important physically-based equations of infiltration are those due to Philip [12] and Green and Ampt [13]. Both equations have a physical basis and utilize parameters that can be evaluated from physical properties of the soil. More details concerning development and limitations of different infiltration equations can be found in Fok [14].

The Green and Ampt model [13] has been the subject of considerable development in the literature because of its simplicity and its satisfactory performance in a great variety of hydrological problems. For instance, it has been extended to soils of non-uniform initial moisture content [15], to layered soils [16], and to crust-topped soils [17]. It has also been applied to infiltration into homogeneous soils from constant and unsteady rainfall [18, 19], and to infiltration in a recharge dam reservoir [20].

The specific objectives of this work are:

1. To run infiltration field experiments at five locations in Ad-Dahna dunes. The locations were on the left and right hand sides of the Riyadh–Hofuf highway. Soil samples were also taken (at the five locations) to determine the initial and final moisture contents and the hydraulic conductivity and porosity of the sands.
2. To calculate infiltration rates for each experiment.
3. To predict the infiltration rates for the five experiments using the Green and Ampt approach and compare the results with field values.
4. To conduct some infiltrometer tests at one of the five sites to determine the infiltration character-

istics of the dunes under different initial moisture contents.

INFILTRATION AT THE FIVE SITES

Study Sites and Experimental Procedure

The Ad-Dahna dunes cover thousands of square kilometers. The most reasonable access to the dunes from Riyadh is through either the Riyadh–Dammam Expressway or the Riyadh–Hofuf highway. The first is a fenced road and it is very difficult to get to the dunes except in few places. After surveying the area of Ad-Dahna, it was decided to choose the five locations on Riyadh–Hofuf highway. These are shown on Figure 1. Locations 1, 2, 3, and 5 are on the left hand side of the highway while Location 4 is on the right hand side. The sites were chosen so that they will be as representative as possible for the dunes in the area. Location 1 was on the crest of a high dune while Location 2 was in the trough area between two high dunes. Location 3 was on the top of a flat dune. The first location (Location 1) is approximately 125 km from Riyadh. Location 2 is about 200 m from location 1. Distances between different sites range from 3 to 6 km.

Before the start of the actual ring infiltrometer tests, a few trial runs were conducted. During these early trials, it was found difficult to keep a constant head of water inside the ring by adding a known volume of water in a certain period of time. This was due to the fast movement of water into the sand. It was therefore decided to pond the water in the ring to a predetermined depth (8 or 9 cm) and measure the time for each 1 cm drop in level. The procedure for all the five experiments consisted of the following steps:

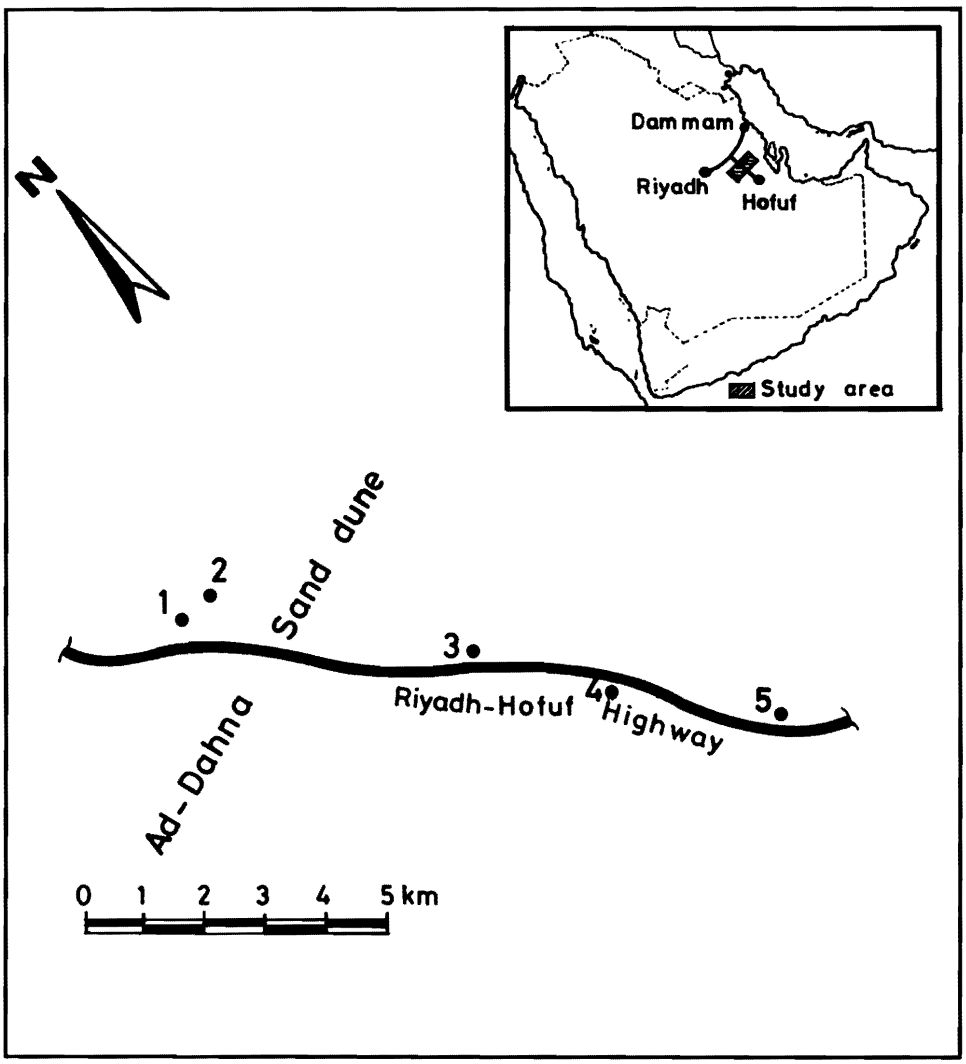

Figure 1. Location Map for Experimental Sites.

