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Experimental and numerical modelling of constructed channels in the desert sand dunes for MAR applications

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ABSTRACT

Hydrology of sand dunes in the deserts of arid regions, specifically, groundwater in aquifers underlying the sand fields (e.g., Wahiba Sands in Oman) has been studied since 1970th. Sustainable water resources management in the desert dunes is essential, particularly in Gulf countries, where no perennial streams exist. Interdunal areas can be explored and tested for managed aquifer recharge (MAR) if natural wadis or small-size constructed channels are used as surface water spreading systems. These channels would both transport and seep tertiary treated wastewater into the vadose zone and enhance the amount of moisture content there. In this paper, a coupled surface-subsurface flow was experimentally and numerically studied in application to MAR through small-size triangular channels. In the field, experiments were done at the crest and slope of a selected dune, a triangular channel had a sand bed and a mild slope (S = 5°). By applying a constant discharge at the inlet of the channel, the length, L, of the water "jets" propagating until their complete seepage extinction has been measured. Numerically, by HYDRUS2D, we simulated saturated–unsaturated transient infiltration by considering a cross-section of triangular channels of different bank slopes λ to find the maximum total volume of infiltrated water from the channel. The boundary condition was a hydrostatic pressure head along the wetted perimeters of the channels with water depth gradually dropping downslope. The Morel–Seytoux shape factor $\mu = q_i/(K_s A_0^{1/2})$ where q_i is the rate of infiltration as a function of λ is plotted. If $q_i X \ll Q$, where X is a characteristic size in the direction of surface flow in the channel, Q is the surface flow rate, that is, for large channels and fast conveyance of surface water, q_i can be assumed independent of X. Then there is a unique minimum of $\mu(\lambda)$ at a given A_0. If q_i is not small, we determine the trench shape of a given A_0, which maximizes the total volume of water infiltrated from the trench. The results in this paper can be used in studies of furrow irrigation in desert agriculture and for evaluation of "transmission losses" from wadi channels flowing after flash floods.

Keywords: Sand dunes; Managed aquifer recharge; Surface–subsurface flow; Finite elements

1. Introduction

In recent years, isolated communities in the desert area have developed alongside sophisticated tourist and oil industry camps constructed in dune fields. Small sewage treatment units generate tertiary treated wastewater (TTW), which must be disposed of in environmentally and economically feasible way. Additionally, Haya Company in Oman is the primary manufacturer of TTW in large-scale plants, and the possibility of utilizing TTW for managed aquifer recharge (MAR), particularly in arid regions, is presently being investigated [1]. TTW has been utilized in Oman to fill surface ponds in Muscat [2] and for injection via a gallery of wells in the Salalah Coastal Plain (South of Oman, [3]). If natural wadis or small-scale built tunnels

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are used as surface spreading systems, large regions of interdunal valleys throughout Oman may be investigated and tested for MAR. These pathways would transport and infiltrate TTW into the vadose zone, increasing the vadose zone's moisture content. The infiltrating TTW, as well as runoff from rare rainstorms, will be directed vertically to refill a nearby unconfined aquifer that is a strategic reserve in Oman. Natural filtering of the infiltrating TTW will occur, and it may be retrieved from this aquifer through wells close to wadi channels and trenches.

The key design question is:

- What should be the length of a MAR portion of the channel to infiltrate all water discharged at the commanding reach, given a certain topographic slope, roughness of the bed, hydraulic conductivity of the sand, and a specific amount of TTW to be infiltrated?

Natural or artificial recharge of deep unconfined aquifers in arid environments via wadis (or other ephemeral and intermittent streams) requires accurate modeling of the conjugation between a relatively rapid horizontal surface flow in the channel and a relatively slow vertical water motion in a porous vadose zone beneath the channel. Numerous models are used to investigate the interplay of these two flows in the context of furrow irrigation and the hydrology of flash floods in wadis. For instance, [4,5] utilized HYDRUS to assess channel seepage. They examined a hybrid flow consisting of a subsurface Darcian flow described by the two-dimensional Richards' equation and a surface flow. Additionally, simpler models of one-dimensional infiltration from a channel have been employed [6–8]. Recently, Al-Shukaili et al. [9] studied surface–subsurface flow in a rectangular channel experimentally and mathematically.

