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A hydroecological technique to improve infiltration of clogged bed of recharge dam in Oman

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ABSTRACT

Recharge dams represent one of few engineering techniques to harvest flashfloods water in arid zones for augmenting the limited water resources. Formation of a low-permeable cake by deposition of suspended particles transported by ephemeral floods is a common problem for dams in arid regions (e.g., Oman, Saudi Arabia, Iran, and Tunisia). Accumulation of surface sediments affects many hydrological properties of dam's reservoir area, including reduced infiltration and deep percolation rates, higher water loss via evaporation, and ultimately lower aquifer recharge and higher flood peaks. The recharge basin downstream the dam receives pulses of suspended sediments after each major flashflood. This causes a "hopping" downward translocation of fine particles into the coarse-texture matrix of the alluvium bed, clogging of the pores which significantly reduces the saturated hydraulic conductivity (K_s). The intermittent flashfloods forms multilayered heterogeneous soil profile and a resultant non-monotonic cumulative infiltration curves have intricate hydro-engineering implications, for example, we observed that the runoff water, released from the dam, instead of a fast vertical infiltration, forms a shallow quasi-horizontal Darcian flow that out-seeps further downstream into local topographic depressions and contributes to undesired runoff-evaporation. Hence, finding practical solutions to overcome the consequences of the siltation problem of dam beds is of a paramount importance. In this work, we investigated the possibility of applying a hydro-ecological method to combat the cake-clogging curse. We experimentally (using pots experiment) and numerically (using HYDRUS-2D code) quantified the effect of roots of indigenous trees, namely Sidr (*Ziziphus spina-christi*) grown in soil pots on increasing infiltration through a clogged layer. The pots were exposed to two flood events over 12 months period of cultivation. The average initial infiltration rates for vegetated pots (240 and 147 mm/h for F1 and F2, respectively) which is 2.4 and 2.1 times higher than that for pots without plants, bare soil (around 85 mm/h in average). For vegetated pots, the final infiltration rates (K_s) were higher by 1.7 and 3.3 times than that for the control pots, ($p < 0.05$). The numerical modeling illustrated the effect of the root system on the dynamics of soil water. The root system enhances the propagation of the soil water in both lateral and vertical directions. The results indicate the feasibility of this hydroecological technique in improving the infiltration rate and hence the recharge efficiency of recharge dams in arid areas.

Keywords: Clogging; Pore space; Infiltration; Arid zone; Recharge dams; HYDRUS-2D; Root water uptake; Ziziphus spina-christi

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1. Introduction

Siltation is a serious common problem for recharge dams in arid regions. As these sediments are brought by ephemeral flashfloods and accumulate at the surface of the dam's reservoir area and hence alter the hydrological properties of the dam's bed and that of the vadose zone. These include reducing infiltration and deep percolation rates, as well as reducing the storage capacity of dams. This adversely affects the recharge to underlying aquifers [1–8]. Therefore, it is very important to find practical solutions to cope with siltation.

The recharge efficiency and the original storage capacity on the upstream area of Al Khoud Dam reservoir bed (located in Muscat Governorate in North of Oman) are greatly influenced by substantial changes in the Pedological and physico-hydrological properties. This is because of the deposition of the brought-in sediments by the detained infrequent Wadi flows. The recharge basin downstream of the dam is continually shrinking because of expanding urbanization. The currently undertaken practice to remove the deposited materials by bulldozers seems to be impractical due to the huge amount of sediments and macro-pores clogging by fine particles migration [4].

This almost-zero salinity silt cake is good as a substrate for plants to grow. Plant roots are well known for improving the permeability of the soil as the roots provide extra passage channels for water to flow through [9,10]. Along with improving infiltration ability of the soil, roots of the plant are expected to break the capillary barrier formed at the interface of the deposited fine texture soil and the original gravely coarse-textured material underneath. Studies have shown that plants' roots are capable to penetrate fine and compacted soils and create preferential channels where water can seep through and ultimately increase the infiltration rate [9–13]. The growth of the plants and their roots can further enhance the infiltrability of the soil. A study by Leung et al. [14] found that the infiltration rate in silty sand soil was directly related to the increase of plant age, root biomass, and root length density. In another study, the roots of *Eucalyptus largiflorens* were found to increase the infiltration by 2–17 times as compared to none vegetated clay-floodplain [11]. Al-Maktoumi et al. [15] found that the growing indigenous *Ziziphus spina-christi* trees can significantly increase the infiltration rate of silt loam sediments by 1.9–5.9 times as compared with bare soil ($p < 0.05$). Additionally, their study demonstrated that the infiltration rate was significantly improved with the growth of plants roots over time.

