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Research Paper

Soil and irrigation heterogeneity effects on drainage amount and concentration in lysimeters: A numerical study

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ABSTRACT

Water and solute fluxes measured from lysimeters located in the field can be used to estimate evapotranspiration, for irrigation scheduling and in solute leaching management. System-imposed heterogeneities are expected to affect the variability of the measured fluxes, and therefore the uncertainty of data obtained using lysimeters. In this study, local heterogeneities in soil hydraulic conductivity and dripper discharge rate were studied and their effect on drainage amount and concentration assessed. Three-dimensional simulations were performed with HYDRUS (2D/3D) with 100 simulations per treatment. The effect of three levels of soil and irrigation heterogeneities was studied for lysimeters of two different sizes (1 m^2 and 0.5 m^2). Additionally, three leaching fraction levels and water uptake reduction due to solute stress were evaluated. Coefficient of variations of the drainage amount and solute concentrations were evaluated for the different scenarios. Irrigation heterogeneity caused higher variability in drainage amount while soil heterogeneity caused higher variability in drainage concentration. The larger the lysimeter, or the higher the leaching fraction, the lower the variability for both drainage concentration and amount. Combined soil and irrigation heterogeneities produced no synergistic effect, suggesting that the variability measured in lysimeters was governed by the factor that caused the highest variability. When water uptake reduction due to salinity was considered, the same trends were observed. The results from this study can help to decide if to use either drainage concentration or amount values, for saline water irrigation management using lysimeters, according to the soil or irrigation heterogeneity levels.

1. Introduction

Lysimeters are widely used for closing water balances by monitoring drainage amount and water storage in the soil profile. Lysimeters are also used as management tools for fertigation scheduling (Ruiz-Peñalver et al., 2015) and salt leaching (Tripler et al., 2012) by monitoring drainage solute concentration and loads. Systems of lysimeters are a good compromise between point measurements with sensors in the soil or plant (water content and salinity, sap flow, etc) and large scale measurements of ET based on near or remote sensing (energy balance, vegetation indices, Bowen ratio, scintillometers, etc) (Skaggs et al., 2012, 2013). When properly calibrated and well representative of the surrounding field, in situ lysimeters have been shown to be easy to operate and perform with relatively small measurement errors (Allen et al., 2011), compared to alternative methods.

The accuracy of lysimeters is often defined as the resolution and precision of the scale or load cell used in the setup (Howell et al., 1991). However, the overall accuracy of water and solute balances measured using lysimeters will depend on the representativeness of the lysimeter in comparison to the field (Evett et al., 2012). This representativeness is defined mainly, but not exclusively, by the similarity of the plants inside and outside of the lysimeter and it is influenced by: edge effects, boundary conditions, soil properties, fetch and lysimeter surface area (Allen et al., 2011; Evett et al., 2015). In addition, the uncertainty of output values measured in a lysimeter will be affected by heterogeneities imposed by the system such as micro-meteorological conditions, plant response, irrigation method and soil hydraulic properties. Heterogeneous atmospheric conditions in greenhouses was the motivation for a rotating lysimeter system proposed by Lazarovitch et al. (2006a). Recently, Hagenau et al. (2015) demonstrated how

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Table 1
Scenarios of lysimeter area, heterogeneity and leaching fraction levels and water or osmotic stresses.

		Heterogeneity level			
Scenario #	Lysimeter size m^2	Drippers discharge rate CV	Soil hydraulic conductivity CV	Leaching fraction	Water or osmotic stress
1	0.5	–	0.25	0.43	Water
2	0.5	–	0.5	0.43	Water
3	0.5	–	1	0.43	Water
4	1	–	0.25	0.43	Water
5	1	–	0.5	0.43	Water
6	1	–	1	0.43	Water
7	0.5	0.02	–	0.43	Water
8	0.5	0.044	–	0.43	Water
9	0.5	0.09	–	0.43	Water
10	1	0.02	–	0.43	Water
11	1	0.044	–	0.43	Water
12	1	0.09	–	0.43	Water
13	0.5	0.044	0.5	0.43	Water
14	0.5	0.044	–	0.2	Water
15	0.5	0.044	–	0.33	Water
16	0.5	–	0.5	0.2	Water
17	0.5	–	0.5	0.33	Water
18	0.5	0.044	–	0.2	Water + osmotic
19	0.5	0.044	–	0.43	Water + osmotic
20	0.5	–	0.5	0.2	Water + osmotic
21	0.5	–	0.5	0.43	Water + osmotic
22	0.5	0.044	0.5	0.43	Water + osmotic

two identical lysimeters were effected significantly by slightly different surrounding conditions in the field.

It is well known that soil heterogeneity will affect the results of measurements (Weihermüller et al., 2006). However, understanding the effect of the type or magnitude of the heterogeneity on water flow and solute transport at different scales still remains a challenge. In general, increased soil heterogeneity causes increased solute dispersion and spreading due to variability in pore water velocity (Mousavi Nezhad et al., 2011; Russo, 1998). Abdou and Flury (2004) studied the effect of different spatially structured soil heterogeneities on water flow and solute transport in free-drainage (h = 0 cm at the lower boundary condition) lysimeters and found that breakthrough of a non-reactive solute was faster in the field in comparison to lysimeters for vertically structured soils. These previous studies, however, do not explain how different levels of soil heterogeneity affect the uncertainty or variability of the results measured in the lysimeters themselves.

Irrigation uniformity has been widely studied (Guan et al., 2013; Lazarovitch et al., 2006b; Li, 1998; Or and Hanks, 1992; Pang et al., 1997; Russo, 1986; Solomon, 1984; Warrick and Gardner, 1983; Wu and Barragan, 2000; Zhao et al., 2012). Most studies focus on the effect of the water application uniformity on yield or soil water content and look for an optimum between irrigation water amount and uniformity. For sprinkler irrigation systems, soil water content uniformity was shown to be higher than the imposed irrigation uniformity (Li, 1998). Similarly, crop yield was found to have higher uniformity than the irrigation imposed uniformity for drip irrigated corn (Or and Hanks, 1992). It is possible to compensate for low uniformity by increasing the irrigation amount (Letey et al., 1984), but this will translate into lower water use efficiency, economical losses, groundwater pollution, waterlogging or salinity problems. It is therefore advisable that uniformity due to its repercussions on crops, water management, and the environment, play a role in irrigation system design (Wu and Barragan, 2000). In addition, dripper clogging can be a major issue affecting irrigation uniformity within or between seasons (Bounoua et al., 2016).

