Effect of water application methods on salinity leaching efficiency in different textured soils based on laboratory measurements and model simulations

Ting Yang\textsuperscript{a,b,1}, Setrag Cherchian\textsuperscript{b}, Xinmin Liu\textsuperscript{c,2}, Hossein Shahrokhnia\textsuperscript{b}, Minghao Mo\textsuperscript{d}, Jirka \v{S}imůnek\textsuperscript{b,3}, Laosheng Wu\textsuperscript{b,7,4}

\textsuperscript{a} Key Lab of Guangdong for Utilization of Remote Sensing and Geographical Information System, Guangzhou Institute of Geography, Guangdong Academy of Sciences, Guangzhou 510070, China
\textsuperscript{b} Department of Environmental Sciences, University of California, Riverside, CA 92512, USA
\textsuperscript{c} Chongqing Key Laboratory of Soil Multi-Scale Interfacial Process, College of Resources and Environment, Southwest University, Chongqing, China
\textsuperscript{d} Jiangxi Academy of Water Science and Engineering, Nanchang 330029, China

\textbf{ARTICLE INFO}

Keywords:
Leaching efficiency
Irrigation methods
Rootzone
HYDRUS-1D/-2D
Agriculture water management

\textbf{ABSTRACT}

Irrigated agriculture has been in a quandary of sustaining its productivity for centuries while attempting to cope with soil and water salinity issues that continue to devastate crop production. Several of the research gaps associated with current irrigation practices include how to assess leaching requirement (LR) and efficiency (LE) for different soils, crops, and irrigation regimes. The objective of this study was to test irrigation water application methods on salinity leaching efficiency using laboratory soil column experiments and computer model simulations. Three water application methods (continuous ponding, CP; intermittent ponding, IP; and unsaturated application, UA) were imposed on packed columns of 3 different soils to evaluate salinity leaching efficiency. The HYDRUS-1D model was employed to inversely estimate water and solute transport parameters from the column experimental data, while the HYDRUS-2D model was used to simulate water and salinity transport under flexible (actual field practice) and fixed frequency irrigation (every 7, 5, and 3 days) under the same field conditions. Our column results showed that water application methods had greater impact on leaching efficiency (LE) in coarse soil than that in fine soil. The soil quality (S index) also changed with water application methods.

Continuous ponding had higher LE for the sandy loam and silt loam, unsaturated application was the best for the silt loam, while intermittent ponding and unsaturated application were good for both the silt loam and clay.

Model simulations indicated that flexible frequency irrigation resulted in lower salinity in the rootzone than that of fixed frequency irrigation, while for the fixed frequency irrigation, more frequent application with smaller amount of water was better for the silt loam. Leaching efficiency under flexible frequency irrigation was 94.2%; while for the fixed frequency irrigation, the LE values were 87.8%, 95.4%, 98.0%, respectively, for 7-, 5-, and 3-d intervals. The findings from this research can help farmers improve water use efficiency by considering water application methods and soil conditions.

\textbf{1. Introduction}

Increasing water use efficiency in irrigated cropland is critical to sustaining water resources and improving agricultural productivity, especially in arid and semiarid regions where soils are most affected by salts. Expansion of irrigated cropland and increased reliance on marginal water sources, combining with low leaching efficiency (LE, the ratio of the drained salt mass to the applied salt mass) and poor soil

https://doi.org/10.1016/j.agwat.2023.108250

Received 16 June 2022; Received in revised form 22 February 2023; Accepted 26 February 2023

0378-3774/© 2023 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).
internal drainage conditions, can often lead to soil salinization (Kita-
mura et al., 2006; Minhas et al., 2020).

Standard guidelines for managing irrigation and salinity are mostly
designed with the goal of meeting the leaching requirement (LR) to
maintain rootzone salinity at a level that avoids any reduction in crop
growth or yield (Yang et al., 2019). An important aspect for the success
of such strategy is the adoption of appropriate irrigation methods for
specific soils and climate conditions. A range of pressurized irrigation
methods (sprinkler, drip) offer alternatives to the traditional surface
irrigation (furrow, basin) in terms of efficiency, environmental impact,
health risks, and more (Barnard et al., 2010). In general, for a water
specific quality and for a given crop, the impact of an irrigation method
on the rate of salinization will depend on several variables including
vertical and spatial distribution of soil properties, topography, irrigation
management, cultural practices, climatic conditions, and regional hy-
drological conditions (Oster et al., 2012; Nassah et al., 2018; Minhas
et al., 2020).

Different irrigation methods such as flood, furrow, sprinkler or drip
can result in different patterns of saturated and unsaturated water flow
in the rootzone. Under continuous ponding (CP), the soil is always
saturated, and the flow is steady during an irrigation event. While under
intermittent ponding (IP), it consists of two periods: a water-application
period and a rest period. During the rest period, the soil is saturated at
the beginning, but flow is interrupted for a predetermined period, and
no convective transport will occur in this period, i.e., it is assumed that
solute transport is only by radial diffusion from the immobile-water
region within the spheres to the mobile-water region between them
(Rezaei et al., 2021).

Pressurized drip irrigation can be treated as unsaturated application
(UA) (Barnard et al., 2010; Callaghan et al., 2017), which allows enough
time for solute diffusing to the surface of aggregates so that it can sub-
sequently be removed by convective dispersion transport through larger
pores and minimize the effects of bypass flow (Barnard et al., 2010).

The traditional leaching guidelines usually follow the leaching
requirement (LR) concept that is based on steady-state water flow and
salt mass balance. Although true steady-state conditions do not exist in
the real-world irrigated systems, steady-state may become a reasonable
approximation over a sufficiently long period (such as a season or more).
Mathematically, a steady-state flow analysis does not include a time
variable, and thus there are many factors that can violate the steady-
state assumption under the field conditions, especially in irrigated
Croplands where alternating wetting and drying conditions are more the
rule than exception (Letey et al., 2011).