This paper explores experimentally (using pot experiments) and numerically (using HYDRUS-2D software) the effect of roots of the indigenous trees (*Ziziphus spina-christi*) locally named "Sidr" on improving infiltration. In practical implementation, the plantation zone has to be far away from the embankment because plant roots may threaten the safety of the clay core of the dam and hence jeopardize its structural stability. The study also investigates the impact of trees' roots and water supply frequency (irrigation scheduling) on moisture dynamic using HYDRUS-2D.

The study assesses the suitability of the suggested eco-hydrological solutions to combat or reduce the potential adverse effects of siltation and growing urbanization and hence improve recharge efficiency in the vicinity of recharge dams and similar reservoirs in arid areas. The study contributes to a better understanding of the water dynamics within the vicinity of the dam under the designed ecological technique, which is of critical importance for better management strategies and augmentation of water resources that will provide the foundation for future decision making by the concerned water agencies.

2. Methodology

2.1. Pots experiment

Circular pots of 40 cm high were packed with soil collected from Al-Khoud dam area. The pots have soil layering similar to the layering observed in Al-Khoud (reservoir). Fig. 1 presents the layout of the experimented pot. The soil was sieved using a big 2 mm soil sieve. A certain volume of water was occasionally applied to the pots during the experiment period. This represents irregular flood events that are due to erratic and sporadic rainfall pattern that characterizes the Omani climate (and arid zone in general). During each flood experiment, the infiltration rate was measured. The infiltration date experiment was analyzed using Horton equation to calculate the final infiltration rate. The experimental site is the Agricultural Experiment Station (AES) at Sultan Qaboos University, where all facilities/necessary logistics needed for the experiment are available (23° 35′ 37.0″ N, 58°09′03.7″ E). The AES is only a few kilometers from the dam area and the weather conditions at both sites are almost the same.

The planted Sider trees were subjected to irrigation as the soil in the tank is of limited volume, while in reality these trees are well known to survive without irrigation because they are water hunters. The irrigation stopped before the flooding (infiltration experiment). The evapotranspiration rate in the pot was estimated at the experimental site and modeled for the dam area.

Out of 12 small pots (of 39 cm in length, 14 cm in diameter), 3 pots were considered as control (without plants).

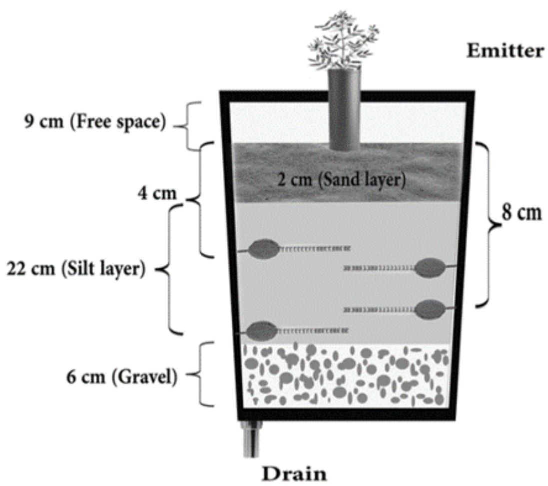

Fig. 1. Schematic diagram for a cross-section of pot experiment.

The inner walls of the pots were plastered with coarse sand and cement to create a rough surface. This helped to reduce the development of macro and micro-cracks between the soil body and the inner wall of the pot because of variation in material affinity between the soil and the pot surfaces. All pots were packed with a small gravel layer (about 5–6 cm) at the bottom, then silt layer of 22 cm depth), and finally sand layer with 2 cm thickness (Fig. 1). The root density and distribution patterns were studied by scarifying one pot at a time for destructive analysis. The bottom side of the pot was equipped with controlled valves to measure the volume of percolating water. The experiment was run for 12 months period.

2.2. Plantation and irrigation

Initially, 9 replicates for Sider were selected for the experiment. The reason behind choosing these trees is lagged behind their morphology and root characteristics since they are indigenous, coarse with deep root trees, and presumably can survive the climatological and water stress condition as observed in the vicinity of Al Khoud Dam and along wadis in Oman (Fig. 2a). The initial height of the seedlings was 72 cm. The seedlings were transferred to a 30 cm high PVC pipe to provide support to the seedlings and space for irrigation (Figs. 1 and 2b).

The average number of leaves/branches and the average height of the plants were measured. A total number of six observations were made during the experiment. The root topology and features were investigated. Additionally, the length of roots and shoots were measured. The dry biomass of roots and shoots was estimated.

All pots were irrigated daily with 133 mm of good quality water (ECi = 0.5 dS/m) using a pressure compensating Heavy Wall drip line (Netafim, USA) attached with a pressure compensated emitter for uniform and constant dripping (4 L/h). The emitters were positioned in the PVC pipes. Hunter controller (Hunter NODE) was used to manage both the timing and frequency of the irrigation.