In this research, we examine a continuous flow of surface water in a triangular soil channel that slopes downward in the horizontal direction OX aligned along the channel's axis in this article (Fig. 1a). This axis is parallel to the channel's rocky bed, which is a straight line that is parallel to the direction of the surface flow. We examine an array of equidistant triangular channels in our numerical model. The channel lattice's period L denotes the distance between two adjacent channels. We examine just one channel of the lattice due to symmetry. Each channel's triangular form (vertical cross-section in Fig. 1c) results in a constant bank slope.

2. Experimental jets in dune trenches

In September 2019, an experiment was conducted at the Agricultural Experimental Station (AES), Sultan Qaboos University (SQU), Oman. We chose a mini dune made of fine sand characterized by saturated hydraulic conductivity, K_s = 0.91 cm/min for trenches' construction [10].

First, for a mild topographic slope ($\omega\pi \approx 5°$) at the dune pedestal, a constant flow rate (Q_0 = 0.18 m^3/h) was discharged for 2 h at the commanding level of a triangular trench. Sand strongly eroded owing to this surface flow and re-settled on the banks of the trench forming a sinuous rather than straight watercourse (Fig. 2a). To prevent erosion, we designed a triangular nylon screen netting (W_n = 25 cm, L_n = 200 cm). The dune sand was pre-saturated and a triangular trench was excavated again to fit the designed frame (Fig. 2b). The anti-scouring netting was placed in tight contact with the subjacent sand. The trench was saturated again to make sure that the frame is in good contact with the surrounding sand. Then, the same Q_0 = 0.18 m^3/h was applied upstream of this reinforced structure. A steady-state surface flow was attained when W_0, H_0, and L_x stabilized. The length, L_x = 148.5 cm of a surface water jet was measured. The width (W_0) and water depth (H_0) of the trench were 5.0 and 2.5 cm, respectively (Fig. 2c and d). Then we evaluated the inlet Reynolds number $Re_0 = \varrho V_0 R_0/\mu\delta$, where $V_0 = Q_0/(W_0 H_0/2)$ is the average velocity at the commanding end of the trench, ϱ is the density of freshwater, $\mu\delta$ is dynamics viscosity and R_0 is the inlet hydraulic radius. Re_0 is more than 50,000 even if the

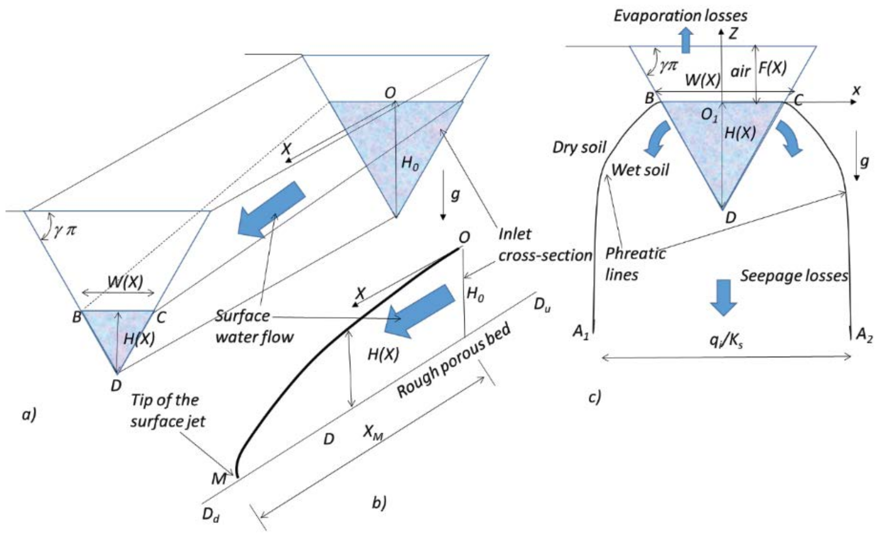

Fig. 1. (a) 3-D sketch of surface flow through a triangular trench, (b) "free jet" of surface flow in a cross-section along the trench axis, and (c) seepage flow in a vertical cross-section perpendicular to the channel axis.

viscosity of water is not adjusted to the high temperature of the trench bed. Therefore, we can use the Manning equation.