For drip irrigation, the use of conventional LR can result in excessive
leaching (Yang et al., 2019). This further justifies the reassessment of
the traditional one-value LR and adopting a more comprehensive approach
to determine leaching requirement by considering the relationships
among water salinity, water application rate, soil texture, and the
amount of leaching (Letey et al., 2011; Oster et al., 2012; Minhas et al.,
2020). The performances of irrigation methods concerning their effi-
ciency and crop response have been extensively studied, but very little
is known about the impact of water application methods on leaching ef-
ciciency in various textured soils with different hydraulic properties. As
indicated by Hoffman (2009), application rates have effects on soil
salinity leaching efficiency, and the leaching coefficient is approxi-
mately 0.3 for ponding and 0.15 for sprinkler application.

Mathematical models can represent the natural system, and objective
use of models can guide both our future research efforts and current
management practices (Mirmarghi, 2004); while column experiments
are useful tools for constructing models and estimating model param-
eters (Li et al., 2007). The overall objective of this research was to assess
irrigation management practices on salinity leaching efficiency in three
soils of different textures. Specifically, we aimed to (1) conduct labora-
tory column experiments to evaluate the effect of water application
methods on salinity leaching efficiency in the test soils; (2) use inverse
modeling of column experiment to estimate water and solute transport
parameters and assess the effect of water application methods on soil
quality (S index); and (3) identify water application methods to achieve
optimal leaching efficiency through a series of simulations under field
conditions by taking into account of soil properties, crop type, irrigation
water quantity and quality, and irrigation methods.

2. Material and methods

2.1. Laboratory leaching experiments

2.1.1. Soil leaching experiments

Three surface soils (0–25 cm) were collected from three field sites in
California. A sandy loam (Coarse-loamy, mixed, superactive, calcareous,
thermic Typic Xerofluvets) was from South Coast Research & Extension
Center (South Coast-REC) in Irvine, CA; a silt loam (Fine, loamy-mixed,
superactive, thermic Durinodic Xerofraptids) was from an almond
orchard in Kern County, CA; and a clay soil (Fine, smectitic, calcareous,
hyperthermic Vertic Torrifluvets) was from the Desert Research &
Extension Center (Desert-REC) in Holtville, CA, respectively. The
collected bulk soils were air-dried, gently crumbled to pass through a 2-
mm sieve and mixed thoroughly before packing. Particle size analysis
was performed to verify soil texture using a laser particle size analyzer
(Backman-Coulter LS 13–320) (Table 1).

2.1.2. Soil column setup and pretreatments

Plex-glass cylinders (10-cm dia. By 35-cm high) were used for
packing the soil columns. In each column, a cellulose sheet was placed at
the bottom of the column, followed by 1-cm homogeneous grain sized
sand (~1 mm dia.) to facilitate free drainage, and ensure one dimen-
sional water movement. The air-dried soil was then packed in 5-cm in-
crements according to the measured field soil bulk density to a total
height of 30 cm (Table 1). The column experimental treatments included
3 soil types and 3 water application methods, and each treatment was
replicated 3 times, resulting in a total of 27 packed soil columns. Two
additional columns of each soil type were also used for measuring initial
soil salinity distribution after pretreatment of the columns.

Before leaching, each packed soil column was slowly saturated from
the bottom with a saline solution applied by a Mariotte bottle (Fig. 1a).
The saline solution was created by mixing 0.90 g/L of CaCl₂ and 0.48 g/L
of NaCl in distilled water (approximately ECw = 3 dS/m, SAR = 16, and
pH = 7.55). After water appeared at the surface for 24 hrs., the soil
columns were allowed to dry for 3 days to stabilize the soil formation so
that the columns can better mimic field conditions (pretreated columns),
as illustrated in Fig. 1b.

After leaching, two columns from each of the three test soils were sec-
tioned into 3-cm layers to measure vertical salinity distributions in
the columns (Fig. 2). The collected soil samples were air dried and
passed through a 2-mm sieve, then using EC1:5 (1:5 soil to water ratio)
method to extract solution. With measured Ca, Mg, Na, Al, CO₃²⁻, HCO₃⁻,
SO₄²⁻, EC1:5 was converted to EC1:1 (ECsw) by the Unsacht model.

2.1.3. Column leaching experiments

Three water application methods: continuous ponding (CP), inter-
mittent ponding (IP), and unsaturated application (UA), were imposed
on the pretreated columns using tap water [Electrical conductivity (EC)

<table>
<thead>
<tr>
<th>Soil sampling location</th>
<th>Clay</th>
<th>Silt</th>
<th>Sand</th>
<th>Soil texture</th>
<th>Bulk density (g cm⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC-REC</td>
<td>4.41</td>
<td>45.64</td>
<td>49.95</td>
<td>Sandy loam</td>
<td>1.56</td>
</tr>
<tr>
<td>Kern County</td>
<td>9.4</td>
<td>51.99</td>
<td>38.61</td>
<td>Silt loam</td>
<td>1.51</td>
</tr>
<tr>
<td>Desert-REC</td>
<td>72.32</td>
<td>19.23</td>
<td>8.45</td>
<td>Clay</td>
<td>1.35</td>
</tr>
</tbody>
</table>

Table 1: Particle size distribution and bulk density of the packed soil columns.
= 0.4 dS/m, SAR = 5, and pH = 8.2) to leach salts in the soils. An individual Marriott bottle was used to apply water and control the pressure head for each column.