1. At the location designated for the infiltration experiment, the ring is first driven into the soil to about 50 cm depth. (The ring used was 90 cm long).
2. A measuring bridge (including a float and measuring rod) is attached to the ring using adjustable screws.
3. The ring is then filled quickly with water up to 8 or 9 cm depth.
4. Record the time for each centimeter of water level drop (using a stop watch) until the ponded water in the ring becomes 2 cm.
5. Refill the ring and continue recording time of drop for every 1 cm of ponded water.
6. Repeat the procedure until a constant infiltration rate is obtained.

At each experimental site, several soil samples were collected and taken to Civil Engineering Department Laboratories (King Saud University) for analysis. These samples included the following:

1. Three samples at different depths were collected (soil surface, 15 cm and 50 cm below surface). These were collected before the beginning of the experiment. They were used to determine the average initial moisture content (θ_i).
2. One sample was also taken at the beginning of the experiment to determine the hydraulic conductivity of the soil (K). This sample was taken at the soil surface.
3. After the completion of the infiltrometer test, another three samples were collected from the same depths shown in (1). These were used to determine the average final moisture content (θ_f).

Data Analysis

Following the completion of the experiments at the five sites, the data was analyzed. Table 1 shows the average initial moisture content (θ_i), average final moisture content (θ_f) and the hydraulic conductivity for the soil at the five locations. The experiments were conducted during the early part of October 1990 when the soil was very dry after at least five months of hot and dry weather. This is clearly shown by the extremely low initial moisture contents (average θ_i for all experiments = 0.0008). The final moisture contents for the five tests ranged between 0.164 at Location 5 and 0.190 at Location 3

Table 1. Soil Parameters at Experimental Locations.

Parameter/ Location	θ_i	θ_f	K (cm/s)
Location 1	0.0008	0.183	0.0325
Location 2	0.0010	0.173	0.0247
Location 3	0.0008	0.190	0.0229
Location 4	0.0007	0.165	0.0172
Location 5	0.0007	0.164	0.0205

(with an average of $\theta_f = 0.175$ for all experiments). Table 1 also shows the hydraulic conductivity at different locations. These values were obtained in the laboratory using constant head permeameter. They range between 0.0172 and 0.0325 cm/s. with a mean value of 0.024 cm/s.

The data of the five infiltrometer tests were used to calculate the infiltration rates and how they vary with time. These results for all infiltration rate start with a relatively high value (I); followed by a sharp reduction until the infiltration rate approaches a somewhat constant value. The durations at different experiments ranged between 713 seconds (at Location 3) and 1326 seconds (at Location 2). The major reason for the variability of the duration of the experiments was the necessity to extend the test until an almost constant infiltration rate was observed. The final infiltration rate was found to be close to the hydraulic conductivity of the sand at the particular site. This was true especially at the Locations 1, 2, and 5.

Green and Ampt Results

The Green and Ampt infiltration rate equation can be written as:

$$I = \frac{dW}{dt} = K\left(\frac{S_f + W}{W}\right), \qquad (1)$$

where:

I is the infiltration rate (LT^{-1}),
W is the cumulative infiltration depth of water (L),
t is the time since the incidence of infiltration (T),
K is the hydraulic conductivity of the wetted zone (LT^{-1}),
S_f is the storage–suction factor (L).

The storage–suction factor can be expressed by the following equation:

$$S_f = (\theta_f - \theta_i)(H_f + H), \qquad (2)$$

where

θ_f is the final water content behind the wetting front, fraction

θ_i is the initial water content for the soil profile, fraction

H_f is the effective capillary drive or suction at the wetting front, (L)

H is the ponded depth of water, (L)

The equation for cumulative infiltration depth can be obtained by integrating Equation (1) with the result:

$$t = \frac{W}{K} - \frac{S_f}{K}\left[\ln\left(1 + \frac{W}{S_f}\right)\right] . \qquad (3)$$

The Green and Ampt method can be applied to any soil provided its basic assumptions are satisfied. These assumptins are: uniform initial moisture content and instantaneous ponding. Both of these assumptions were satisfied in this study.

The Green and Ampt approach was used to estimate infiltration rates for all the five experiments. The procedure consisted of the following steps:

1. The parameters θ_i, θ_f, and K for the particular experiment were taken from Table 1.
2. The ponded head H was estimated to be 5 cm for all the tests. This is about the average water depth since the ponded depth varied between 2 and 9 cm.
3. The effective capillary drive H_f was taken as 15 cm for sand. It was reported that H_f for sand ranges from about 10 cm to 35 cm and a value of 14.7 cm was estimated for plainfield sand [21]. It was also reported that for most soils a value of 15.4 cm for H_f is reasonable [22]. Moreover, Brakensiek [23] has estimated H_f for sand as 12.2 cm.
4. Equation (3) was then used to generate plots of W *vs* t for each experiment.
5. Infiltration rates were then calculated at times corresponding to the times of the field experiments.