The primary objective of this study was to investigate the influence of local heterogeneities in soil hydraulic conductivity and irrigation discharge rate, individually and combined, on the variability of drainage amount and solute concentration obtained from lysimeters. Additional objectives included quantification of the effects of lysimeter size, leaching fraction, and ET reduction due to salinity on the generated variabilities of drainage amount and concentration.

2. Methods

2.1. Heterogeneity analyses

The effect of heterogeneity stemming from soil hydraulic conductivity and dripper discharge rate on drainage amount and chloride concentration was studied. One hundred numerical simulations were performed for each scenario that consisted of a different combination of: soil hydraulic conductivity or dripper discharge rate heterogeneity, lysimeter size, leaching fraction level and salinity stress. A summary of the 22 unique scenarios is presented in Table 1. Irrigation and soil heterogeneity levels (3 for each) are expressed as the coefficient of variation (CV) values used to generate each simulation (Sections 2.3 and 2.4). Lysimeter size, expressed as surface areas (0.5 m^2 and 1 m^2) was chosen so as to be relevant when different drippers discharge heterogeneity levels were applied. Further explanation on how the irrigation heterogeneity was applied is found in Section 2.3. Drainage results were evaluated every 4 days in order to reduce the noise consequential to daily variability in ET (Fig. 2). A total of 2200 simulations were run, each with an average running time of 8.5 h. Some of the simulations were run on an Intel Core i7-6700 CPU 3.4 GHz with16 GB of memory while others on an Intel Core i5-4570 CPU 3.2 GHz with 8 GB of memory.

2.2. Numerical simulations

Lysimeters with two surface areas (1 m × 1 m and 0.5 m × 1 m) and a depth of 0.6 m were simulated using HYDRUS (2D/3D) (Šimůnek et al., 2016). This model represents the most used and most accessible simulation tool for three dimensional water flow and solute transport in soils (Dudley et al., 2008). The 1 m^2 lysimeters were defined by 18 equally spaced horizontal planes and discretized using an unstructured finite element mesh, resulting in a total of 18,078 nodes and 52,224 three-dimensional tetrahedral elements (Fig. 1). The 0.5 m^2 lysimeters were defined by 21 equally spaced horizontal planes with a finite element mesh having 14,156 nodes and 40,080 three-dimensional tetrahedral elements. The soil hydraulic and transport properties were as defined in Raij et al.

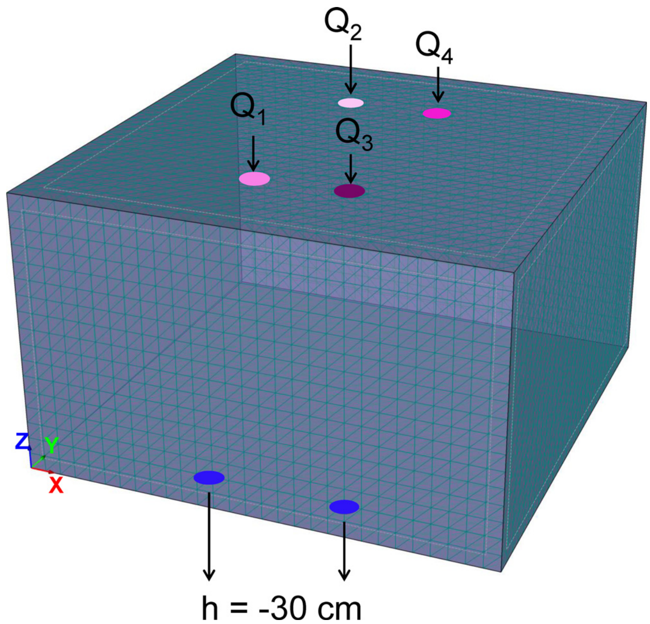

Fig. 1. Three dimensional finite element mesh domain in HYDRUS (2D/3D) for the 1 m^2 lysimeter. Areas with different shades of pink are those with different variable flux boundary condition (Q_1–Q_4) and blue areas are those with a seepage face of h = −30 cm boundary condition. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Hydraulic and transport parameters of the loamy sand soil.[a]

Soil parameter	Units	Value
θ_r	($cm^3\ cm^{-3}$)	0.004
θ_s	($cm^3\ cm^{-3}$)	0.36
α	(cm^{-1})	0.016
n	(−)	3.43
l	(−)	0.5
K_S	(cm day^{-1})	145.44
ρ_b	(g cm^{-3})	1.5
λ_L	(cm)	1.7
λ_T	(cm)	0.17

[a] θ_r, residual water content; θ_s, saturated water content; α and n, empirical shape parameters; l, tortuosity factor; K_S, saturated hydraulic conductivity; ρ_b, bulk density, λ_L and λ_T,g longitudinal and transverse dispersivities, respectively.

Table 3
Root water uptake parameters.[a]

Water stress response function parameters			
P50	cm	−800	
P3	[−]	3	
PW	cm	-1.00E + 10	
Salinity stress response function parameters			
Cl_{50}	mg cm^{-3}		3.198
P3	[−]		1.435
Osmotic coefficient		1	

[a] P50, the pressure head by which the root water uptake is reduced by 50%; P3, exponent in the root water uptake response function associated either with water or salinity stress; PW, pressure head at wilting point below which transpiration stops; Cl_{50}, chloride concentration at which the root water uptake is reduced by 50%.

(2016) for a loamy sand soil (Table 2). Raij et al. (2016) calibrated the HYDRUS (2D/3D) model with major ion transport in drip irrigated lysimeters with the same boundary conditions as those simulated in this study. Vertical root distribution was defined according to the model of Vrugt et al. (2001), with maximum rooting depth of 50 cm, depth of maximum intensity of 10 cm and the shape parameter *Pz* set as 2. Horizontal root distribution was homogeneous.