For the CP and IP methods, the ponding head for the soil columns was maintained at 1 cm (Fig. 1b). For the IP, water ponding was maintained for about 8–10 hrs in all the columns, then it was turned off for approximately 4–8 hrs in the sandy loam, 5–8 hrs in the silt loam, and 10–30 hrs in the clay soil, respectively, to collect approximately same amount of drainage water each time after water application was turned off and before it was resumed for next ponding.

For the UA method, a 2-cm layer of fine-grained glass beads was used both at the bottom and the top in each of the packed soil columns. The air-entry value of the glass beads layer is about −10 cm, and thus it acts like a porous plate and allows to control water application under negative pressure at the top of the column (like a suction permeameter). A 0.5-cm diameter and 9-cm long plastic tube (closed end) with three small holes was attached to the water supply line and buried in the glass beads to ensure water was evenly distributed at the column surface. Aluminum foil was used to cover the soil columns to prevent water loss from evaporation during the entire experimental period.
Drainage water (leachate) was collected with a 200-ml flask at an interval of approximately 100 ml, and EC of the leachate was measured by an electric conductivity meter (Accumet Research AR50 pH/mV/Ion/Conductivity Meter, Fisher Scientific, IL).

2.2. Leaching efficiency simulations in the columns and under field conditions

The HYDRUS-1D model was used to simulate the effects of different application methods of continuous ponding, unsaturated application, and intermittent ponding methods on leaching efficiencies in the soil columns. To mimic the irrigation scheme at the almond orchard field, the simulations used the fixed frequency methods (every 7, 5 and 3 days) to evaluate the leaching efficiency. In addition, the HYDRUS-2D model was used to simulate the effects of fixed/flexible frequency intervals (every 7, 5, and 3 days vs actual scheduling) on leaching efficiency for drip irrigation in the almond orchard under the field conditions.

2.2.1. Transport equations

In the HYDRUS-2D model, the Richards equation is numerically solved to simulate water flow (Simůnek et al., 2016):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[ K(h) \frac{\partial h}{\partial z} \right] - \frac{\partial K(h)}{\partial z} - R(h)$$

where $\theta$ is the volumetric water content (cm$^3$ cm$^{-3}$) as a function of soil matric pressure head (h, cm H$_2$O), $K(h)$ is the soil hydraulic conductivity (cm h$^{-1}$) as a function of h, $x$ is the horizontal coordinate (cm), and $R(h)$ is the root water uptake term (cm$^3$ cm$^{-3}$ h$^{-1}$). $\theta(h)$ and $K(h)$ are calculated from the van Genuchten model (van Genuchten, 1980) and Mualem’s (1976) model, respectively.

Our preliminary results showed that the original HYDRUS-1D model did not simulate water and solute transport well in the clay columns. Thus, the dual-porosity version of the HYDRUS-1D was used to simulate water and solute transport in the clay soil columns where soil water may exist both in the mobile ($\theta_m$, moving in inter-aggregate) and immobile ($\theta_{im}$, stagnant in intra-aggregate) regions. Under such circumstance, the soil water content can be expressed as:

$$\theta = \theta_m + \theta_{im}$$

The dual-porosity formulation for water flow used in the HYDRUS-1D uses the Richards equation to describe water flow in the fractures (macropores) and a mass balance equation to describe moisture dynamics in the matrix as follows (Simůnek et al., 2003):

$$\frac{\partial \theta_m}{\partial t} = \frac{\partial}{\partial z} \left[ K(h) \left( \frac{\partial h}{\partial z} + 1 \right) \right] - S_m - \Gamma_v$$

$$\frac{\partial \theta_{im}}{\partial t} = -S_{im} + \Gamma_v$$

where $S_m$ and $S_{im}$ are the sink terms for the two respective regions, and $\Gamma_v$ is the transfer rate for water from inter- to the intra-aggregate pores.

The dual-porosity formulation for solute transport in the HYDRUS-1D is similarly based on the convection-dispersion and mass balance equations as follows (Simůnek et al., 2016):

$$\frac{\partial c_m}{\partial t} + \frac{\partial f \rho_s c_m}{\partial z} = \frac{\partial}{\partial z} \left( \theta_m \frac{\partial c_m}{\partial z} \right) - \frac{\partial c_m}{\partial z} - \Phi_m - \Gamma_s$$

$$\frac{\partial c_{im}}{\partial t} + \frac{\partial (1-f) \rho_s c_{im}}{\partial z} = - \Phi_{im} + \Gamma_s$$

where $c_m$ and $c_{im}$ are solute concentrations of the mobile and immobile regions (g cm$^{-3}$), respectively; $f$ is the fraction of sorption sites in contact...
with the mobile water content (dimensionless), $\rho$ is soil bulk density (g cm\(^{-3}\)), $s_m$ and $s_{im}$ are sorbed solute concentrations of the mobile and immobile regions (g g\(^{-1}\)), respectively; $D_m$ is the dispersion coefficient in the mobile region (cm\(^2\) h\(^{-1}\)), $q$ is the volumetric fluid flux density in the mobile region (cm h\(^{-1}\)), $\Phi_m$ and $\Phi_{im}$ are sink-source terms that account for various zero- and first-order or other reactions in the two respective regions (g cm\(^{-3}\) h\(^{-1}\)), and $\Gamma_s$ is the mass transfer term for the solutes between the mobile and immobile regions (g cm\(^{-3}\) h\(^{-1}\)).

The obtained hydraulic parameters for the van Genuchten equation were further used to calculate slope $S$ (Eq. (7), Dexter, 2004) for each of the soil columns under different water application method:

$$S = n(\theta_s - \theta_i) \left(1 + \frac{1}{m}\right)^{[1-n]}$$  \hspace{1cm} (7)

where, $S$ is used as a soil physical quality index that indicates the extent to which part of the soil porosity is concentrated into a narrow range of pore size.