According to the soil texture analysis, the packed soil was classified as silt loam using the hydrometer approach. This soil has 75.5% silt, 19.8% clay, and 4.7% sand (Table 1). This soil also has a pH of 8.4 with an electrical conductivity of 1.25 dS/m. The irrigation water has a pH of 8.2 and electrical conductivity of 0.23 dS/m. Generally, the physico-chemical properties of soil and water support the good growth of plants. The soil pH and the electrical conductivity (EC_{e-} for saturated extract) were measured using pH meter and electrical conductivity meter respectively [16].

Table 1
Physico-chemical properties of the soil

Soil properties	Values
Sand (%)	4.7
Silt (%)	75.5
Clay (%)	19.8
Textural class	Silt loam
pH	8.4
Ece (dS/m)	1.25

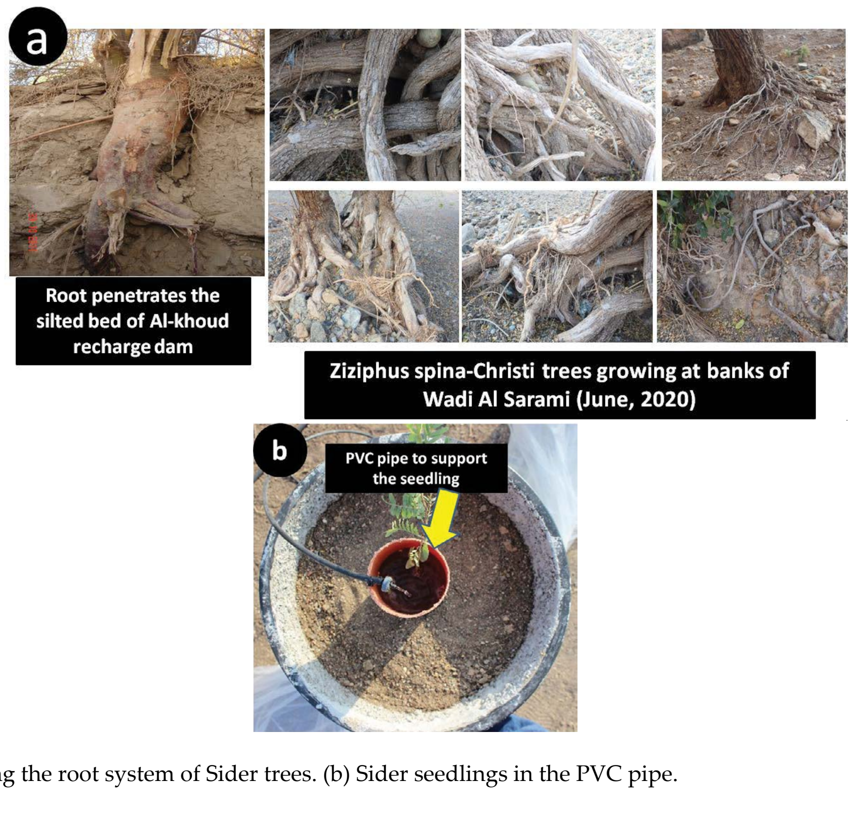

Fig. 2. (a) Photos showing the root system of Sider trees. (b) Sider seedlings in the PVC pipe.

2.3. Infiltration measurements

All pots were ponded during the infiltration tests. In order to prevent direct disturbance of the soil, date palm residues (leaf sheath) were placed at the topsoil of each pot. Then the water slowly poured and the falling of the water level in the pots was measured with the aid of a 15 cm graduated ruler at 2-min intervals for the first 10 min, 5-min intervals for the next 20 min, and, finally, 10-min intervals until reaching a steady-state condition.

2.4. Set up of the numerical modeling using HYDRUS-2D

HYDRUS-2D [17] was used to simulate axisymmetric moisture dynamic in a hypothetical soil cylinder with root water uptake (RWU) by a tree (resembling Sider tree) under three different water supply patterns (irrigation regimes). The first regime models the experiment with Sidr (*Ziziphus spina-christi*) of Al Yamani et al. [18]. The irrigation flux for this scenario was 0.273 cm/h for a duration of 7 h every day. The second-scenario was the same as for the first scenario (i.e., same flux and duration) but with deficit irrigation (i.e., irrigation done once every 2 d). In the third scenario, the irrigation flux was doubled (=0.546 cm/h) while maintaining the same duration (7 h) and frequency (once every 2 d) as for the second-scenario.