Figures 2–6 show the variation of infiltration rates with time for the five experiments. Two sets of curves are shown on Figures 2–6; one for infiltration curves resulting from observed field values while the other set are for the Green and Ampt predicted values. As can be seen from these figures, the differences between field and predicted values are reasonable except at the beginning of the experiment. The

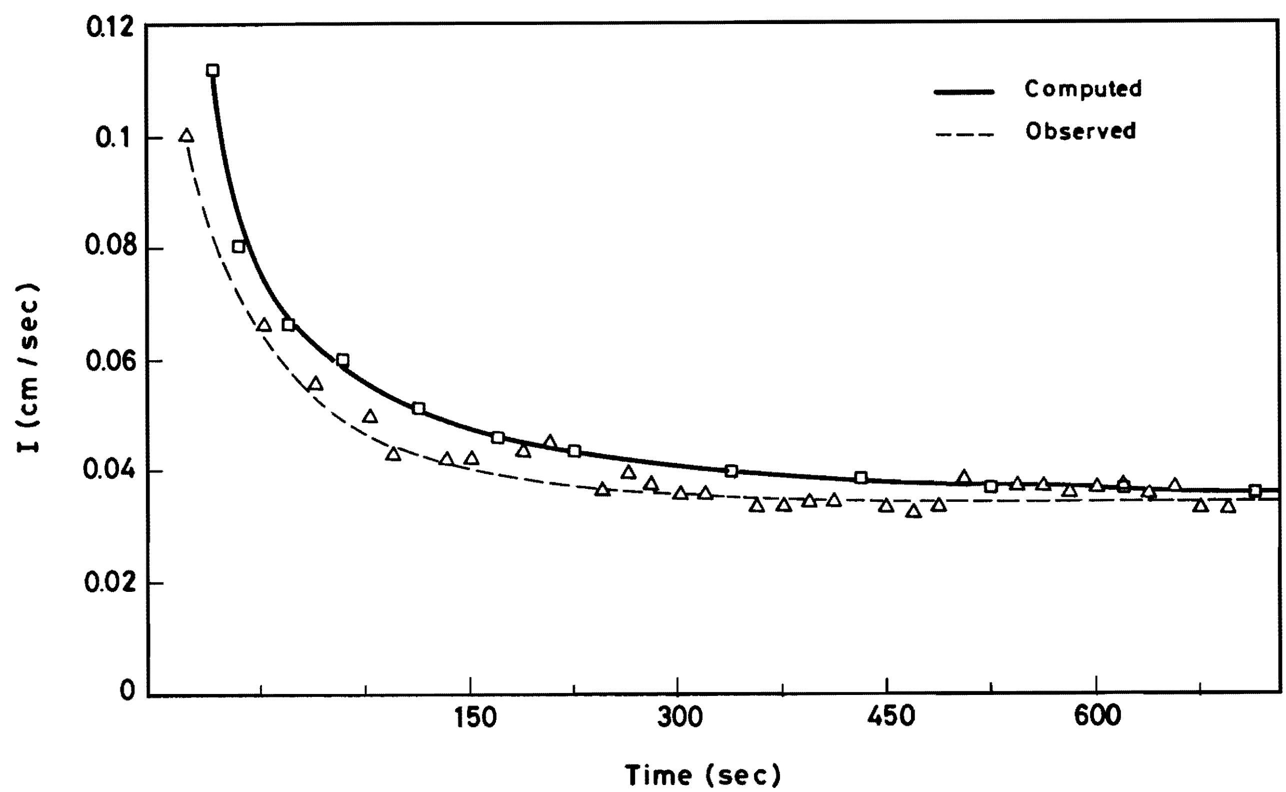

Figure 2. Comparison of Observed and Computed Infiltration Curves for Location 1.