2.2.2. Initial and boundary conditions

The initial EC\(_{dw}\) distributions in the soil columns are shown in Fig. 2. The initial soil water condition was expressed as pressure head (cm), which increased linearly from the top (~30 cm) to the bottom (0 cm).

The upper boundary conditions of water flow in the columns receiving continuously ponding (CP) and unsaturated water applications (UA) were set to a constant positive pressure (CP, 5 cm) and negative pressure (UA, -2 cm), respectively. In the columns receiving intermittent ponding (IP), the upper boundary condition used variable pressure heads, which was entered as a time series in the model input file. Salt flux for the upper boundary condition was based on the concentration of the infiltrating water (3 dS/m).

The lower boundary condition in the columns was imposed as 'seepage face' on the sandy and silt loams for all the three water application methods. While in the clay soil columns, a vacuum pressure of -40 cm at the seepage face was applied to facilitate the collection of leachate. A zero-concentration gradient was used at the lower boundary condition for solute transport in all soil columns.

For simulations under field conditions, the initial matric pressure...
head was −1500 cm, the upper boundary condition was set as variable flux (field irrigation scheme) and atmosphere boundary conditions for evapotranspiration (ET\textsubscript{0}) (Fig. 3a). The lower boundary condition was free drainage for all the treatments. The initial EC\textsubscript{sw} distribution in the profile was set to the same for the three water application methods as measured in the field (Fig. 3b).

Salinity effect on root distribution and root water uptake was considered in the simulations under the field conditions. The maximum rooting depth of almond was set to 122 cm (4 feet), and the maximum rooting radius was 152.4 cm (5 feet), and the shape parameters of P\textsubscript{z} and P\textsubscript{x} were 1. The matric-pressure head parameters in the Feddes et al. (1978) model were: h\textsubscript{1} = 10 cm, h\textsubscript{2} = 25 cm, h\textsubscript{3} = 500 cm, and h\textsubscript{4} = 8000 cm. The threshold salinity value was EC\textsubscript{e} = 3 dS/m and the slope of almond yield function was 19%.

The climate and crop information of the almond orchard in Kern County, CA was based on the CIMIS station (#5, Shafter, CA) near the field as well as field measured data. Irrigation water was applied by double-line drip irrigation in the orchard and the amount of water application was calculated based on ET\textsubscript{0} multiplying the almond crop coefficients ranged from 0.8 to 1 (K\textsubscript{irr}). The changes of daily irrigation scheme and ET\textsubscript{0} are showed in Fig. 3a.

### 2.3. Leaching efficiency evaluation

The total drained salts can be calculated as follows (Yang et al., 2019):

\[
T_{\text{salts}} = D_{\text{dw}} TDS
\]

where \(T_{\text{salts}}\) is total salts drained per unit area (g/cm\textsuperscript{2}), \(D_{\text{dw}}\) is drainage water depth (cm), \(TDS\) is total dissolved solids: TDS (mg/L or ppm) = EC\textsubscript{dw} (dS/m) × 640 (EC\textsubscript{dw} from 0.1 to 5 dS/m); and TDS (mg/L or ppm) = EC\textsubscript{dw} (dS/m) × 800 (EC\textsubscript{dw} > 5 dS/m), EC\textsubscript{dw} is EC of drainage water (dS/m). Leaching (or drain) efficiency is defined as the ratio of the drained salt mass to the applied salt mass, and can be calculated as follows (Grismer, 1990; Yang et al., 2019):

\[
LE = \frac{D_{\text{dw}} EC_{\text{e}}}{D_{\text{iw}} EC_{\text{iw}}} = \frac{LF_{\text{e}}}{LF_{\text{w}}}
\]

where \(LE\) is leaching efficiency, \(LF_{\text{e}}\) is leaching fraction based on EC (EC\textsubscript{e}/EC\textsubscript{iw}), \(LF_{\text{w}}\) is leaching fraction based on depth of drainage water and irrigation water (\(D_{\text{dw}}/D_{\text{iw}}\)), and \(D_{\text{dw}}\) and EC\textsubscript{ew} are depth and EC of irrigation water, respectively. A lower \(LE\) indicates that more salts are retained (higher salinity) in the rootzone.
Inversely estimated hydraulic parameters of the three study soils under different water application methods.

<table>
<thead>
<tr>
<th>Soil Water application</th>
<th>θᵣ (cm⁻¹)</th>
<th>θₛ (cm⁻¹)</th>
<th>α (cm⁻¹)</th>
<th>n (cm/hr⁻¹)</th>
<th>Kᵣ (cm/hr⁻¹)</th>
<th>l (cm/hr⁻¹)</th>
<th>θₛₛ (hr⁻¹)</th>
<th>αₛ (hr⁻¹)</th>
<th>S (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandy loam</td>
<td>0.02</td>
<td>0.5</td>
<td>0.064</td>
<td>1.4</td>
<td>0.225</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Inter.</td>
<td>0.02</td>
<td>0.5</td>
<td>0.064</td>
<td>2.5</td>
<td>0.42</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Unsat.</td>
<td>0.02</td>
<td>0.483</td>
<td>0.064</td>
<td>1.16</td>
<td>2.0</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Silt loam</td>
<td>0.048</td>
<td>0.45</td>
<td>0.11</td>
<td>1.17</td>
<td>2.71</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Inter.</td>
<td>0.048</td>
<td>0.45</td>
<td>0.11</td>
<td>1.18</td>
<td>3.75</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
<td>0.044</td>
</tr>
<tr>
<td>Unsat.</td>
<td>0.048</td>
<td>0.45</td>
<td>0.31</td>
<td>1.2</td>
<td>2.0</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
<td>0.038</td>
</tr>
<tr>
<td>Clay soil</td>
<td>0.048</td>
<td>0.45</td>
<td>0.43</td>
<td>1.27</td>
<td>0.22</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
<td>0.062</td>
</tr>
<tr>
<td>Inter.(1st)</td>
<td>0.068</td>
<td>0.38</td>
<td>0.008</td>
<td>1.15</td>
<td>0.0087</td>
<td>0.5</td>
<td>0.002</td>
<td>0.15</td>
<td>0.02</td>
</tr>
<tr>
<td>Inter.(2nd)</td>
<td>0.068</td>
<td>0.265</td>
<td>0.0093</td>
<td>1.14</td>
<td>0.05</td>
<td>0.5</td>
<td>0.002</td>
<td>0.15</td>
<td>0.02</td>
</tr>
<tr>
<td>Unsat.(1st)</td>
<td>0.048</td>
<td>0.45</td>
<td>0.31</td>
<td>1.2</td>
<td>2.0</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
<td>0.038</td>
</tr>
<tr>
<td>Unsat.(2nd)</td>
<td>0.048</td>
<td>0.45</td>
<td>0.43</td>
<td>1.27</td>
<td>0.22</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
<td>0.062</td>
</tr>
</tbody>
</table>