The length of time for each scenario in HYDRUS was 720 h (30 d) with a print time equal to 30. The geometry of the HYDRUS-2D model is axisymmetric with z = 10 m and r = 3.95 m (Fig. 3). The origin of the Cartesian coordinate system was at the bottom left corner of the domain geometry. The mesh size for the domain was 10 cm and was refined to 1 cm near the vicinity of the tree. The domain was discretized into 11,125 nodes (475 and 21,773 1D and 2D elements, respectively). The maximum number of iterations was 10 and the water content tolerance was 0.001. van Genuchten–Mualem (VG-M) hydraulic model with no hysteresis was used for the simulations.

The soil texture for all three scenarios was assumed to be homogeneous sand (Table 2). We used the HYDRUS Rosetta package to estimate the VG-M properties of this sand based on the textural properties and bulk density. The predicted K_s and θ_s were modified to measured values reported by the study of Al Yamani et al. [18]. We also used Eq. (1) from Ghezzehei et al. [19] to convert α_G of Al Yamani et al. [18] into α_{vG} We then put the converted value into HYDRUS.

$$\alpha_G = 1.3\alpha_{vG}n \quad (1)$$

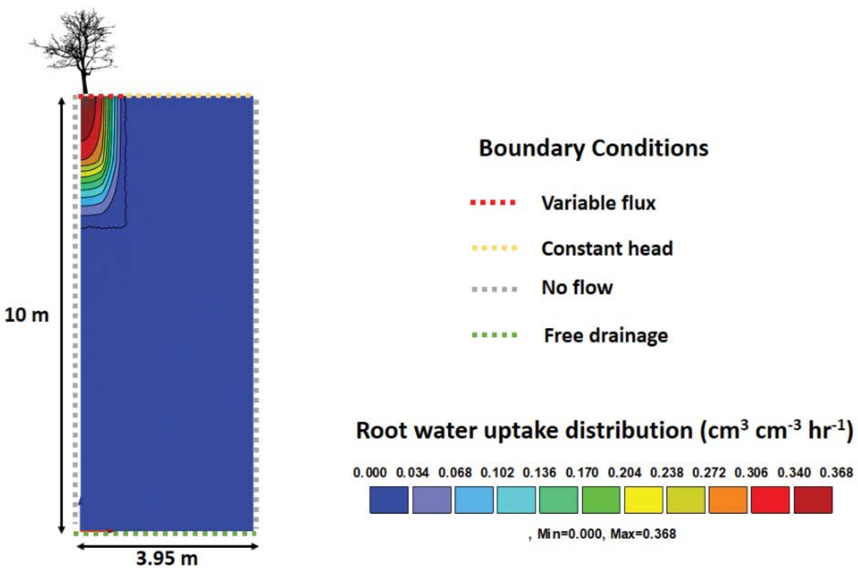

Fig. 3. Geometry and selected HYDRUS boundary conditions.

Table 2
Soil properties for the sand: θ_r and θ_s are the residual and saturated water contents, respectively; α and n are shape parameters for the van Genuchten–Mualem equation; and K_s and L denote the saturated hydraulic conductivity and pore-connectivity parameter, respectively

Soil type	Soil particles (%)			Bulk density (g/cm³)	θ_r (cm³/cm³)	θ_s (cm³/cm³)	α (cm)	n (–)	K_s (cm/h)	L (–)
	Sand	Silt	Clay							
Sand	95	1	4	1.54	0.055	0.41	0.046	3.34	900	0.5

Note: Soil particles, bulk density, θ_s, and K_s were obtained from Al Yamani et al. [18] while n and L were obtained by Rosetta.

where α_G (constant > 0) is sorptive number (1/m) [20], $n \geq 1.5$ and α_{vG} are shape parameters for the van Genuchten–Mualem equation.

HYDRUS-2D uses [20] equation to model RWU as a function of soil water pressure head. The 2D form of Feddes et al. [21] equation is given by Eq. (2):

$$S(h, x, y) = \propto (h) S_p(x, y) \tag{2}$$

where $S(h,x,y)$ is the actual RWU or volume of water removed from a unit volume of soil per unit time (t^-), $\infty(h)$ is a dimensionless stress response function of the pressure head ($0 \leq \infty \leq 1$), and $S_p(x,y)$ is the potential RWU rate (t^-). This equation assumes that the actual RWU is zero close to saturation and the permanent wilting point (PWP). At saturation, the root zone experiences lack of oxygen, and at the PWP plants cannot extract water [22]. Plants are also considered water-stressed if the actual RWU is below 0.5 cm/d [23].

The initial condition was constant pressure head and was set at –1,000 cm. The boundary conditions were set as follows: variable flux boundary condition for the top surface at 1 m radial distance from the tree trunk, constant pressure head = –1,000 for the remaining part of the upper boundary condition, free drainage at the bottom boundary, and no flow boundary allowed through the vertical sides of the transport domain due to symmetry (Fig. 3).