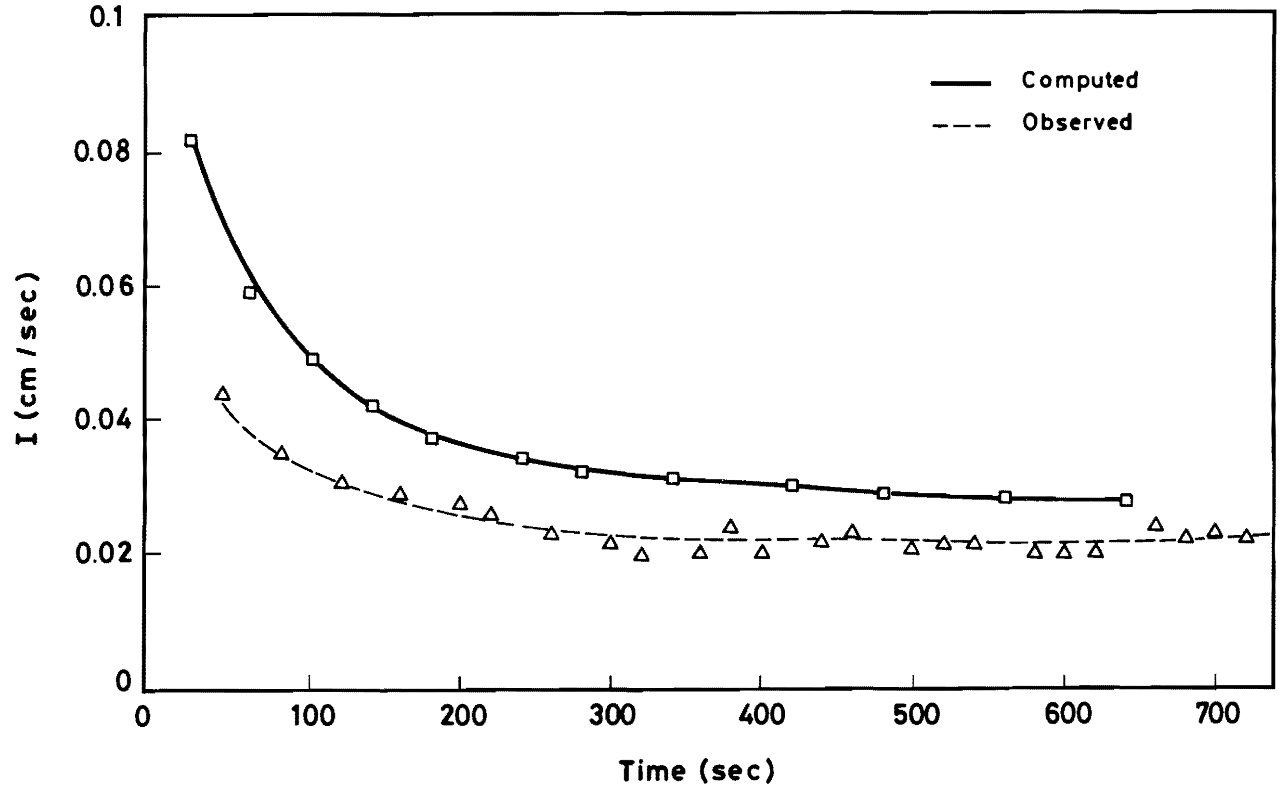

Figure 3. Comparison of Observed and Computed Infiltration Curves for Location 2.

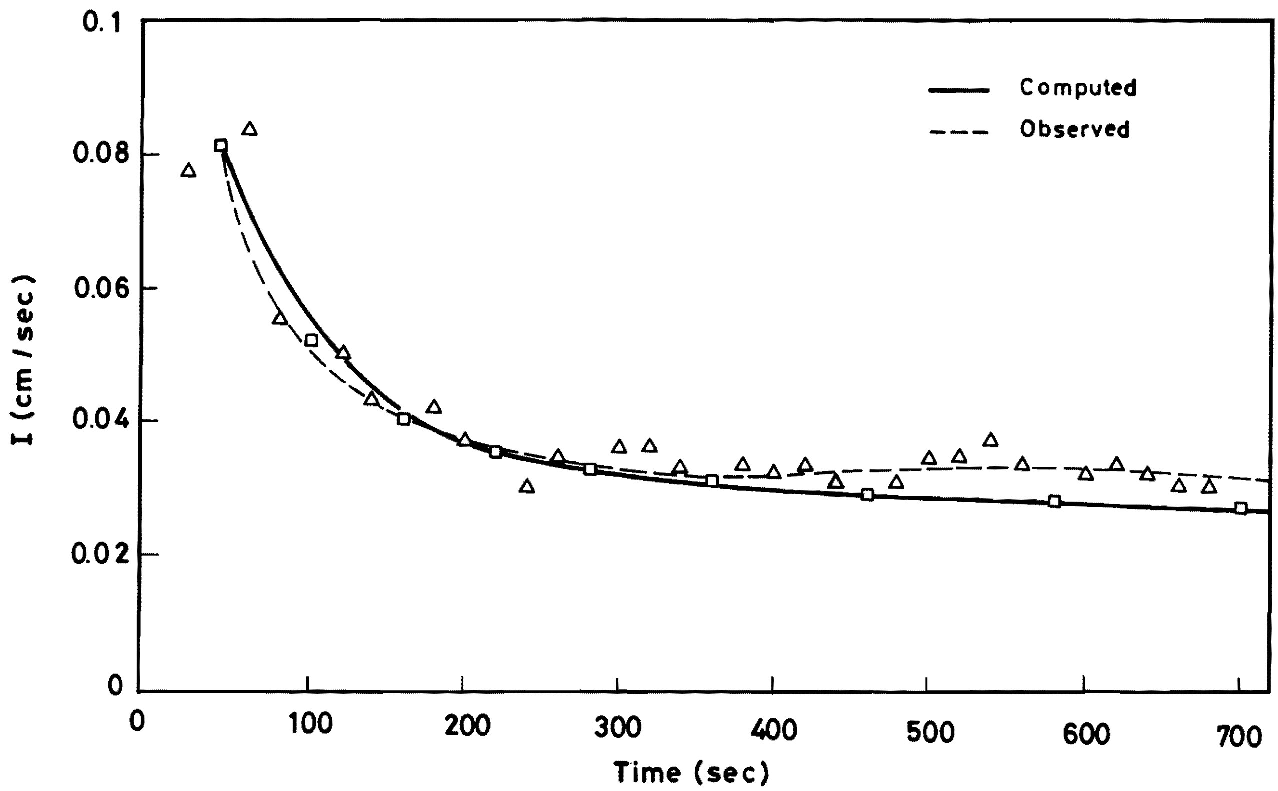

Figure 4. Comparison of Observed and Computed Infiltration Curves for Location 3.