2.4. Data analysis

Three commonly used evaluation criteria, the coefficient of determination ($R^2$), the root mean square error (RMSE), and the mean error (ME) of the measured vs calculated values, were used to evaluate the accuracy of model simulation:

$$R^2 = 1 - \frac{\sum (\hat{y}_i - y_i)^2}{\sum (y_i - \bar{y})^2}$$ (10)

$$RMSE = \left( \frac{1}{N} \sum_{i=1}^{N} (y_i - \hat{y}_i)^2 \right)^{1/2}$$ (11)

$$ME = \frac{\sum |\hat{y}_i - y_i|}{N}$$ (12)

Where $\hat{y}_i$ is observed data, $y_i$ is the mean of the observed data, and $p_i$ is the predicted data.

### Table 2

Inversely estimated solute transport and reaction parameters of the three study soils under different water application methods.

<table>
<thead>
<tr>
<th>Soil Water application</th>
<th>Dispersion (cm)</th>
<th>Fraction (hr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandy loam</td>
<td>1.2</td>
<td>1</td>
</tr>
<tr>
<td>Inter.</td>
<td>1.2</td>
<td>1</td>
</tr>
<tr>
<td>Unsat.</td>
<td>1.2</td>
<td>1</td>
</tr>
<tr>
<td>Silt loam</td>
<td>1.2</td>
<td>1</td>
</tr>
<tr>
<td>Inter.</td>
<td>1.2</td>
<td>1</td>
</tr>
<tr>
<td>Unsat.</td>
<td>1.2</td>
<td>1</td>
</tr>
<tr>
<td>Clay soil</td>
<td>1.2</td>
<td>1</td>
</tr>
<tr>
<td>Inter.(1st)</td>
<td>1.2</td>
<td>1</td>
</tr>
<tr>
<td>Inter.(2nd)</td>
<td>1.2</td>
<td>1</td>
</tr>
<tr>
<td>Unsat.(1st)</td>
<td>1.2</td>
<td>1</td>
</tr>
<tr>
<td>Unsat.(2nd)</td>
<td>1.2</td>
<td>1</td>
</tr>
<tr>
<td>Cont.(1st)</td>
<td>1.2</td>
<td>1</td>
</tr>
<tr>
<td>Cont.(2nd)</td>
<td>1.2</td>
<td>1</td>
</tr>
<tr>
<td>Unsat.</td>
<td>1.2</td>
<td>1</td>
</tr>
</tbody>
</table>

3. Results

3.1. Effect of water application methods on salinity leaching in the packed soil columns

To assess the salinity leaching efficiency, leachate from each of the 27 packed soil columns subjected to different treatments (3 soil textures and 3 water application methods with 3 replications) was collected and the EC of the leachate ($EC_{dw}$) was measured.

On average, the observed $EC_{dw}$ breakthrough curves with respect to dimensionless time (relative pore volumes, RV) differed substantially under various water application methods (Fig. 4), with most of salts coming out at approximately 2 RPV. For the sandy loam, the $EC_{dw}$ came out and reached the plateau earlier (< 1 RPV), and the peak $EC_{dw}$ values were lower (< 8 dS/m with $EC_{iw}$ = 1 dS/m) under IP and UA than that under CP (≈ 1 RPV, $EC_{dw}$ = 18 dS/m) (Fig. 4a).

In the silt loam, the $EC_{dw}$ reached the plateau (22 dS/m at < 1 RPV) earlier under IP than that under CP (≈ 1 RPV, $EC_{dw}$ = 20 dS/m) and UA (≈ 1 RPV, $EC_{dw}$ = 8 dS/m) methods (Fig. 4b). However, all the three water application methods have very similar breakthrough time (≈ 1 RPV) and peak value ($EC_{dw}/EC_{iw}$ = 14 dS/m) in the clay soil (Fig. 4c).

The above observations indicate that the effect of water application methods on salinity leaching is more profound in coarse soils (sandy and silt loam) than that in fine soils (clay), which agrees with the observations by Russo et al. (2009). For a given irrigation water quality ($EC_{iw}$), coarse textured soils have weak capillary force, thus the amount of water (∼ 2 RPV) required to leach out the salts in coarse soils is less than that in fine soils, as shown by the ratio of $EC_{dw}/EC_{iw}$. Besides, most of the soils were leached out before 2.2 RPV for all the three test soils (Fig. 5a-c). In the sandy loam (Fig. 5a), almost all salts were removed at 1.2 RPV, with 2.42 g and 2.03 g salts, respectively, removed by CP and UA in their respective columns, which were slightly higher than that of IP (1.69 g). As RPV increased from 1 to 2, there was little increase in total salt removal among the three methods (CP: 2.76 g, IP: 2.08 g, and UA: 2.44 g).