HYDRUS also requires partitioning reference evapotranspiration (ET_0) into evaporation (E) and transpiration (T). To do so, we first selected and obtained the average reference evapotranspiration (ET_0) (mm/d) for a summer month (i.e., June; ET_0 = 7.15 mm/d) from Al Yamani et al. [18]. We also obtained the value of leaf area index (LAI = 1.97) for *Ziziphus spina-christi* from Zait and Schwartz [24]. Next, we used Eq. (3) to calculate surface cover fraction (SCF) from LAI as follows:

$$\mathrm{SCF} = e^{(-\mathrm{rExtinct} \times \mathrm{LAI})} \tag{3}$$

where rExtinct = 0.463. Then, we calculated E and T by using Eqs. (4) and (5), respectively:

$$T = \mathrm{ET}_0 \times \mathrm{SCF} \tag{4}$$

$$T = \mathrm{ET}_0 \times (1 - \mathrm{SCF}) \tag{5}$$

The calculated values of SCF, T, and E were 0.598, 4.276, and 2.874 mm/d, respectively. Next, the values of T and E were input in the HYDRUS time-variable boundary condition table. HYDRUS-2D asked about surface area associated with transpiration. We assumed that the canopy cover 1 m around the tree. Therefore, the area associated with transpiration for the axisymmetric domain was calculated by ($\pi r^2/2$ and found to be 15,707.96 cm^2).

Table 3 shows the RWU parameters for the water stress response function in the model for *Ziziphus spina-christi*. P0 in Table 3 is the value of the pressure head below which roots start to extract water from the soil. POpt is the value of the pressure head below which roots extract water at the maximum possible rate. P3 is the value of the pressure head below which root water uptake stopped (usually set at the PWP). r2H and r2L are upper and lower threshold potential transpiration rates, respectively. P2H is the value of the limiting pressure head below which roots can no longer extract water at the maximum rate (assuming a potential transpiration rate of r2H). P2L is defined as P2H but it assumes a potential transpiration rate of r2L. The vertical and horizontal distribution parameters for the root are shown in Table 4. The maximum vertical and horizontal root distribution were 3 and 1 m, respectively.

Table 3
RWU parameters for the water stress response function for Sider trees (*Ziziphus spina-christi*)

Parameter	Value
P0 (cm)	–10
POpt (cm)	–25
P2H (cm)	–400
P2L (cm)	–400
P3	–8,000
r2H (cm/d)	0.5
r2L (cm/d)	0.1

Finally, three observation points (OP) were placed parallel to surface with the variable flux boundary condition (OP1 (x = 0, z = 9.7 m); OP2 (x = 0.75 m, z = 9.7 m); OP3 (x = 1.4 m, z = 9.7 m)).

3. Results and discussions

The graphically presented results of the pots experiments (Fig. 4) shows that the average initial infiltration rates for vegetated pots (240 and 147 mm/h for F1 and F2, respectively) were 2.4 and 2.1 times higher than that for the control pots (100 and 70 mm/h for F1 and F2, respectively). The steady-state infiltration rates for pots with Sider trees were approximately 10 mm/h for F1 and 19.5 mm/h for F2, which are significantly higher by 1.7 and 3.3 times than that for the control pots ($p < 0.05$).

At the end of the experiment, the bulk density was measured using a core sampler for four planted and one-control pots. It varied from 1.49–1.53 g/cm^3 for the Sider pots and was 1.51 g/cm^3 for the control pot.

At the end of the experiment, the average plant height of the Sider tree was about 69–73 cm (Fig. 5). The Sider showed no significant increase in height during the relatively short period of the experiment; however, their canopy developed as quantified by the average number of the leaf. The number of leaves increased from 63 to 500 during the experiment (Fig. 5a). By the end of the experiment, the average dry biomasses of the shoot and roots of the Sider were 26 and 15 g, respectively. The fast growth of the shoot and the canopy of the plants likely correspond with a similar growth rate of the root system. Sider plant is known to have a high root-to-shoot ratio [25]. Its root development is tightly coupled to canopy photosynthesis [26]. This was evidenced by the topology of the root system of the Sider after cutting the pots (Fig. 5b).

Table 4
Spatial distribution parameters of the roots

	Value
Vertical distribution	
Maximum rooting depth (m)	3
Depth of maximum intensity (m)	1.5
Parameter P_z (–)	1
Horizontal distribution in *x*-axis	
Maximum rooting radius (m)	1
Radius of maximum intensity (m)	0.5
Parameter P_x (–)	1

Note: P_x, P_y and P_z are empirical parameters.

The roots of the planted Sider tree penetrated the full depth of the pot and proliferated all over the soil. The average height of the Sider at the end of the experiment was about 85 cm (Fig. 5a). The roots of the plants create biochannels that can increase macroporosity of the soil, especially when the roots decay [27–30]. The roots also may cause the formation of cracks and hence preferential flow occurs [31]. At the end of the experiment, the bulk density was measured using a core sampler for four planted and one control pot. It varied from 1.49 to 1.53 g/cm^3 for the Sider and was 1.51 g/cm^3 for the control pot.