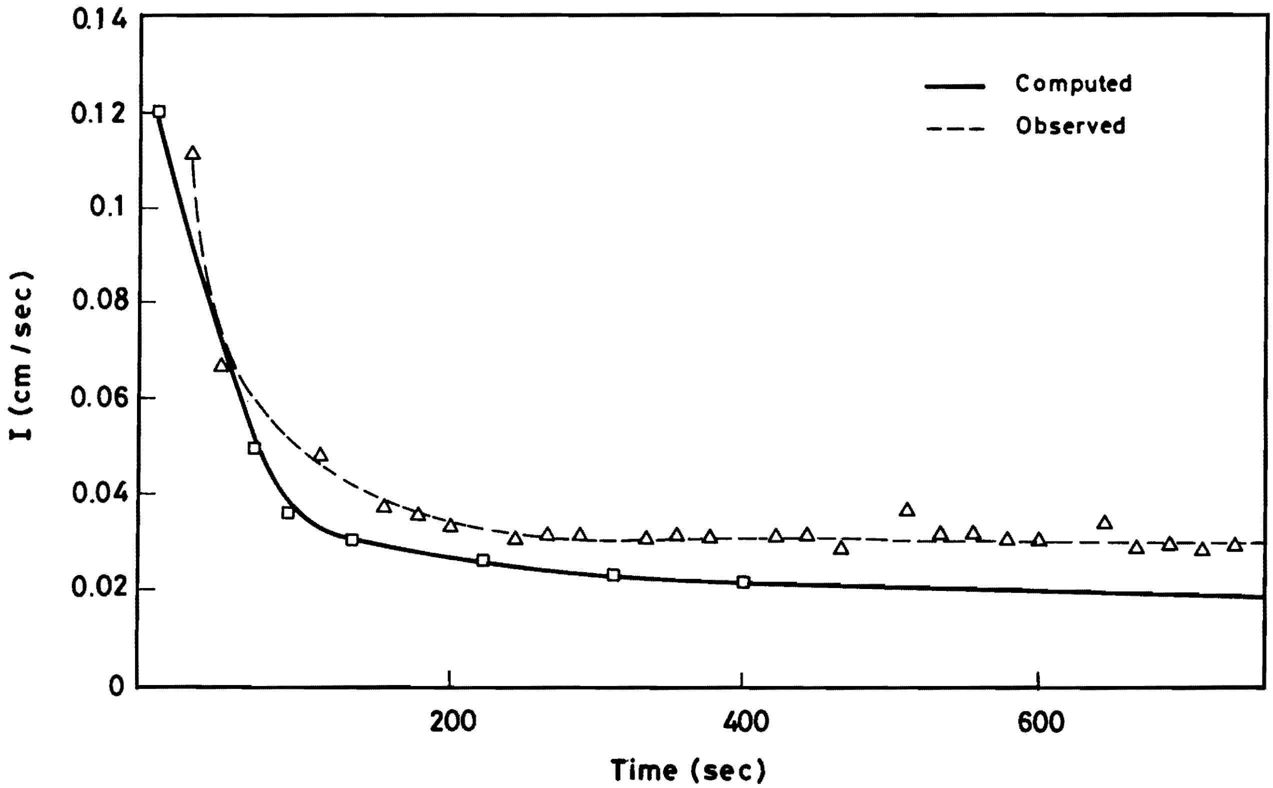

Figure 5. Comparison of Observed and Computed Infiltration Curves for Location 4.