2.1. Coupling surface–subsurface flow numerically

The experimental results were compared with simulations in HYDRUS2D, where in a vertical cross-section, we considered a triangular trench having the inlet width $W_0 = 5$ cm and depth $H_0 = 2.5$ cm. The modeled flow domain (Fig. 3) was a rectangle of sizes $(x,z) \approx (25, 50)$ cm. The mesh size of the HYDRUS domain was 1.0 cm, which we refined to 0.1 cm near the trench bed. The domain was discretized into 231 and 6,715 of 1D and 2D elements, respectively. The water content tolerance was 0.001 and the maximum number of iterations was 10.

The van Genuchten (VG) parameters were retrieved from the Rosetta package by using a default sand material ($n = 2.68$, and $\alpha = 0.1451$/cm). The predicted K_s from Rosetta were modified to the measured value $K_s = 0.91$ cm/min.

We assumed that the initial pressure head $p_0 = -50$ cm at $t < 0$. Along the outlet segment (GJ in Fig. 3), a free drainage boundary condition was imposed. The sides NB, CE, EJ, and GN in Fig. 3 were fixed as no flux boundaries. A constant hydrostatic head was maintained along a wetted perimeter of the channel (segment BDC in Fig. 3). After 30 min of simulations, a steady state seepage was established. The bottom segment GJ outlet was selected to determine the infiltration rate, q_{i0}, at steady-state conditions. In vertical cross-sections downstream along the OX axis, W and H decrease due to seepage but we kept modeling seepage in HYDRUS as two-dimensional in the corresponding vertical planes. We computed $q_i(H)$ for $H_m < H < H_0$ with $H_0 = 2.5$ cm and $H_m = 0.5$ cm (Table 1). The choice of H_m was determined by the limitation of the numerical method: the trench sizes

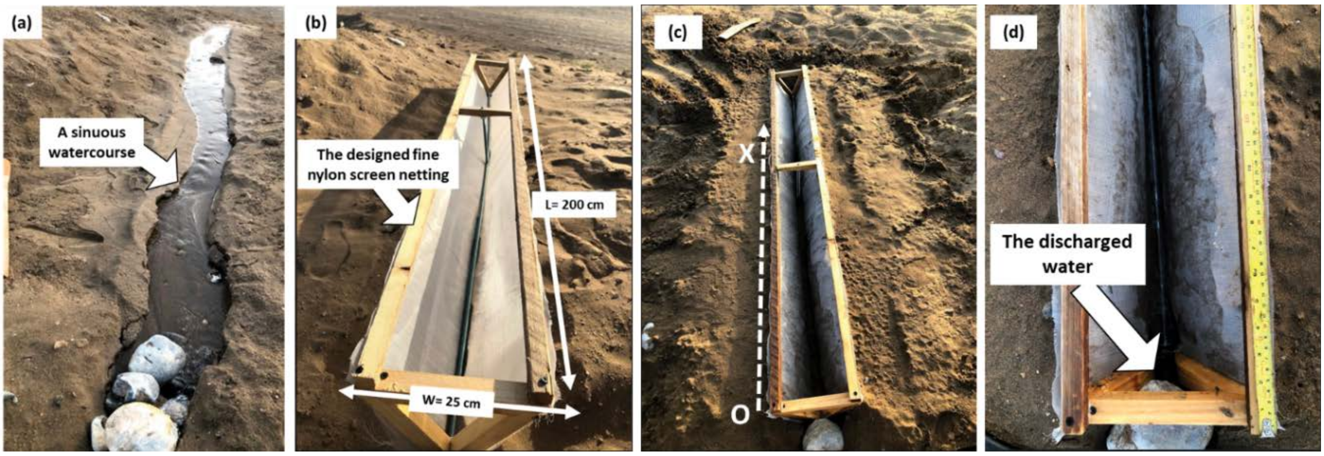

Fig. 2. Sand dune at AES, Oman, (a) the first channel subject to sand erosion morphed into a sinuous channel, (b) the designed fine nylon screen used as trench's stabilizer, and (c) surface flow direction OX in a buried frame, and (d) channel's inlet.