4. Numerical simulations

Figs. 6a–c show HYDRUS simulated water content curves at the three selected observation points for the three scenarios. The consistent sinusoidal oscillations in these curves indicate that the soil reaches the steady-state condition. It can be also observed that the oscillation of OP1 and OP2 are concise with almost the same amplitude and period as compared to OP3, indicating the impact of roots on the distribution of moisture content in the soil profile. The root water uptake for the three scenarios is higher closer to the vicinity of the tree (RWU = 0.0000995 h^{-1}) but it decreased till it reached 0 h^{-1} as you move away (with depth or horizontally) from the tree. Although all the three observation points are located at the same depth (about 0.3 m from the soil surface), OP1 and OP2 are located within the highest horizontal distribution density of the roots (Fig. 3 and Table 4). Our results also illustrate that the change in the water supply regime (or irrigation pattern) can influence the distribution dynamics of moisture content and roots in the soil profile (Figs. 6a–c and 7a–c). When deficit irrigation or irrigation with reduced frequency and increased flux are applied, a clear perturbation in OP3 can be more observed than that of scenario a. This may be attributed to the fact that plants tend to send their roots deeper and laterally away from the trunk to hunt for water [32]. The penetration of roots creates channels or also known as bio-pores that increases the macroporosity of the soil and ultimately infiltration rate [27,33]. The actual root water uptake for the three scenarios is shown in Fig. 8. In scenario a, the actual root water uptake attained steady-state at 0.018 cm/h after 120 h. Applying deficit irrigation can delay the time needed to attain steady-state actual root water uptake by 65 h. However, reducing the frequency and increased irrigation flux regime lead to earlier arrival by almost 16 h to a steady-state actual root water uptake as compared to scenario a.

5. Conclusion

This study explored the feasibility of applying a hydro-ecological technique to improve the infiltration of ponded water in recharge dams in Oman. We experimentally

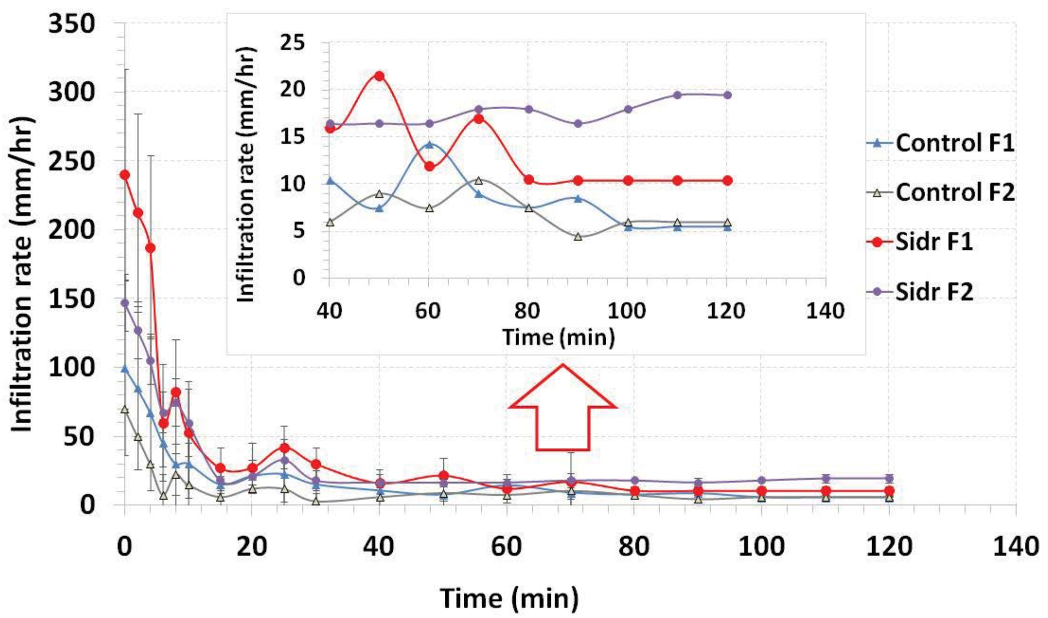

Fig. 4. Infiltration for Sider trees for F1 and F2 experimental runs.