Like the sandy loam, most of the salts were leached out at 2.2 RPV in the silt loam (Fig. 5b). As RPV increased from 1 to 2, there was only small increase in salt removal. After 3 RPV, no more salts were removed under CP (4.79 g) and IP (4.92 g), but salt leaching continued after 3 RPV under UA (3.38 g), indicating that in the silt loam, leaching is more efficient under CP and IP than that under UA.

In the clay soil, more salts were leached out under CP (11.12 g) and IP (11.4 g) than that under UA (7.8 g) at the same drainage volume of 2.2 RPV. Among the three soils, more salts were leached out from the clay columns than from that of the sandy loam (3.2–5.5 times) and the silt loam (2.3–2.75 times) columns at 2.2 RPV for all the three water application methods (Fig. 5c). Nevertheless, because the initial salinity in the clay columns was much higher than that in the sandy loam and silt loam columns, it requires more water to remove all salts in the clay columns (about 5 RPV) (Fig. 5c).

Our laboratory results indicate that salt leaching efficiency varies with soil texture as well as water application methods. In the packed soil columns, CP led to saturated soil, steady flow and convective-dispersion solute transport in the soil. For IP, the soils were saturated at the beginning, but flow was interrupted for a predetermined period and no convective transport occurred during this period, which allowed the soils have more time for salts to diffuse out of the aggregates during leaching. The experimental data from the columns suggest that leaching efficiency in coarser soils (sandy and silt loam) is higher than that in fine soils (clay) under the three water application methods (CP, IP, and UA).
3.2. Model estimated hydraulic and solute transport parameters

The effects of both soil texture and water application methods on salinity leaching are reflected in the hydraulic parameters (Table 2), and solute transport and reactive parameters (Table 3) that were obtained by inverse modeling through simulating the observed cumulative drainage (Fig. 6) and EC$_{dw}$ of the drainage water (Fig. 7) as a function of time under CP, IP, and UA, respectively, in the soil columns.

Fig. 6. Observed (symbols) and HYDRUS-1D fitted (lines) cumulative drainage water under continuous ponding (CP), intermittent ponding (IP), and unsaturated application (UA): a. sandy loam, b. silt loam, c. clay soil, and d. stepwise curve fitting.
For the sandy loam and silt loam, the parameters were inversely estimated based on the van Genuchten hydraulic function (Eq. (1)) and the equilibrium solute transport model (Eq. (5)), while for the clay soil, they were obtained based on the dual-porosity (mobile-immobile water) model (Eqs. (2)-(4)) and the physical non-equilibrium model (Eq. (6)) by considering that a suction was applied at the bottom of the soil columns, since the dual-porosity model fitted the experimental data better for the clay soil.

Using the estimated hydraulic parameters, the HYDRUS-1D simulated cumulative drainage (cm) as a function of time matched the experimentally measured data well in the sandy loam for all the three water application methods (Fig. 6a). To better fit the experimental data of the cumulative drainage depth vs. time for the silt loam and clay soil, the measured drainage curves were divided into two pieces (first stage and second stage of leaching) based on the turning point as shown in Fig. 6b-c. The simulated data at the end of the first period were set as the initial conditions for the second period. The two-piece model fittings matched the experimental data much better than those of the simple linear regression model fittings (Fig. 6d).

The observed EC\textsubscript{dw} change with time under CP, IP, UA fitted by equilibrium (sandy loam and silt loam) and non-equilibrium (clay soil) models are shown in Fig. 7, and the data error analysis for the three soils under different treatments are shown in Table 4.

![Figure 7](image-url)

**Table 4** Statistical analysis of drainage EC\textsubscript{dw} between model simulation and sampling soils under different irrigation treatments.

<table>
<thead>
<tr>
<th>Soil Water application</th>
<th>R\textsuperscript{2}</th>
<th>RMSE</th>
<th>ME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandy loam</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cont.</td>
<td>0.94</td>
<td>0.35</td>
<td>0.16</td>
</tr>
<tr>
<td>Inter.</td>
<td>0.97</td>
<td>0.20</td>
<td>0.11</td>
</tr>
<tr>
<td>Unsat.</td>
<td>0.96</td>
<td>0.80</td>
<td>0.05</td>
</tr>
<tr>
<td>Silt loam</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cont.</td>
<td>0.6</td>
<td>6.12</td>
<td>1.4</td>
</tr>
<tr>
<td>Inter.</td>
<td>0.91</td>
<td>0.79</td>
<td>0.23</td>
</tr>
<tr>
<td>Unsat.(1st)</td>
<td>0.74</td>
<td>0.69</td>
<td>0.24</td>
</tr>
<tr>
<td>Unsat.(2nd)</td>
<td>0.86</td>
<td>0.72</td>
<td>0.41</td>
</tr>
<tr>
<td>Clay</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cont.(1st)</td>
<td>0.99</td>
<td>0.074</td>
<td>0.032</td>
</tr>
<tr>
<td>Cont.(2nd)</td>
<td>0.88</td>
<td>0.18</td>
<td>0.056</td>
</tr>
<tr>
<td>Inter.(1st)</td>
<td>0.93</td>
<td>0.29</td>
<td>6.9</td>
</tr>
<tr>
<td>Inter.(2nd)</td>
<td>0.88</td>
<td>0.187</td>
<td>3.5</td>
</tr>
<tr>
<td>Unsat.</td>
<td>0.99</td>
<td>0.12</td>
<td>0.11</td>
</tr>
</tbody>
</table>

For the sandy loam and silt loam, the parameters were inversely estimated based on the van Genuchten hydraulic function (Eq. (1)) and the equilibrium solute transport model (Eq. (5)), while for the clay soil, they were obtained based on the dual-porosity (mobile-immobile water) model (Eqs. (2)-(4)) and the physical non-equilibrium model (Eq. (6)) by considering that a suction was applied at the bottom of the soil columns, since the dual-porosity model fitted the experimental data better for the clay soil.
very poor quality (Dexter, 2004).