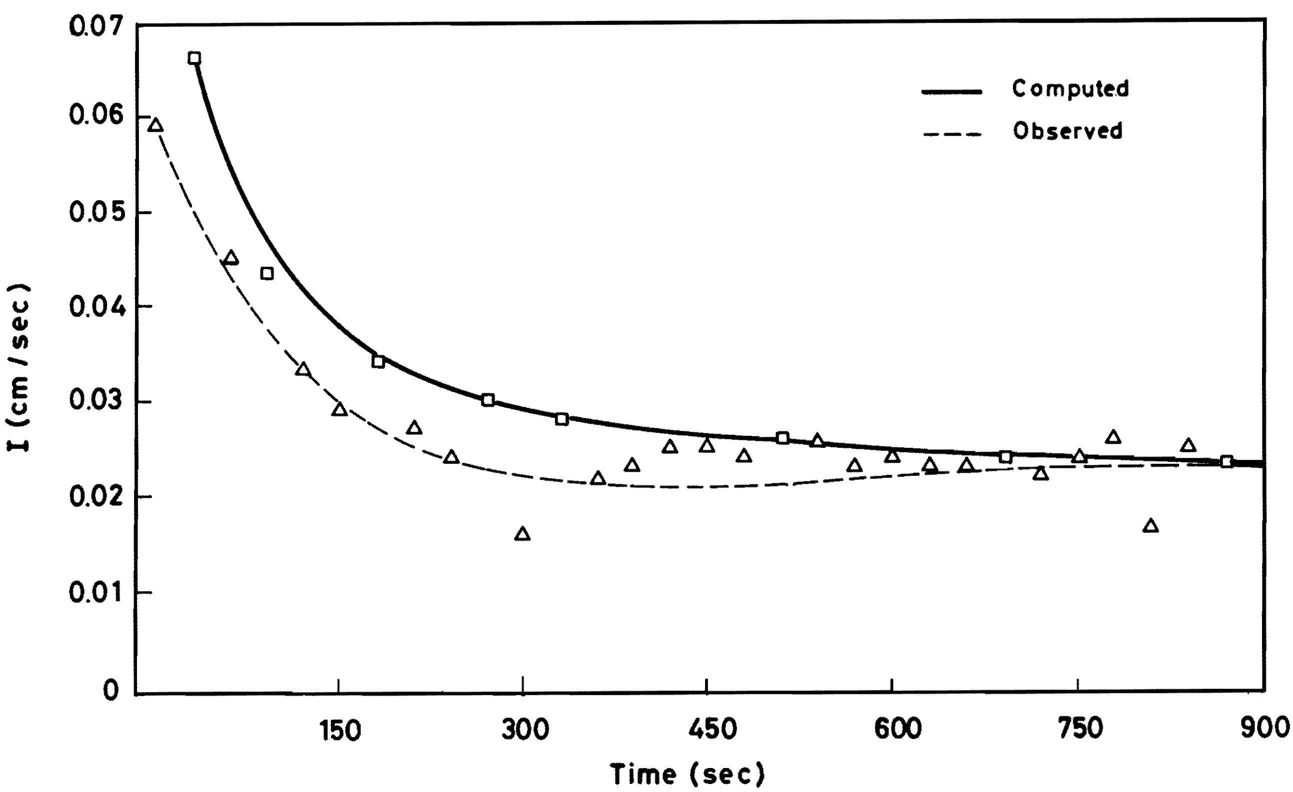

Figure 6. Comparison of Observed and Computed Infiltration Curves for Location 5.

Green and Ampt approach overpredicted infiltration rates at Locations 1, 2, and 5. For Locations 3 and 4, the Green and Ampt equation gave slightly less infiltration rates than field values with Location 3 predictions being closer to field results.

INFILTROMETER TESTS WITH VARIABLE INITIAL MOISTURE CONTENT

Location 1 at Ad-Dahna site was used to study the variability of infiltration rates with the initial moisture content in the sand dune. This will be useful in predicting infiltration and percolation of water through the dunes given certain season with storms each beginning at different initial moisture value.

The first experiment carried out at Location 1 as one of the five experiments explained in the first part of the study was considered the first experiment for the new set of experiments. The initial moisture content for that experiment was very low (average $\theta_i = 0.0008$, see Table 1). That experiment was carried out on 9 October 1990. Three other infiltrometer tests were conducted at the same location but at later dates. Samples were taken at the beginning of each test at soil surface, 15 cm and 50 cm depths from surface to find the average initial moisture content. The experimental procedure during these tests was exactly the same as the one used in the first set of experiments. Table 2 presents information on the four tests used in this part of the study. The average initial moisture content for each experiment was calculated based on weighted values of θ obtained at the three depths mentioned earlier.

The infiltration rates and how they vary with time for the four experiments listed in Table 2 are shown on Figure 7. The infiltration rates were calculated in a similar manner as was done in the first part of the study.

Table 2. Infiltration Experiments, Variable Initial Moisture Content.

Experiment No.	Date and Time	Total Depth of Water Applied, cm	Average Initial Water Content
1	Oct. 9, 1990 11:30 am	32	0.0008
2	Oct. 10, 1990 5:05 pm	27	0.018
3	Oct. 11, 1990 9:15 am	30	0.019
4	Oct. 16, 1990 2:35 pm	27	0.014

DISCUSSION

Table 1 shows that the initial and final moisture contents for sand in Ad-Dahna area are within a narrow range. This indicates the uniformity of sand within the area. However, the average final moisture content (based on values in Table 1) was 0.175 which is considerably less than the estimated porosity of the sand dune. That value was estimated to be 0.325. This shows that the sand in the dune area can not be fully saturated for even a short time and that it losses moisture very rapidly. The results in the first part of the study have also shown the uniformity of infiltration characteristics in sand dunes. The final infiltration rate for the five locations ranged between 0.0333cm/s (Location 1) and 0.020cm/s (Location 2) with an average value of 0.026cm/s. Infiltration rate calculations show that infiltration on the crest of a dune or the top of a large flat dune is higher than that in a trough between dunes. Finally, the Green and Ampt approach which was used to predict infiltration rates at the five locations seems to slightly overpredict field values. The only parameter that was assumed with not very strong justification in the approach was H_f. In obtaining values shown on Figures 2–6, H_f was assumed to be 15 cm. If a somewhat lower value of H_f was used, the prediction of the Green and Ampt method would have been better.