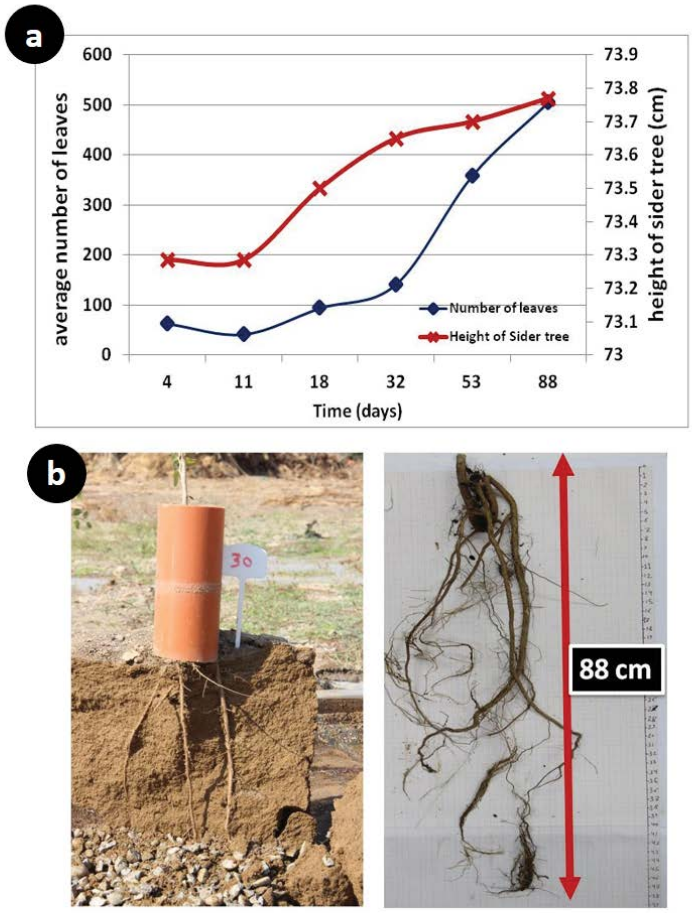

Fig. 5. (a) Plant growth parameters: average plant height and average leaf number for Sider trees. Error bars are standard deviations. (b) Main and fibrous roots penetrated the silty loam sediment reaching the bottom of the pot (left photo), and washed roots, length reached about 48 cm (right photo) – (Adapted from Al-Maktoumi et al. [15]).

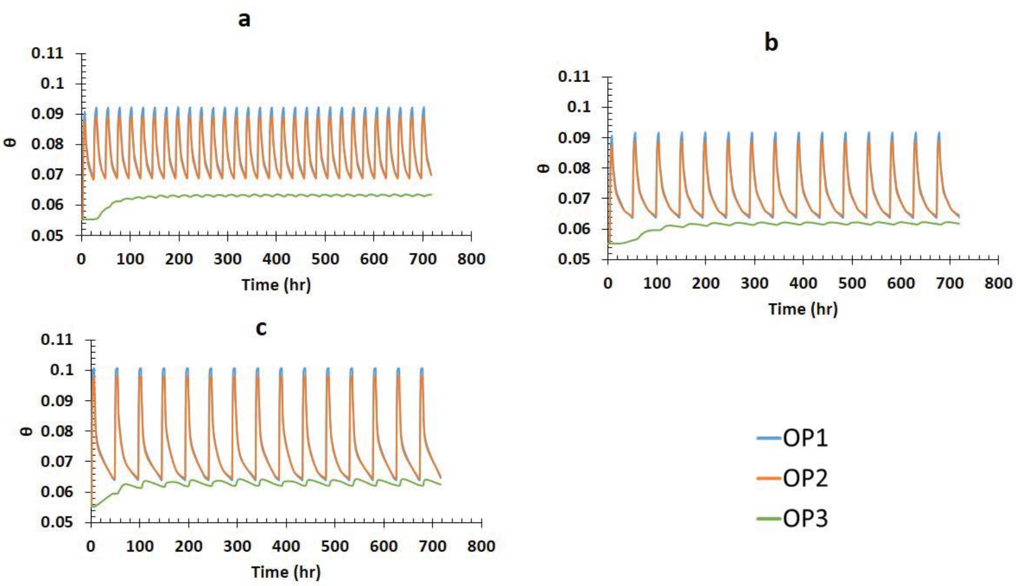

Fig. 6. HYDRUS simulated water content curves at the three-set observation points for the three scenarios: (a) background regime, (b) deficit irrigation, and (c) irrigation under reduced frequency and increased flux as compared to scenario a.