Sigmoidal response functions were used in order to simulate both water and osmotic stresses (van Genuchten, 1987). When both stresses were included in the simulation, their effect was assumed to be multiplicative (van Genuchten, 1987). The parameters defining the sigmoidal shaped functions are defined in Table 3 as calculated in Groenveld (2010) for similar conditions. Compensated root water uptake was considered by setting the critical stress index to 0.8 (Šimůnek and Hopmans, 2009). All simulations were considered to have potential root water uptake reduction due to water stress. Five cases for the 0.5 m^2 lysimeter (Table 1) were considered to have additional solute stress according to the parameters in Table 3.

Initial condition for water flow in all simulations was defined as hydrostatic equilibrium with a pressure head of −30 cm at the bottom of the soil profile. Initial soil solution concentration was defined as 1.3 mg cm^{-3}, a value close to the steady state drainage concentration.

Irrigation was applied in four or two circular areas, for the 1 m^2 and 0.5 m^2 lysimeters respectively, representing drippers, each with a radius of 2.5 cm defined as variable flux boundary conditions (Fig. 1 –1 m^2 domain). Two circular drainage exits, each with a radius of 2.5 cm, were delineated at the lower boundary of the

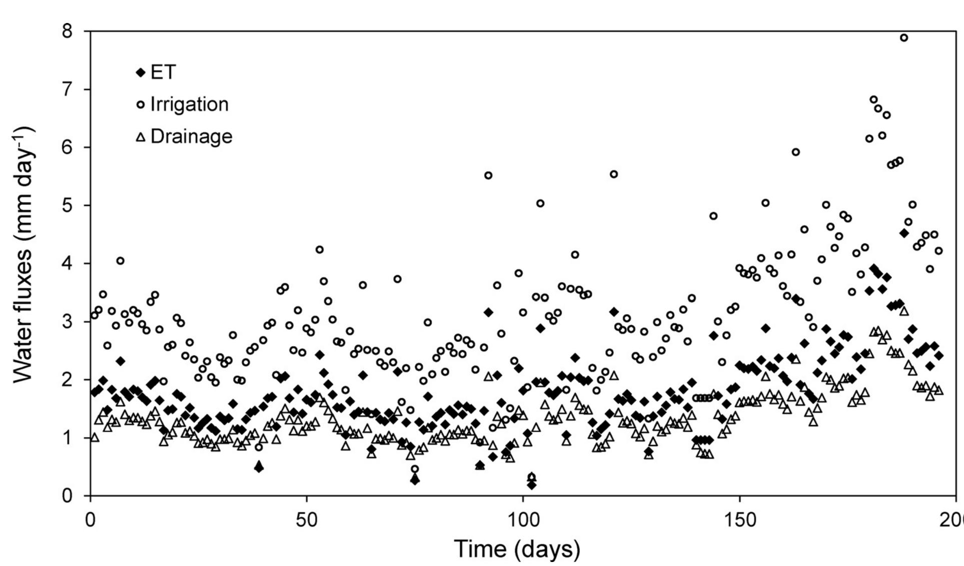

Fig. 2. Modeled water fluxes: average irrigation, drainage and ET in mm per day for the 1m^2 lysimeter with a coefficient of variation of 0.02 in the irrigation discharge rate.

lysimeter. This boundary was specified as a seepage face with a pressure head of −30 cm such that outflow occurs when the pressure head at the bottom boundary reaches −30 cm. The rest of the boundaries of the domain were designated as no flow. Solute transport at both the upper and lower boundaries was assigned as a Cauchy boundary condition.

Although this study focuses on numerical work, soil hydraulic and transport parameters, ET, leaching fraction and irrigation quality were obtained from a field experiment performed with lysimeters similar in their design as the ones simulated. In the preliminary field experiment, bell pepper plants were grown in five 1 m^2 weighing lysimeters filled with loamy sand soil, and daily evapotranspiration (ET) was measured. Irrigation with brackish (EC = 3.4 ds m^{-1}) water was applied daily in order to maintain a leaching fraction (LF) of 0.43 (Fig. 2). Leaching fraction was defined as volume of water draining from the lysimeter divided by volume of irrigation water. In the model, ET was considered only as root water uptake, without separation between evaporation and transpiration. The measured ET values were set as the potential transpiration or root water uptake. Chloride concentration in the irrigation water was 0.8 mg cm^{-3}.

2.3. Modeled irrigation variability

Average dripper discharge rate was 1.6 L h^{-1} with a predefined variability. A normal distribution was assumed for each of three coefficient of variation (CV) levels: 0.02, 0.044 and 0.09. The middle value, 0.044, was measured under field conditions for 108 drippers with an average discharge rate of 1.6 L h^{-1} (UniRam-RC, Netafim, Israel). For each simulation, every dripper in the model, represented as a variable flux area, received a different discharge rate according to the CV level and normal distribution (2 and 4 values for the 0.5 m^2 and 1 m^2 respectively).

2.4. Modeled soil variability

Knowledge of soil hydraulic properties is crucial for a proper evaluation of physical and chemical processes within the vadose zone involved in variably saturated water flow and transport of water-dissolved salts (Lazarovitch et al., 2007). The van Genuchten-Mualem (Mualem, 1976; van Genuchten, 1980) soil hydraulic model was used to relate the unsaturated hydraulic conductivity and volumetric water content to the pressure head (parameters in Table 2). Average saturated hydraulic conductivity for loamy sand soil was taken from Raij et al. (2016) as 145 cm day^{-1}. The coefficient of variation of the saturated hydraulic conductivity (Eq. (1)) was set to three levels: 0.5 (expected variability (Warrick, 2003)), 0.25 (low) and 1 (high).

$$\sigma = CVK_S \tag{1}$$

Where σ is standard deviation and K_S is average saturated hydraulic conductivity. The randomly distributed saturated hydraulic conductivity, K_{Sn} was represented by a log-normal distribution (Lazarovitch et al., 2006b) and therefore log-transformed:

$$K_{Sn}{}^{*} = \ln K_{Sn} \tag{2}$$

where $K_{Sn}{}^{*}$ is the log-transformed randomly distributed saturated hydraulic conductivity.