Under CP, the $S$ values were 0.097 for the sandy loam, 0.044 for silt loam, and 0.031 for the first stage of leaching, and 0.019 for the second stage of leaching in the clay soil, respectively. In terms of $S$, the quality of the sandy loam is very good, the silt loam is good, and the clay soil is poor.

Under IP, the $S$ values were 0.25, 0.046 and 0.042 for the sandy loam, silt loam and clay soil, respectively. The $S$ values of silt loam (0.046) and clay soil (0.042) were very close, and they were higher under IP than those under CP, which implies that compared with CP, water transmission of the three soils was improved under IP.

Under UA, the $S$ values were 0.049 for the sandy loam, 0.05 and 0.062 for the first and second stage of leaching for the silt loam, and 0.042 for the clay soil. Different from the $S$ values obtained under CP and IP, the silt loam had a very high $S$ value under UA, indicating the silt loam and clay soil quality in terms of water transmission was improved under UA, while the sandy loam quality declined from very good to good quality level under UA.

The $S$ index change with water application methods indicates that this soil quality index ($S$) can be improved through irrigation management. Based on our data, CP and IP were better irrigation methods for the sandy loam (very good quality) than UA (good quality). For the silt loam, UA performed better (very good quality) than CP and IP (good quality); and for the clay soil, IP and UA were substantially better (good quality) than CP (very poor quality). In other words, continuous ponding was the best choice for coarser soils to maintain soil quality at very good level. For finer soils, intermittent ponding and unsaturated application were better water application methods, and unsaturated application was the best for the silt loam.

### 3.3. Effect of irrigation frequency on leaching efficiency in the almond orchard

Salinity leaching efficiency under different irrigation schemes of 7, 5, and 3-day intervals versus the actual field irrigation scheme (flexible frequency) was evaluated for the almond orchard located in Kern County, CA. Daily drainage flux, water balance, salt flux, and cumulative drained salts during the growing season, and $EC_{sw}$ distribution in the soil profiles at the end of the season for the 4 irrigation schemes are shown in Fig. 8a-d.

Compared with the ET-based actual field irrigation scheme (flexible frequency, Fig. 8a), the daily drainage fluxes under fixed frequency irrigation decreased as irrigation frequency increased. The simulated peak drainage fluxes and cumulative drainage depths decreased gradually from the 7- to 3-day irrigation interval (from lower to higher frequency) since shorter irrigation interval provided more opportunity for root water uptake. Compared with fixed irrigation frequency, drainage flux was reduced and cumulative root water uptake and evapotranspiration increased in the flexible frequency irrigation (the orchard irrigation scheme). Thus, we conclude that fixed interval, high frequency irrigation can help to provide more water for root uptake (Fig. 8b).

The simulated daily salt flux and cumulative drained salts under flexible frequency irrigation (orchard irrigation scheme) and fixed frequency irrigation (3-, 5-, and 7-day intervals) are shown in Fig. 8c. For the flexible frequency irrigation, the first peak of salt leaching out of the rootzone started about 125 days and the second peak started about 225 days after irrigation initiated (see cum. drained salts). After then the salts drainage rate started declining.

Salinity distributions in the soil profiles at the end of the season
under different irrigation schemes are shown in Fig. 8d. The salinity in the rootzone (0–152.4 cm) decreased (from 40 to lower than 5 dS/m). Salinity near the emitter was lower, but the cumulative drained salts was less, under flexible frequency irrigation than that under fixed frequency irrigation of 7-, 5- or 3-day interval. For fixed frequency irrigation, more frequent irrigation with smaller amount of water is preferable in the almond orchard soil, which indicates that fixed, higher frequency irrigation scheme can reduce the effect of salinity stress on the crop due to lower EC in the rootzone.

4. Discussion

4.1. Dominant factors affecting soil salinity leaching

The effect of both soil texture and irrigation water application methods on soil salinity leaching can also be observed from the hydraulic and solute transport parameters. Salinity leaching is coupled with water movement thus it depends on the Darcy velocity, which differs among the water application methods of saturated (CP), semi-saturated (IP), or unsaturated (UA) condition (Al-Sibai et al., 1997; Hoffman, 2009; Chu et al., 2016; Callaghan et al., 2017).

In the silt loam, the model overestimated the cumulative drainage depths after 200 hrs of leaching under UA due to a decrease in drainage rate during the leaching experiment (Fig. 6b). There exist large
differences between the measured and simulated cumulative drainage depths between CP and IP methods in the clay soil (Fig. 6c). The discrepancies between the simulated and observed data under UA in the silt loam, and under CP and IP in the clay soil are attributed to the possible clogging and interaction between ions and soil particles in these soil columns, which changed the soil structure and permeability, and consequently, the drainage rate (van der Zee et al., 2014). Besides, a finer soil has greater specific surface area and porosity, and their adsorption capacity is generally greater than that of the coarse soils (Liu et al., 2020).

Under different irrigation methods, the inversely estimated hydraulic and solute transport parameters are different (Tables 2 and 3) for the same soil, which can be attributed to the soil water hysteresis effect. Structured clay soils benefit mostly from leaching under unsaturated flow conditions (Tanton et al., 1988; Armstrong et al., 1998) and intermittent water applications (Tagar et al., 2010; Hoffman, O’Connor, 1980). Under saturated conditions, fine soils can retain some of the original soil solution during continuous leaching, whereas drier soils with intermittent ponding allow a larger fraction of water flowing through the fine pores and displacing the salts more efficiently (Hoffman, O’Connor, 1980).