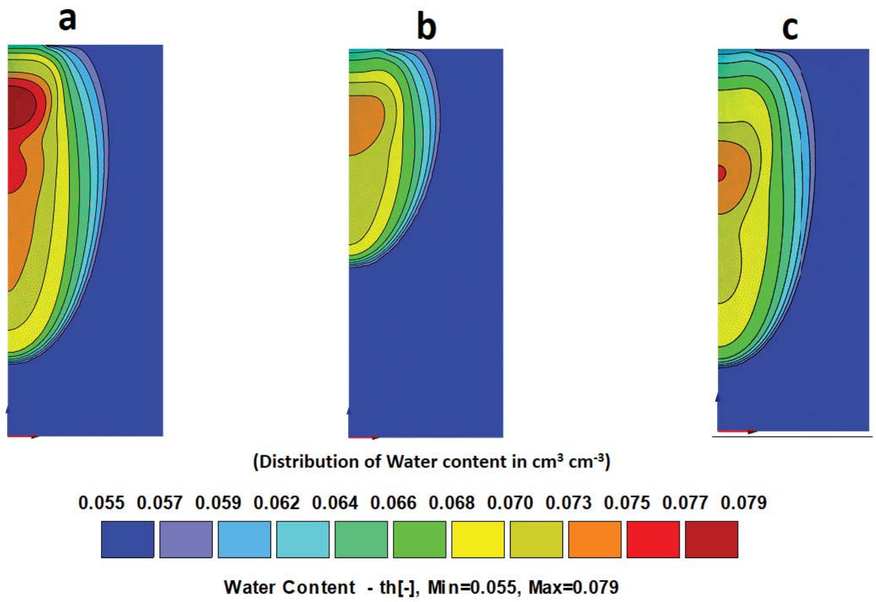

Fig. 7. Distribution of water content in HYDRUS domain after steady state was attained (t = 720 h): (a) background regime, (b) deficit irrigation, and (c) irrigation under reduced frequency and increased flux as compared to scenario a.

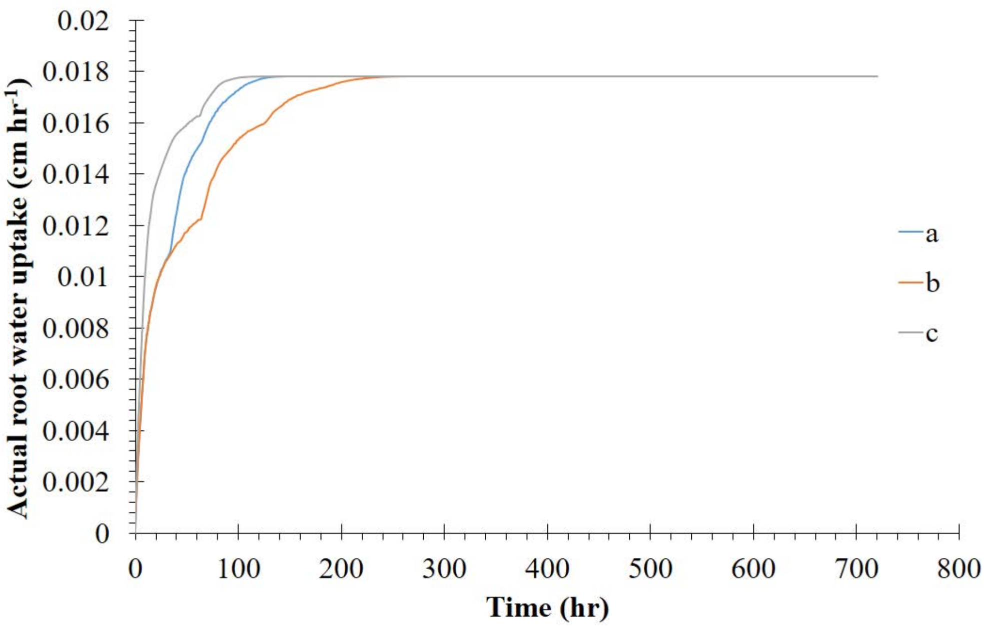

Fig. 8. Actual root water uptake (cm/h) obtained from HYDRUS: (a) background regime, (b) deficit irrigation, (c) irrigation under reduced frequency and increased flux as compared to scenario a.

quantified the effect of roots of indigenous trees, *Ziziphus spina-christi* (Sider) grown in soil pots on increasing infiltration through a cake layer. The results of the pot experiment and the numerical simulations show that the trees significantly increase the steady state infiltration rate of the sediments by 1.7–3.3 times compared to the control (bare soil) in the ($p < 0.05$). The numerical modeling illustrated the effect of the root system on the dynamics of soil water. The root system enhances the propagation of the soil water in both lateral and vertical directions.

The results indicate the potential of this hydro-ecological technique for improving the infiltration rate and hence the recharge efficiency of dams in arid areas. Moreover, intensified infiltration through dams' lakes would contribute to decrease the possibility of flashfloods to the intensely urbanized area downstream of the dam.

For practical application to a silted recharge dam, a detailed field study to measure the entire water budget for the study area is required. Moreover, the interactions between surface water and the underneath unconfined aquifer are needed. This will support the optimum design of aquifer recharge to avoid all possible complications as waterlogging due to groundwater mounds under the afforested area of the dam lake.

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