The log-transformed hydraulic conductivity $K_S{}^{*}$ together with its log-transformed standard deviation σ^* was defined by Warrick (2003) Eqs. (3) and (4), as:

$$K_S = \exp\left(K_S{}^{*} + 0.5\sigma^{*2}\right) \tag{3}$$

$$\sigma^2 = \exp\left(2K_S{}^{*} + \sigma^{*2}\right)\left[\exp\left(\sigma^{*2}\right) - 1\right] \tag{4}$$

The corresponding $K_{Sn}{}^{*}$ is:

$$K_{Sn}{}^{*} = K_S{}^{*} + \sigma^{*}Z \tag{5}$$

where Z is a random number from a normal distribution with a mean of zero and a variance of unity.

From Eqs. (2) and (5), K_{Sn} was calculated as:

$$K_{Sn} = \exp\left(K_S{}^{*} + \sigma Z\right) \tag{6}$$

A Gaussian sequential simulation was used in order to generate a random field for Z in three dimensions (SGEMS software). A random sample was generated using an exponential model:

$$\gamma(h) = C_0\left[1 - \exp\left(\frac{-h}{a}\right)\right] \tag{7}$$

where γ is the sample variogram, a is the practical range (30 cm used in this case), h is the lag distance [L] and C_0 is the sill value (1). Finally K_{Sn} values were divided by the average K_S and the values were imported as scaling factors (α_k in Eq. (8)) in the three-dimensional mesh in HYDRUS (2D/3D). These scaling factors were used by the model according to Eq. (8) for the simulation of the heterogeneous unsaturated hydraulic conductivity $K(h)$. A visualization of the scaling factors of one representative simulation for each CV value is presented in Fig. 3.

$$K(h) = \alpha_k K^{*}(h^{*}) \tag{8}$$

2.5. Combined heterogeneities

A set of simulations was performed for the 0.5 m^2 lysimeters with combined heterogeneity of irrigation rate and heterogeneity of hydraulic conductivity (scenario 13 in Table 1). This combination was performed by using the previously generated files of the 100 simulations in which soil and irrigation heterogeneities were evaluated individually. The files describing the time dependent atmospheric boundary conditions (ATMOSPH.IN) and the graphic domain information (DOMAIN.DAT) including irrigation and soil heterogeneity information, respectively, were included in each simulation.

2.6. Sensitivity analysis – leaching fraction

A sensitivity analysis was performed in order to study the effect of LF on the variability of each drainage amount and concentration. Two LFs, 0.20 and 0.33, were simulated in addition to the previously simulated LF of 0.43 (scenarios 14–17, 2 and 8 in Table 1).

3. Results and discussion

3.1. Soil and irrigation heterogeneities

As expected, the higher the imposed irrigation or soil heterogeneity, the higher the variability of either the measured drainage amount or concentration. While increasing heterogeneity of the soil hydraulic conductivity brought about higher variability regarding the drainage Cl^- concentration, heterogeneity in irrigation rate produced higher variability in the drainage amounts (Figs. 4–7). Drainage flux is a result of the balance between the irrigation amount and precipitation, ET, and water storage in the soil profile. In this study, there was no precipitation and a fixed high irrigation regime supplying excess water to insure salt leaching was maintained so that there was no ET reduction due to water stress. These conditions drove the system to a quasi-steady state with minimal changes in soil water storage (Tripler et al., 2012). Therefore, drainage flux was directly affected by the irrigation amount, controlled in this case by the irrigation heterogeneity. Variability in the quantity of drainage reached even larger values than the imposed