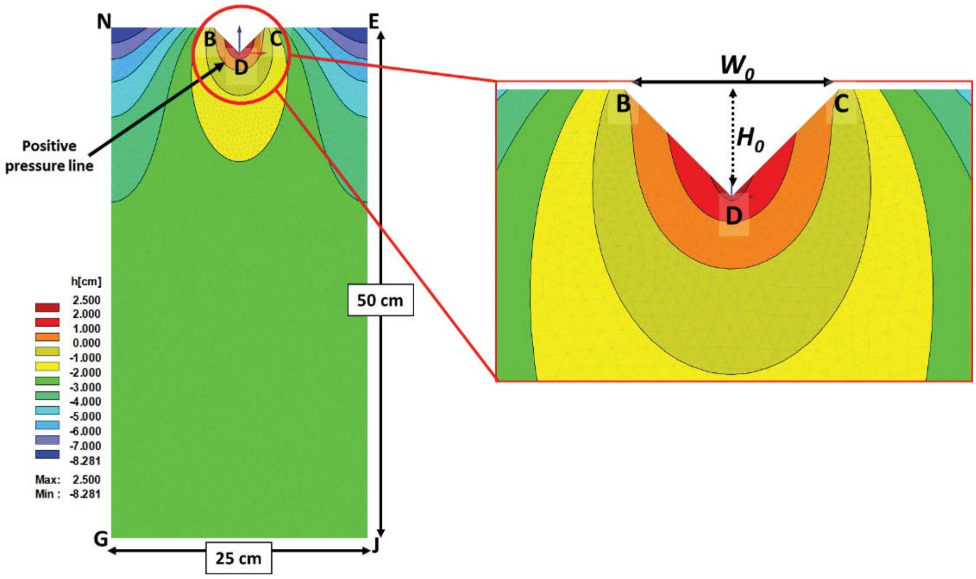

Fig. 3. The distribution of pressure head in HYDRUS domain at steady-state seepage.

in HYDRUS cannot be too small as compared with the size of finite elements.

Next, we used Manning's friction slope equation:

$$S_f = n_M^2 \frac{Q^2(X)}{A^2(X)R^{4/3}(X)} \quad (1)$$

HYDRUS-computed $q_i(H)$ and surface hydraulics were conjugated. The Manning roughness of the netting is not known and we took the value of $n = 0.02$ s/m$^{1/3}$. Miguel et al. [11] and Castellano et al. [12] reported intrinsic permeability of the netting material ranging from 6.5×10^{-9} to 2×10^{-11} m^2. We assumed $\mu\delta = 10^{-3}$ Pa·s and evaluated K_s.

In the computations, we took $W_0 = 0.05$ m, $H_0 = 0.025$ m and $K_s = 1.4 \times 10^{-2}$, 8.9×10^{-4} and 2.0×10^{-4} m/s. The corresponding dimensionless depths of jets are shown in Fig. 4 by curves 1–3. The netting material in our experiments is finer than sand and acts as a surface seal but the apparent (effective) conductivity of a two-layered medium (netting-sand) has not been measured. The experimental extinction length of the "free jet" is between ones shown by curves 1 and 2 in Fig. 4.

Table 1
HYDRUS-computed $q_i(H)$ values for various trench depths

H (cm)	q_i (cm^2/min)
0.5	6.974
0.7	8.096
1.0	9.450
1.2	10.417
1.5	11.629
1.7	12.500
2.0	13.626
2.2	14.395
2.5	15.259