The four curves plotted on Figure 7 show that the initial infiltration rates for Experiments 1 and 4 (of the second set of tests) are high compared to the other two tests. Comparing curves shown on Figure 7, it is clear that the higher the initial moisture content, the lower the infiltration rate. The final infiltration rates (as estimated from the infiltration curves) for the four experiments are 0.035, 0.026, 0.024, and 0.026 cm/s, respectively. It is interesting to note the closeness of the final infiltration rates for Experiments 2, 3, and 4 with Experiment 1 having a distinctly higher final infiltration rate. The reason is that Experiment 1 was conducted with a very low initial moisture content and to reach a final infiltration rate similar to the other three experiments would require huge amounts of water and a very long time of application. Table 2 shows that the moisture content dropped to a low value within about 24 hours in going from Experiment 1 to

2 and from Experiment 2 to 3. It should be noticed, however, that in comparing initial moisture contents of Experiments 3 and 4, the drop in moisture content was small in spite of a difference of 5 days between the two experiments. It is clear that the sandy nature of the dunes makes the movement of water very fast and the moisture content drops to a low value (within a day or so) which can be considered close to field capacity of the sand. After that the decrease in moisture content slows down substantially.

CONCLUSIONS

The first set of experiments were conducted at different locations in the Ad-Dahna sand dune area. The purpose was to study how infiltration characteristics vary at different sites in Ad-Dahna dunes. From this part of the study, the following conclusions can be drawn:

1. After the long and very hot summer prevailing in the area, the initial moisture content in the dunes was found to be very small indeed. Down to a depth of 50 cm, the initial moisture content was very low and within a narrow range throughout the area.
2. Final moisture content reached after each experiment was considerably less than porosity.
3. Average hydraulic conductivity of dune sand in the Ad-Dahna area was found to be 0.024 cm/s (20.8 m/d). This is comparable to values found in textbooks on sand. The average final infiltration rate for the five tests was 0.026 cm/s, which is slightly over the hydraulic conductivity value.
4. The Green and Ampt approach gave reasonable predictions of infiltration rates and those predictions were comparable to field results.

The second part of the study was to perform infiltrometer tests at one location in the Ad-Dahna sand dunes with different initial moisture contents. The major conclusions of this part of the study can be stated as follows:

1. After saturation, moisture content will drop at a fast rate in sand dunes. This continues for up to 24 hours until the sand reaches field capacity. Following that, the rate of decrease of moisture content seems to slow down substantially.
2. Average final infiltration rates found in experiments with a variable initial moisture content

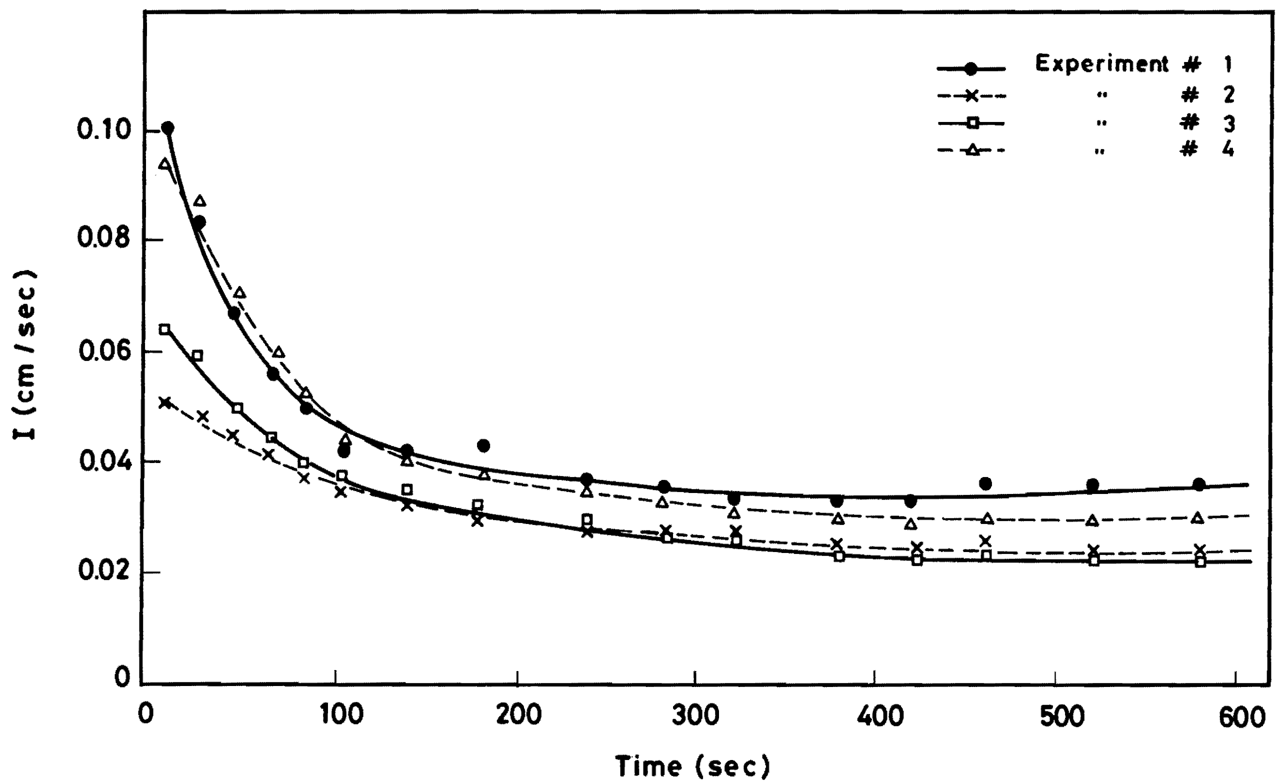

Figure 7. Variability of Infiltration Rate with Different Initial Moisture Contents.