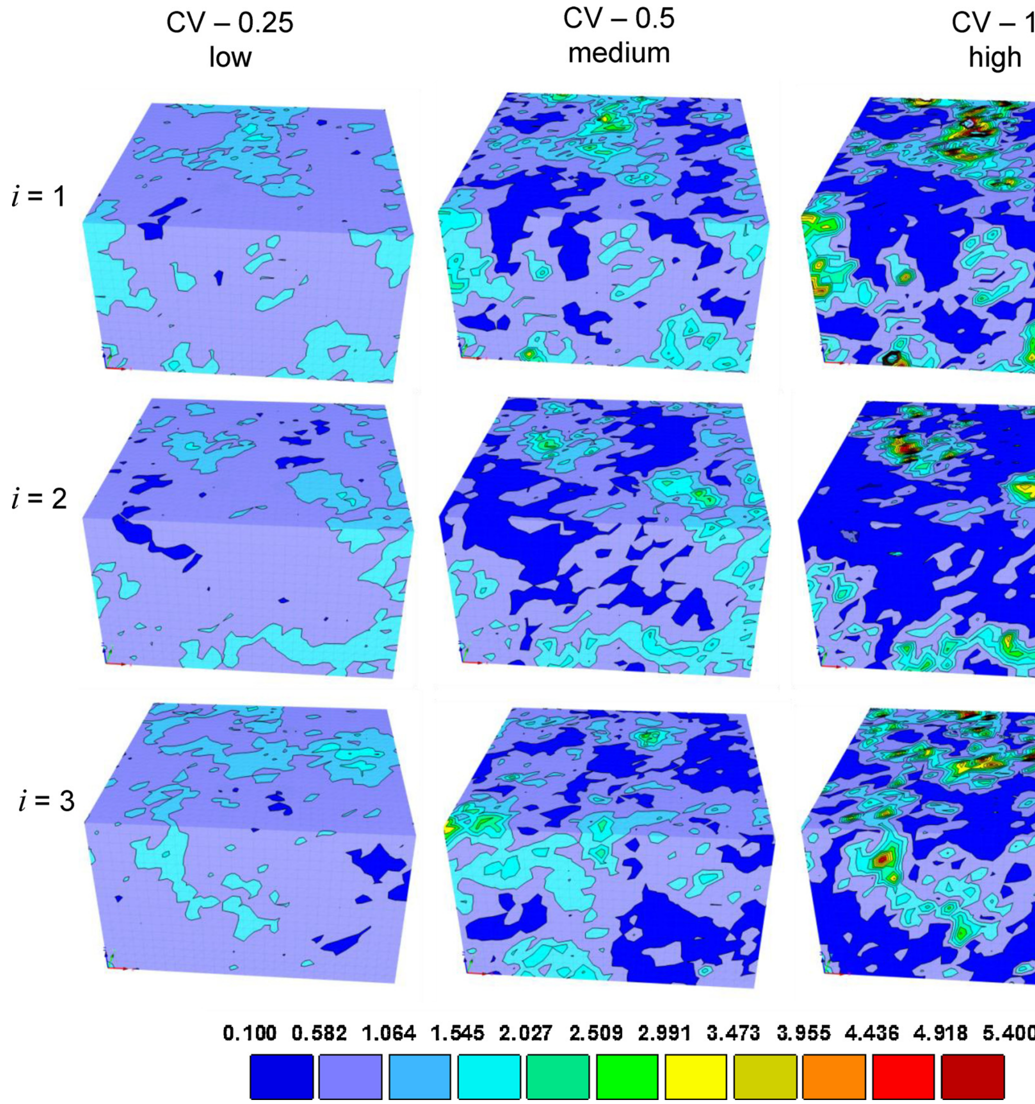

Fig. 3. Visualization of three representative simulations (i = 1–3) of soil hydraulic conductivity scaling factors in 1 m^2 lysimeters simulated for three levels of soil heterogeneity (low, medium and high).

CV of the irrigation rates (Fig. 7-A). Water content and velocities in the profile were affected by the heterogeneity of $K(h)$, but did not affect water uptake, or alter the water balance. Therefore, variability of the drainage amount when soil heterogeneity was applied remained low (Fig. 5 – A). Despite the consideration of a 4-day average for the calculation of drainage amount CV, a high variability of the CV values was observed (Fig. 5 – A) due to the strong variability in drainage amount (Fig. 2).

The fixed irrigation-to-ET ratio insured equilibrium of the drainage water chloride concentration so that heterogeneity in irrigation quantity caused only a small variability in the drainage concentration. Conversely, heterogeneity of $K(h)$ caused higher variability of the drainage concentration due to increased or reduced solute dispersion and spreading as pore water velocity was varied (Mousavi Nezhad et al., 2011; Russo, 1998; Weihermüller et al., 2006).

Variability in drainage flux or concentration decreased when lysimeter surface area increased; the larger the lysimeter, the smaller the resulting CV (Figs. 5 and 7). This was found for concentration of Cl^- in drainage when either heterogeneity of irrigation rate or $K(h)$ were applied (Figs. 5 and 7 – B). Variability of drainage volume was found to increase with increased surface area only when heterogeneity of irrigation rate was applied (Fig. 7 – A) and was not consistently affected by heterogeneity of $K(h)$ (Fig. 5 – A). There was a gradual decrease in the ratio of the variability between the lysimeters with different surface areas as the imposed irrigation heterogeneity increased for both drainage amount (1.49, 1.40 and 1.36 for irrigation rate CVs of 0.02, 0.044 and 0.09, respectively, Fig. 7 – A) and for chloride concentration (1.08, 1.05 and 1.01 for CVs of 0.02, 0.044 and 0.09, respectively, Fig. 7 – B). These data show that, as heterogeneity in irrigation rate increased, the relative gained benefit from increasing the lysimeter size decreased. No such effect was observed regarding heterogeneity of soil hydraulic conductivity.

3.2. Combined heterogeneities

A set of 100 simulations for each of the 1 and 0.5 m^2 lysimeters was performed for cases of simultaneous dripper discharge rate and $K(h)$ heterogeneities. The variability of drainage volume that resulted from the combined heterogeneities, for both lysimeter dimensions, was very similar to that obtained when only irrigation heterogeneity was simulated (Fig. 8 – A). In a similar manner, the variability in drainage Cl^- concentration of the combined het-

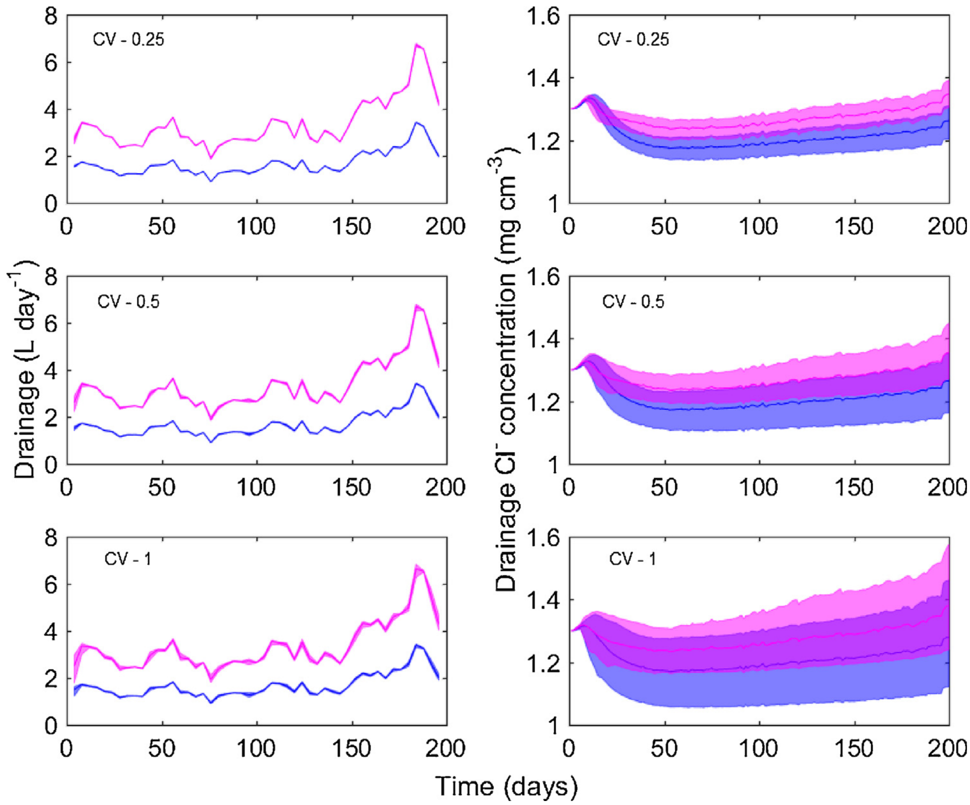

Fig. 4. Averages and 96% confidence intervals for simulated drainage amount and Cl^- concentration for 1 m^2 (pink) and 0.5 m^2 (blue) lysimeters for three levels of heterogeneity of soil hydraulic conductivity ($K(h)$). Confidence intervals for drainage amounts were very small and therefore almost not visible in the figure. CV values indicate those used for the generation of spatial heterogeneity of $K(h)$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