At the same matric pressure, a coarse textured soil has low water content and high leaching efficiency under continuous ponding. However, saturated volumetric water content does not affect leaching efficiency among different soils under intermittent ponding (Hoffman, O’Connor, 1980). Under saturated conditions, fine soils can retain some of the original soil solution during continuous leaching, whereas drier soils with intermittent ponding allow a larger fraction of water flowing through the fine pores and displacing the salts more efficiently (Hoffman, O’Connor, 1980).

4.2. Effect of salinity on rootzone water and salt balance

The effect of salinity on transpiration is usually attributed to its effect on water flux from a given soil volume to the plant roots (Carl et al., 2014; Zhou et al., 2018). Under surface drip irrigation, the salt accumulation in a radial pattern above the wetting zone may reduce the effective soil volume from which water is extracted, thus reduce transpiration (Dudley et al., 2008). At the field scale, large differences in salinity at the end of season in the soil profiles under various irrigation schemes and plant water uptake are due to disruption of water flux, and distribution of water and salinity in the rootzone.

Although the same amount of water is applied, the soil moisture and wetting pattern can be different under various irrigation schemes. Root water uptake rate under flexible frequency irrigation was lower than that under fixed frequency irrigation; while for the fixed frequency irrigation, water uptake rate was lower under lower frequency irrigation (longer interval) than that under higher frequency irrigation, indicating that high-frequency irrigation can improve irrigation water use efficiency (IWUE) and water use efficiency (WUE) of plants (Wang et al., 2006; Kassem, 2008). Kanber et al. (1991) reported that the amount of irrigation water decreased when IWUE and WUE values increased. Studies have shown that more frequent irrigation with smaller amount of water increases the yield because ET is higher when irrigation starts at higher soil water content or matric pressure (Stansell and Smittle, 1989).

For the fixed frequency irrigation schemes, salt leaching appeared at approximately 100 days after the beginning of irrigation, which is much earlier than that (~150 days) of flexible frequency irrigation, and the cumulative drained salts at the end of season was 749 g for the 7-day interval, which is less than that of the flexible frequency irrigation (802 g), but it increased as the irrigation frequency increased (813 g and 838 g, respectively, for the 5- and 3-day interval).

Root water extraction affects not only soil water content and salinity, but also the movement of water and salts in the rootzone. Plant water uptake is subjected to osmotic stress effect. The soil water salinity (ECso) was lower in the upper layer but higher in the lower layer as irrigation frequency decreased (longer irrigation intervals) (Fig. 8d), indicating that less water uptake under lower frequency irrigation tends to push the salinity to lower layers.

In terms of salinity leaching, our results indicate that more frequent application with smaller amount of water (every 3, 5 days) is preferable to that of less frequent with larger amount of water (every 7 days), as well as to the flexible frequent irrigation due to its higher LE (Table 5). Similar results were obtained by Kumar et al. (2007) and Zhou et al. (2018).

5. Conclusions

In this study, laboratory column study was conducted to evaluate salinity leaching in three soils of different textures under three irrigation methods. Our results showed that the test soils responded to water application methods differently: continuous ponding (CP) was the best for the coarse soils (sandy loam) to maintain soil quality at very good level. For the fine soil (clay), intermittent ponding (IP) and unsaturated application (UA) were better, and UA was the best method for the silt loam. Using the hydraulic and solute transport parameters estimated by HYDRUS-1D from the column experiments to calculate the 5 index, we found that proper water application methods can improve water transmission and salinity leaching.

HYDRUS-2D simulations based on the estimated hydraulic and solute transport parameters further indicated that irrigation schemes (fixed and flexible frequency) can affect plant water uptake, drainage volume, and salinity leaching under the field conditions of the almond orchard in Kern County, CA. Salinity leaching efficiency (LE) under flexible frequency irrigation is higher than that of 7-day fixed irrigation interval, but lower than those of 3- and 5-day fixed irrigation intervals. For the fixed frequency irrigation, the cumulative root water uptake as well as the salinity leaching efficiency (LE) increased, while the cumulative drainage decreased as the frequency decreased (longer interval). Hence, more frequent application with smaller amount of water is recommended to achieve higher leaching efficiency for the almond field.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Table 5

Salts balance and leaching efficiency under different irrigation treatments for fields simulation.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Actual input salts (g)</th>
<th>Cum. Drained salts (g)</th>
<th>LFw</th>
<th>LE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexible frequency</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Actual field scheduling</td>
<td>870</td>
<td>802</td>
<td>0.276</td>
<td>94.2</td>
</tr>
<tr>
<td>Fixed frequency</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Every 7 days</td>
<td>870</td>
<td>749</td>
<td>0.279</td>
<td>87.8</td>
</tr>
<tr>
<td>Every 5 days</td>
<td>870</td>
<td>813</td>
<td>0.26</td>
<td>95.4</td>
</tr>
<tr>
<td>Every 3 days</td>
<td>870</td>
<td>838</td>
<td>0.255</td>
<td>98.0</td>
</tr>
</tbody>
</table>
Acknowledgements

We are very thankful to anonymous reviewers and editors for their valuable time in reviewing and providing constructive comments on the manuscript. We also acknowledge the financial support by the Division of Agriculture and Natural Resources, University of California Competitive Grants Program, USA; GDAS’ Project of Science and Technology Development, China (2021GDASYL-20210102008); and Guangdong Basic and Applied Basic Research Foundation, China (2021A1515110957).

References