(Experiments 2, 3, and 4) was 0.025 cm/s which is similar to the value found for the experiments in the first part of the study. This indicates that no matter what the initial moisture content of the dune was, the final infiltration rate should be the same.

REFERENCES

[1] Ministry of Agriculture and Water, *Water Atlas of Saudi Arabia,* 1984, p. 112.

[2] A. S. Tokhais, "A Quantitative Study of the Wasia Well Field", *M.S. Thesis, Ohio University,* 1982, p. 413.

[3] R. C. Prill, "Movement of Moisture in the Unsaturated Zone in a Dune Area, Southeastern Kansas", *USGS Paper 600-d,* 1968, p. D1-9.

[4] F. J. Frank, "Groundwater Resources of the Clatsop Plains Sand-Dune Area", *USGP Water Supply Paper 1899A,* 1970, p. 41.

[5] T. Dincer, A. Al-Mugrin, and U. Zimmermasn, "Study of Infiltration and Recharge through the Sand Dunes in Arid Zones with Special Reference to the Stable Isotopes and Thermonuclear Tritium", *Journal of Hydrology,* **23(1−2)** (1974), p. 79.

[6] G. B. Allison, W. J. Stone, and M. W. Hughes, "Recharge on Karst and Dune Elements of a Semi-Arid Landscape as Indicated by Natural Isotopes and Chloride", *Journal of Hydrology,* **76(1−2)** (1985), p. 1.

[7] T. C. Winter, "Effect of Groundwater Recharge on Configuration of the Water Table Beneath Sand Dunes and on Seepage in Lakes in the Sandhills of Nebraska", *Journal of Hydrology,* **86(3−4)** (1986), p. 221.

[8] A. N. Kostiakov, "On the Dynamics of the Coefficient of Water Percolation in Soil and the Necessity of Studying it from a Dynamic Point of View for Purposes of Amelioration", *Trans. Com. International Society of Soil Science, 6th Moscow, Part A,* 1932, p. 17.

[9] R. E. Horton, "The Role of Infiltration in the Hydrologic Cycle", *Trans. of the American Geophysical Union,* **14** (1933), p. 446.

[10] R. E. Horton, "An Approach Toward a Physical Interpretation of Infiltration Capacity", *Proceedings of the Soil Science Society of America,* **5** (1939), p. 399.

[11] H. N. Holtan, "Concept for Infiltration Estimates in Watershed Engineering", *USDA, Research Service Publication,* 1961, p. 41.

[12] J. R. Philips, "The Theory of Infiltration 1—The Infiltration Equation and Its Solution", *Soil Science,* **83(5)** (1957), p. 345.

[13] W. H. Green and G. A. Ampt, "Studies on Soil Physics. I—The Flow of Air and Water Through Soils", *Journal of Agricultural Science,* **4** (1911), p. 1.

[14] Y. S. Fork, "Evaluation of Algebraic Infiltration Equations", *Proceedings of the International Conference on Infiltration Development and Application, Hawaii,* 6−9 January 1987.

[15] H. Bouwer, "Infiltration of Water into Non Uniform Soil", *Journal of Irrigation and Drainage, ASCE,* **95(IR4)** (1969), p. 451.

[16] E. C. Childs and M. Bybordi, "The Vertical Movement of Water in a Stratified Porous Material. I—Infiltration", *Water Resources Research,* **5(2)** (1969), p. 446.

[17] D. Hillel and W. R. Gardner, "Transient Infiltration into Crust-Topped Profiles", *Soil Science,* **109** (1970), p. 410.

[18] D. S. Swartzendruber, "Infiltration of Constant-Flux Rainfall into Soil as Analyzed by the Approach of Green and Ampt", *Soil Science,* **117** (1974), p. 272.

[19] S. T. Chu, "Infiltration During Unsteady Rain", *Water Resources Research,* **14(3)** (1978), p. 461.

[20] A. S. Al-Turbak, "Infiltration in a Recharge Dam Reservoir Using a Green and Ampt Model and a Water Budget Approach", *Arabian Journal for Science and Engineering,* **15(2A)** (1990), p. 155.

[21] H. J. Morel-Seytoux and J. Khanji, "Derivation of An Equation of Infiltration", *Water Resources Research,* **10(4)** (1974), p. 795.

[22] H. J. Morel-Seytoux and J. P. Verdin, "Extension of the Soil Conservation Service Rainfall-Runoff Methodology for Ungaged Watersheds", *Rep. FHWA/RD-81/060, Federal Highway Administration,* 1981.

[23] D. Brakensiek, "Estimating Effective Capillary Pressure in the Green and Ampt Infiltration Equation", *Water Resources Research,* **13(3)** (1977), p. 680.

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