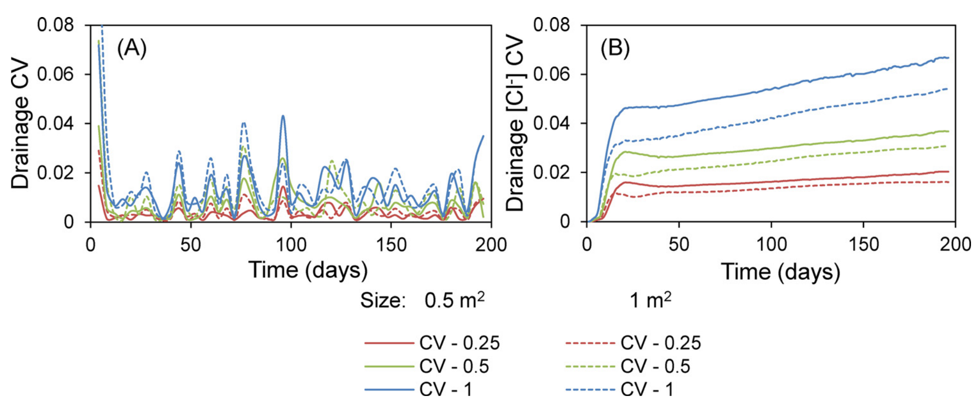

Fig. 5. Drainage amount (A) and Cl^- concentration (B) variability (CV values) along the season for three heterogeneity levels of soil hydraulic conductivity and two lysimeter sizes.

erogeneities was very similar to that obtained when only $K(h)$ heterogeneity was simulated (Fig. 8 – B). The fact that the CV of the results approximated the highest CV value obtained when considering each source of heterogeneity separately indicates that simultaneous heterogeneities did not cause a synergistic effect and did not add variation (Fig. 8 – A and B). Warrick and Gardner (1983), similarly found that soil and irrigation variability were not additive in their effects on yield. These results can be useful if there is knowledge of the factors causing heterogeneity in the field, allowing investment of energy to reduce only the factor which most influences heterogeneity and according to the type of data that wants to be collected from the lysimeter.

3.3. Sensitivity analysis of the leaching fraction

Variabilities in drainage amount and Cl^- concentration were tested for three LFs in the 0.5 m^2 lysimeter. There was no root water uptake reduction due to matric stress, such that average actual LFs were constant along the season. Small changes in actual LF from day to day (data not shown) were related to the response time between irrigation and drainage and the daily ET variability (Fig. 2). An increase in LF decreased the effect of soil and irrigation heterogeneity on drainage Cl^- concentration variability (Fig. 9 – B). For the variability of drainage amount, a change in LF had influence only when heterogeneity of the irrigation rate was considered (Fig. 9 – A).

The variability of the drainage amount as a function of heterogeneity in irrigation rate was higher for the smaller LF. However,

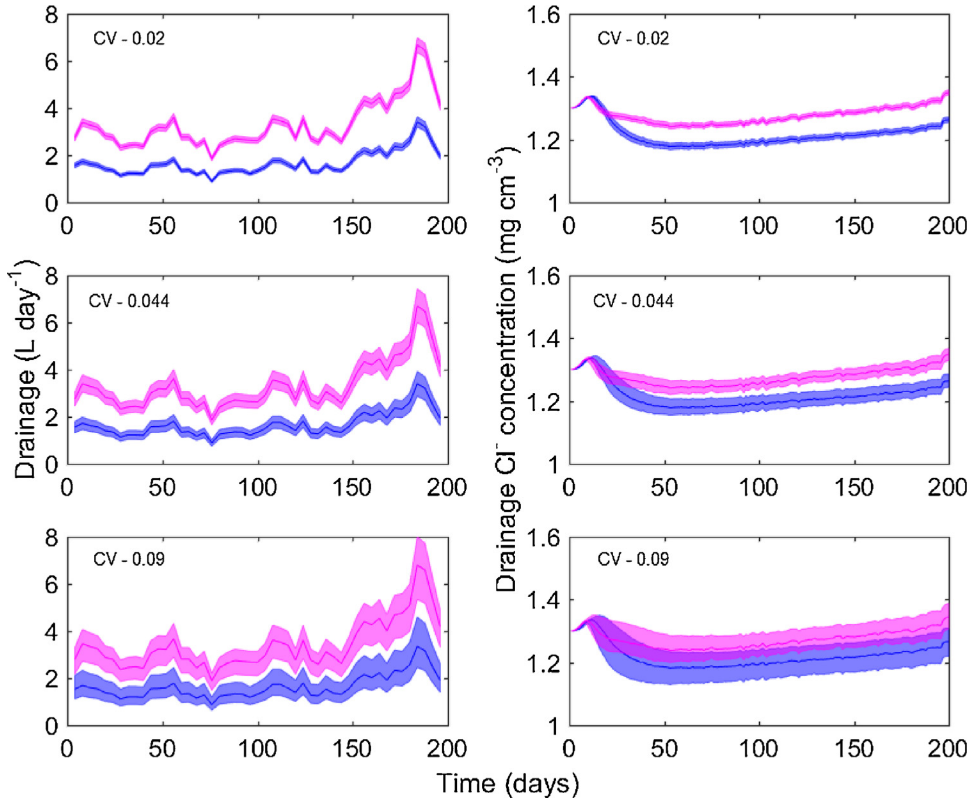

Fig. 6. Averages and 96% confidence intervals for simulated drainage amount and Cl^- concentrations for 1 m^2 (pink) and 0.5 m^2 (blue) lysimeters for three heterogeneity levels of dripper discharge. CV values are those used for the normal distribution function of the dripper discharge rate. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

