A Theoretical Study of Subsurface Drainage Model Simulation of Drainage Flow and Leaching in Salt Affected Irrigated Fields

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Abstract

A three-dimensional variable-density groundwater flow model, the SEAWAT model, was used to assess the influence of subsurface drain spacing, evapotranspiration and irrigation water quality on salt concentration at the base of the root zone, leaching and drainage in salt affected irrigated land. The study was carried out on a conceptual uniform homogenous irrigated field of shallow *watertable* depth of 0.5 m and aquifer salt concentration of 7200 mg/l with an impermeable layer at 10 m depth and impermeable field boundaries. The model was run for 10 years with an irrigation rate (applied recharge) of 8 mm/d and salt concentration of 1,500 mg/l, over a range of drain spacings. During the 10-year drainage period, the simulated concentrations at the base of the root zone and the discharge rates were the same at all the spacing when evapotranspiration was not included. However, upon inclusion of evapotranspiration, the simulated concentration at the base of the root zone ranged from about 5,200 to about 6200 mg/l, the discharge rate ranged from 2.3 to 1.9 mm/d. When the applied recharge concentration was changed to 1,000 mg/l and 700 mg/l, but with all the other parameters maintained, the simulated concentration at the base of the root zone ranged from 3,700 to 4,400 mg/l, and from 2,800 to 3200 mg/l for the different spacing, respectively.

Introduction

For irrigated fields with subsurface drainage systems, drainage flow and leaching in the soil profile are influenced not only by the drain spacings but also evapotranspiration and quality of the irrigation water. Water that moves upward through capillary rise from shallow groundwater can enter the atmosphere through evapotranspiration. In arid and semi-arid regions, the groundwater contribution to evapotranspiration can meet the crop water requirements (Khan *et al*., 2006). However, the salinity in the groundwater can lead to soil salinity and, consequently, crop damage (SJVDP, 1990). FAO (1994) also noted that soils in irrigated fields contain a similar mix of salinity as the irrigation water but the extent to which salinity accumulates in the soil depends on the irrigation water quality, irrigation management and the adequacy of drainage system. However, Chhabra (1996) observed that under arid and semi-arid conditions irrigation water is instrumental in the accumulation of salinity in the rootzone.

Salinity affects millions of hactares of once productive lands in many countries (Dandekar & Chougule, 2010) and soil salinity poses a major problem for irrigated agriculture (Tanji & Wallender, 2011). In many cases artificial drainage systems are required to control the salinity level in the soil (Tanji, 1990). However, without proper drainage systems, salts tend to accumulate

West African Journal of Applied Ecology, vol. **22**(1), 2014: 59–76.

in the upper soil profile, especially when intense evapotranspiration is associated with insufficient leaching (Yeo, 1999). Sharma & Gupta (2005) noted that subsurface drainage is the essential intervention necessary to maintain a suitable growing environment for crops in irrigated field.

The study sought to theoretically assess SEAWAT model's simulation of drainage flow and leaching for different drain spacings as follows: (a) with or without evapotranspiration, and (b) when the irrigation water (applied recharge) quality was changed. There are several models available to design subsurface drainage systems (Ali *et al*., 2000), and most of these models are developed by using the conventional drainage equations that mostly consider only the gross amount of water removal from the soil profile (Skaggs, 1980; van Dam *et al*., 1997; El-Sadek, 2001. However, transient numerical groundwater models provide an opportunity to capture the full range of all influencing parameters, including the flow path, the amounts of leached salt and those left in the soil profile. One such promising transient numerical groundwater model is SEAWAT (Guo & Langevin, 2002), and, hence, its usage for the study.

SEAWAT was designed, tested and widely used in determining the extrusion of seawater into coastline aquifers and freshwater from coastline into sea (Guo & Langevin, 2002). However, very little or nothing is known about its application on agricultural land. In addition, groundwater flow equation for the SEAWAT model is based on mass balance that is appropriate for groundwater of variable density (Bear, 1997; Evans & Raffensperger, 1992), hence, the need to theoretically assess the possibility of its usage on irrigated field.