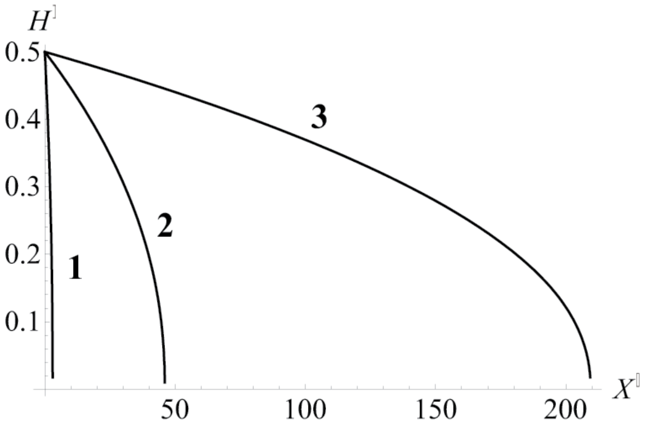

Fig. 4. Dimensionless depths of the jets as functions of dimensionless longitudinal coordinate for $W_0 = 0.05$ m, $H_0 = 0.025$ m, $n = 0.02$ s/m$^{1/3}$, topographic slope of 5°; curves 1–3 correspond to $K_s = 1.4 \times 10^{-2}$, 8.9×10^{-4} and 2.0×10^{-4} m/s.

3. Conclusion and discussion

Rural areas in arid regions, particularly in Oman's sand dunes, are expanding and require sustainable and autonomous water supply for their desert agriculture and domestic consumption. In addition, contemporary tourism and oil industry camps are constructed in the dune fields of Oman. Thus, the utilization of small sewage treatment units in remote areas to locally recuperate poor quality water is common. Therefore, a smart management of treated wastewater is necessary. TTW can be discharged in natural interdunal wadis (dry most of the time) or smaller scale channels constructed in the compacted sandy beds (covered by a thin layer of loose sand) of these wadis in many desert places across Oman (e.g., dune fields).

In this paper, a steady-state 1-D surface gradually varying water flow in a triangular channel is experimentally and numerically studied. The numerical model of infiltration (Richards' equation for saturated–unsaturated flow) from a triangular trench is solved in a vertical-cross-section, a pentagon made of the Van Genuchten soil. This flow is also coupled with a "normal" or quasi-normal surface flow. The length of propagation of a "free jet" downslope from the inlet is found. A given quantity of water is released at the inlet and vanishes from the trench due to infiltration.

In addition, optimal shape design problems are addressed, with the selection of the infiltration rate and channel's cross-sectional area (or volumetric flow rate) as a criterion. The Morel–Seytoux shape factor $\mu = q_i/(K_s A_0^{1/2})$ where q_i is the rate of infiltration as a function of λ is plotted. If $q_i X << Q$, where Q is the surface flow rate, that is, for large channels, q_i can be assumed independent of the longitudinal coordinate, X, along which the surface water is rapidly moving. Then there is a unique minimum of $\mu(\lambda)$ at a given A_0. If q_i is not small, we determine the trench shape of a given A_0, which maximizes the total volume of water infiltrated from the trench. The experimental results were compared with HYDRUS2D simulations. Gravity and capillarity are the main controlling physical phenomena, while the soil is a resistor to water motion along the downstream topographic slope (in surface flows) and downstream through the vadose zone (in subsurface Darcian flows). These three physical factors are amalgamated in a single dimensionless coefficient, which involves the topographic slope, channel's width, and the Darcian–Manning frictions as quantifiers of subsurface–surface medium resistances.

The results of this paper can be used not only for planning MAR operations but also for furrow irrigation in desert agriculture of arid lands. The results can be also used for evaluation of "transmission losses" from large-size wadi channels flowing after flash floods.

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Symbols

θ_v	—	Volumetric water content, –
θ_r	—	Residual water content, –

θ_s	—	Saturated water content (porosity), –
K_s	—	Saturated hydraulic conductivity, cm/d
n	—	VG parameter in the soil water retention function, –
α	—	VG parameter in the soil water retention function of the matrix, cm^{-1}
p	—	Capillary pressure head, cm
h	—	Total pressure head, cm
t	—	Time, d
m_e	—	Effective porosity, –
n_M	—	Manning's roughness, s/m$^{1/3}$
x	—	Horizontal Cartesian coordinate in the vertical cross-section, used in HYDRUS and analytical model, cm
y	—	Vertical Cartesian coordinate in the analytical model, cm
z	—	Vertical Cartesian coordinate in HYDRUS, cm
v	—	Vertical component of Darcian velocity, cm/d
λ	—	Slope of the channel bank, °
q_i	—	Seepage losses per unit length, cm^2/d
H	—	Depth of water in the channels, cm
W	—	Channel's width, cm
R	—	Hydraulic radius, cm
Q	—	Volumetric discharge, cm^3/s

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