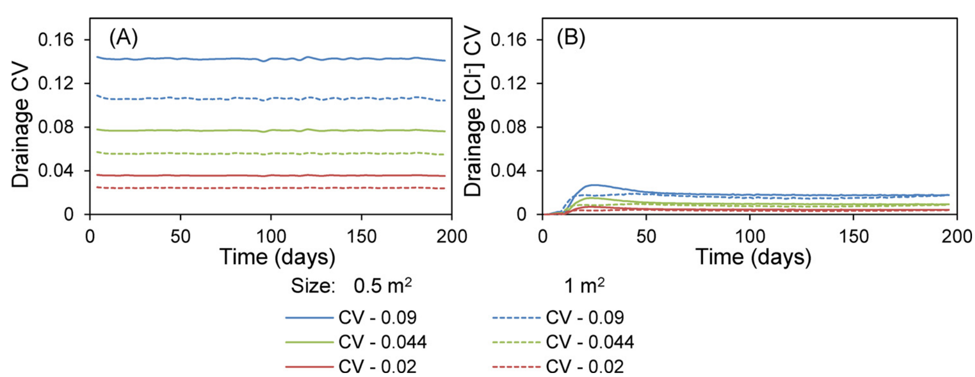

Fig. 7. Drainage amount (A) and Cl^- concentration (B) variability (CV values) along the season for three levels of heterogeneity of dripper discharge rate and two lysimeter sizes.

the standard deviation of the drainage amount was lower for the smaller LF. This was due to the large differences in average drainage amount as a consequence of the different LFs.

These results support the classic approach of increasing irrigation amount in order to overcome the negative effects of low irrigation uniformity on yield (Letey et al., 1984). When irrigating with brackish water, there is a basic need to irrigate in excess in order to prevent salt accumulation. Such practice could therefore eliminate any effect of irrigation uniformity on yield as in the study presented by Zhao et al. (2012) where different irrigation uniformity levels did not affected drip irrigated cabbage growth, yield or quality. In addition, variability in soil water content may be lower than irrigation imposed variability due to water movement and redistribution in sprinkler irrigation (Li, 1998), causing consequential lower variability of water availability sensed by plants. For the hypothetical crop in the present work, and under the specified conditions, no root water uptake reduction was simulated and therefore no yield reduction was predicted. Different levels and types of heterogeneity did not produce any variability or uncertainty in the hypothetical yield (a function of ET). However, the focus of this numerical exercise was to understand the uncertainty from lysimeter data, regarding water and solute balances, and not to evaluate yield or its variability.

3.4. Osmotic stress

Five cases were chosen in order to understand the behavior of variability for a salt sensitive crop under conditions leading to reduced root water uptake in the smaller lysimeters. The five cases included low and high LFs with soil or irrigation heterogeneity and low LF with combined soil and irrigation heterogeneity (Table 1). Overall CVs were lower for simulations where root water uptake

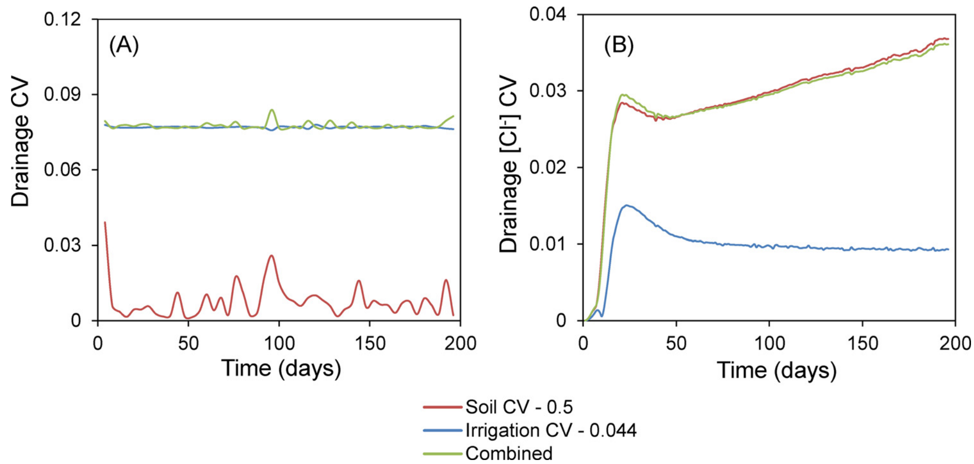

Fig. 8. Variability (CV) of drainage amount (A) and Cl^- concentration (B) resulting from heterogeneities due to soil hydraulic conductivity (red), irrigation rate (blue) and combination of the two (green) in 0.5 m^2 lysimeters. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

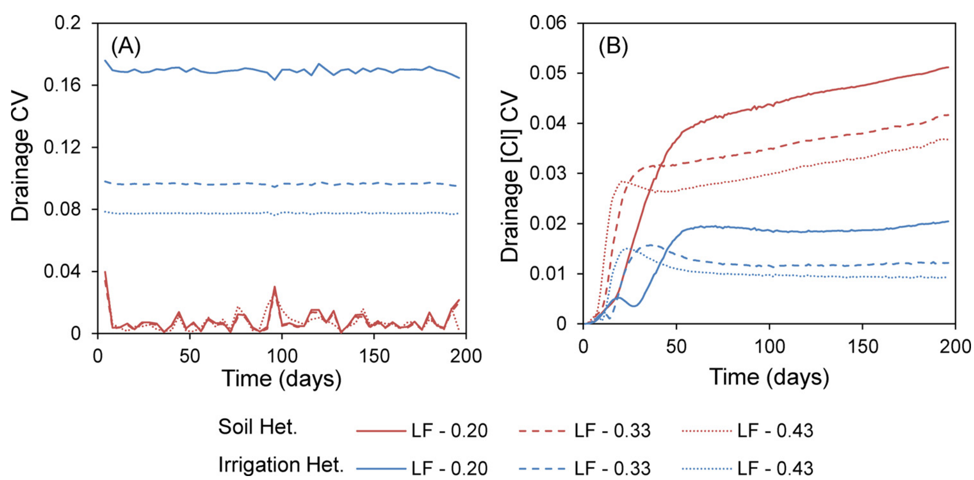

Fig. 9. Variability (CV) of drainage amount (A) and Cl^- concentration (B) in 0.5 m^2 lysimeters for heterogeneities resulting from soil hydraulic conductivity (CV 0.5, red) and irrigation rate (CV 0.044blue) at three irrigation levels: leaching fraction (LF) of 0.20, 0.33 and 0.43. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