Transient numerical groundwater model

SEAWAT model (Langevin *et al*., 1992) is a modular three-dimensional finite-difference computer programme that combines the modified version of the MODFLOW model (McDonald & Harbaugh, 1988) and the MT3DMS (Modular 3-Dimensional Transport of Multi-Species) model (Zhen & Wang, 1999) into a single programme to approximate the coupled governing nonlinear groundwater flow and salt transport equations. The SEAWAT contains all the processes distributed with the MODFLOW except that MODFLOW numerically solves constant-density groundwater flow whilst SEAWAT numerically solves variable density groundwater flow equation (Guo & Langevin, 2002). The governing equation for the SEAWAT (Guo & Langevin, 2002) is given as:

$$\frac{\partial}{\partial x}\left\{\rho K_x\left(\frac{\partial h_f}{\partial x}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial Z_1}{\partial x}\right)\right\}+\frac{\partial}{\partial y}\left\{\rho K_y\left(\frac{\partial h_f}{\partial y}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial Z_1}{\partial y}\right)\right\}+\frac{\partial}{\partial z}\left\{\rho K_z\left(\frac{\partial h_f}{\partial z}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial Z_1}{\partial z}\right)\right\}=\rho S_f\frac{\partial h_f}{\partial t}+\theta\frac{\partial \rho}{\partial C}\frac{\partial C}{\partial t}-\bar{\rho}q_s \quad \ldots 1$$

where ρ = density of saline aquifer water (kgm^{-3}); ρf = density of freshwater (kgm^{-3}) K_x, K_y and K_z = hydraulic conductivity head (ms^{-1}) along the x, y, and z axes, respectively; h = equivalent freshwater head (m); Z_1 = elevation at the measurement point (m); S_f = specific storage, in terms of freshwater head (m^{-1}); C = salt concentration that affect aquifer water (kgm^{-3}); θ = porosity (-); ρ = source/sink water density (kgm^{-3}); and q_s= source/sink volumetric flow rate per unit volume of aquifer (s^{-1}).

Material and methods

The SEAWAT model was applied to a 36-ha homogeneous block of land of length 600 m and a width of 600 m of a hypothetical irrigated field with shallow watertable of 0.5 m from the surface to simulate drainage flow and leaching for drain spacings of 30, 45, 60, 90, 150, 200 and 250 m. The drain depth was fixed at 2.0 m (FAO, 1988). The aquifer was an isotropic homogeneous silt loam. The groundwater was considered saline with a concentration of 7,200 mg/l. The base of the aquifer was assumed flat and lying 10 m below a flat field surface.

Spatial and temporal discretization of the field

The aquifer was discretized into a grid of cells consisting of 60 rows, 60 columns and 10 layers. Each cell, with the exception of the cell in which the drains were housed (drain cells), had a dimension of 10 m × 10 m × 1 m. The drain cells had dimensions of 0.2 m horizontal and 0.2 m vertical in order to more accurately approximate the drain size. The base of the aquifer, used as a reference, had an elevation of zero. The top of layer 1, which coincided with the land surface, had an elevation of 10 m relative to the base. The grid system was based on blocked-centred formulation and, therefore, the salt concentrations and hydraulic heads applied to the centre of the cells.

Model input data

Aquifer parameters. The hydraulic conductivity was assigned a homogeneous isotropic value of 0.8 m/d to reflect a silt loam soil field. The aquifer was assigned a specific yield of 0.2, applicable to a medium textured soil (Johnson, 1967) and a storativity, Ss, of 10^{-6}, calculated using the equation:

$$Ss = \gamma\ (\beta p + n\beta_w) \ldots\ldots 2$$

where, γ is specific weight of water (kgm^{-2} 2s^{-2}), βp is the compressibility of bulk aquifer material = 1×10^{-9} (ms^2 kg^{-1}), n is the total porosity and β_w is the compressibility of water = 4.6×10^{-10} (ms^2 kg^{-1}) (Fine & Millero, 1973).

For solute transport, the processes that cause solute dispersion are mechanical dispersion and molecular diffusion. The relevant aquifer parameters for solute transport include porosity (total and effective), longitudinal and transverse dispersivity and molecular diffusion coefficients. A uniform total porosity of 0.30 (applicable to silt loam) was assigned and an effective porosity of 0.2 (Sanders, 1998) was used, a similar value as the specific yield Langevin, 2001).

The longitudinal dispersivity, $\langle\alpha_L$, was estimated using the formula:

$\alpha_L = 0.1L_s$ (Gelhar, 1986; Xu & Ecskstein, 1995) 3

where L_s is the mean linear distance travelled by the solute (m), and was taken as distance from the centre of one model cell to the centre of the next. The transverse dispersivity, α_T is less than the longitudinal dispersivity in the order of magnitude of -1 (Bear and Verruijt, 1990). The molecular diffusion coefficient, D*, was estimated using the formula:

$D^* = D_o / T^2$ (Berner, 1980; Shen & Chen, 2007) 4

where D_o is the free molecular diffusion coefficient of salt = 1.73×10^{-4} m^2/d and T is the tortuousity = 1.8 [29].