was reduced due to relatively high drainage amounts and higher drainage Cl^- concentrations (Fig. 10 – A and B). The same trends observed in the simulations with no osmotic stress were repeated in these simulations (Fig. 10): 1) Heterogeneity in soil hydraulic conductivity yielded higher variability in drainage concentration while heterogeneity in irrigation rate caused higher variability in drainage amount; 2) When considering both sources of heterogeneity simultaneously, no synergistic effect was observed, CVs of both drainage volume and concentration were very similar to those produced by either heterogeneity of irrigation rate or soil $K(h)$ alone; 3) Higher irrigation levels produced lower variabilities in both drainage amount and concentration. Actual LFs increased along the season due to root water uptake reduction. Final LF values were 0.38 and 0.37 for simulations with target LF of 0.20 (soil $K(h)$ and irrigation rate respectively) and 0.51 for all the simulations with target LF of 0.43. Variability (CV values) of actual root water uptake (after reduction due to solute stress) was generally low with maximum values, at day 200, of 0.02 for heterogeneity due to soil $K(h)$ and 0.01 for heterogeneity due to irrigation rate, for both irrigation levels (data not shown).

4. Conclusions

When relying on lysimeter data for irrigation management with low quality water, either drainage amount or concentration can be used. The drainage amount allows estimation of ET while the drainage solute concentration or EC (electrical conductivity) provides capability to calculate actual LF. The results from the numerical experiments performed in this study can add confidence to decision making using either drainage amount or concentration according to the variability found for each. Variability was found to depend on the level of heterogeneity imposed by the system (soil hydraulic conductivity or irrigation discharge rate, in this case), leaching fraction, and/or lysimeter size. When heterogeneity of irrigation supply rate was high, the drainage Cl^- concentration had a lower variability, leading to the conclusion that it can be more reliable for management decisions than the highly uncertain drainage amount. Contrarily, in a case of low heterogeneity or uncertainty of irrigation application rate, the ET calculated with the water balance of the lysimeter will represent a more accurate measurement than the LF calculated using drainage Cl^- concentration. Combining heterogeneities of soil hydraulic conductivity and irrigation discharge rate did not cause a synergistic effect; the measured variability in

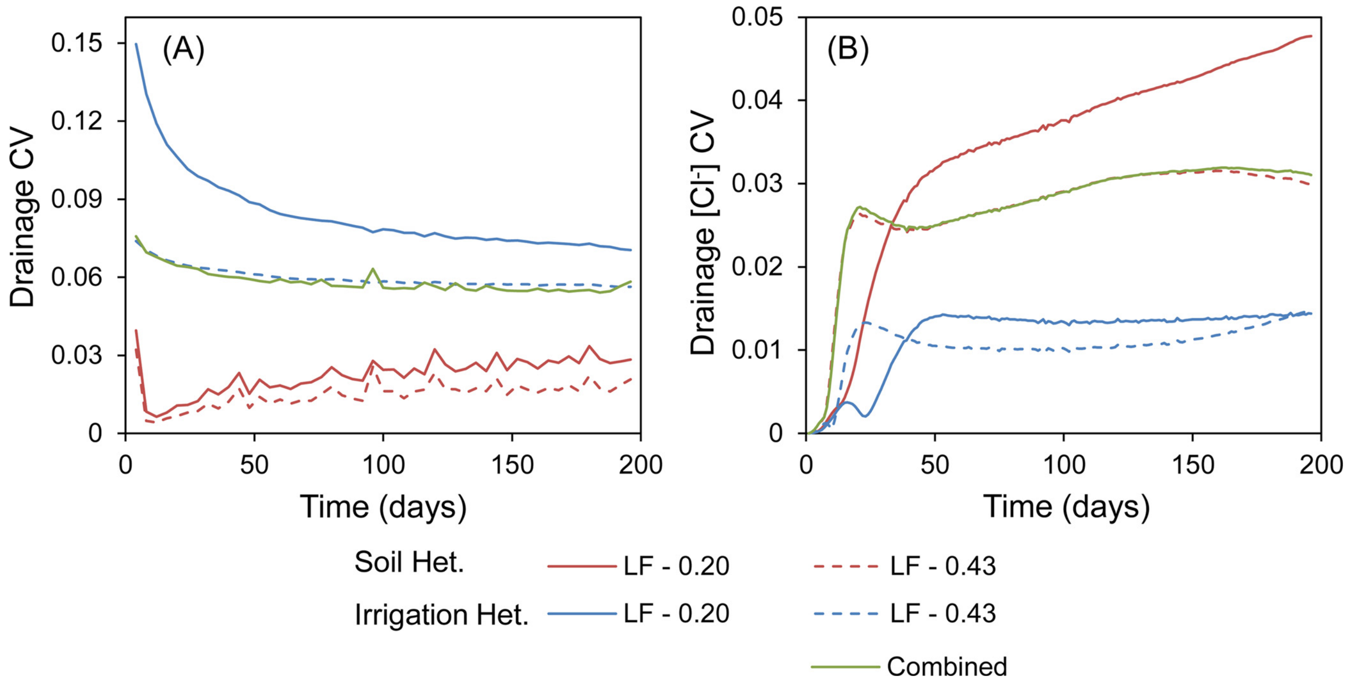

Fig. 10. Simulations with osmotic stress in 0.5 m^2 lysimeters. Variability (CV) of drainage amount (A) and Cl^- concentration (B) for heterogeneity due to irrigation rate (blue) and soil hydraulic conductivity (red) at two irrigation levels (leaching fraction (LF) of 0.20 and 0.43 and for combined heterogeneities at the high irrigation level (green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the results was very similar to the highest value caused by either of the imposed heterogeneities when applied alone. Higher irrigation levels (increased LFs) decreased the variability of the drainage concentration for both sources of heterogeneity and also decreased the variability of drainage amount under heterogeneity due to irrigation discharge rate. Increasing the irrigation amount did not decrease variability in drainage amount when heterogeneity was due to soil hydraulic conductivity. The results of these numerical experiments are also applicable to cases of irrigation with water high in salts and conditions causing reduced water uptake.

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