Applied recharge parameters. The applied recharge (irrigation rate) value was based on a water application rate of 56 mm per 7 days (8 mm/d) similar to the value used in simulating maize stress using the CROPWAT and EPIC models (Caviero *et* *al*., 2000), and with a salt concentration of 1500 mg/l (2 dS/m) (FAO, 1994).

Evapotranspiration parameters. The SEAWAT model simulates only evapotranspiration (ET) from the saturated zone (watertable). The evapotranspiration package in SEAWAT is then treated as a head-dependent flux boundary. The functional relationship between watertable depth and groundwater contribution to evapotranspiration rate, ETg (i.e. ground-water evapotranspiration rate), is expressed using line segment. The model simulates the ETg as a linear fraction of the potential evapotranspiration rate based on maximum water extraction when the watertable is at the land surface and zero extraction when the watertable is at the extinction depth. Thus, the ETg reached maximum evapotranspiration rate, ETm, (or potential evapotranspiration rate) when the watertable was at the land surface (SURF). The ETg, on the other hand, attained a value of zero when the watertable was at the extinction depth (EXTD). The evapotranspiration package of the model then required three parameters (McDonald & Harbaugh, 1988) maximum evapotranspiration rate, ETm; evapotranspiration surface, SURF, (taken as the land surface), and extinction depth, EXTD.

Since the model does not simulate the unsaturated zone, it treats all applied (irrigation) water as entering the saturated zone. To enable simulation of ETg, it was assumed that crop water stress was avoided and that, at any depth in the aquifer, water was available for the crop need. Therefore, to maximise the watertable dependent function on evapotranspiration rate, the extinction depth was set as deep as 10 m in this study, a value equal to the depth of the aquifer. The maximum evapotranspiration rate, ETm, was assigned a value that was calculated using the equation:

$$ET_m = RCH\ (1\text{-}LF)\ \text{(FAO, 1994)} \quad \text{.........5}$$

where, RCH was the applied recharge (irrigation rate) (mm/d), and LF was leaching fraction. The LF was assigned a value of 22%, a value when used avoids excess accumulation of salt within the root zone (FAO, 1994).

For this study, the percentage of irrigation water that remained in the aquifer after the groundwater contribution to evapotranspiration and runoff were withdrawn was referred to as net recharge. However, for the study, it was assumed that there was no runoff. The net recharge rate was as a result of the model's simulation and equalled drain discharge.

Drain parameters. The dynamic exchange of water between the aquifer and the drains was simulated using the drain (DRN) package within the SEAWAT programme. This assigned a head-dependent flux to each cell intersected by the drains. Drain parameters included the drain head (the elevation of the water in the drain relative to the base of the aquifer), drain invert (bottom) elevation relative the base of the aquifer and hydraulic resistance between the drain and the aquifer (drain conductance, CD). The drain was assumed to run half-full and of a negligible thickness. The drain head was assigned a value 8.1 m and the drain invert elevation 8.0 m with reference to the base of the aquifer. The drains were laid parallel to each other with each having a length of 300 m.

Table 1 summarizes the input data for the model for the simulation of drainage flow and leaching. The model was run when there was no evapotranspiration for the first analysis, and then run when evapotranspiration was included for all the subsequent analysis. Again, investigating the effects of recharge quality on drainage flow and leaching for the different drain spacings, the applied recharge concentration was varied from 1500 mg/l to 1000 mg/l and 700 mg/l, while maintaining the same applied recharge irrigation rate and potential evapotranspiration rate. The simulations were undertaken for 12 time periods of 30 days (0.08 year), 180 days (0.49 year), 365 days (1 year), 730 days (2 years), 1095 days (3 years), 1460 days (4 years), 1825 days (5 years), 2190 days (6 years), 2555 days (7 years), 2920 days (8 years), 3285 days (9 days) and 3650 days (10 years).

Results

Sensitivity analysis of SEAWAT model

A sensitivity analysis was performed to evaluate the effects of some key aquifer parameters and boundary conditions on the simulated watertable elevation, leached salt load, salt load remaining in the aquifer and salt concentration within the soil layers. The aquifer parameters analysed were the saturated hydraulic conductivity, K (1.6, 0.8, 0.4 and 0.2 m/d); the longitudinal dispersivity, α_L(1.0, 0.5, 0.1 and 0.01 m);

TABLE 1
Main inputs data specified for the SEAWAT model simulations

Parameter (unit)	*Value*
Aquifer thickness (m)	10
Initial groundwater salt concentration (mg/l)	7,200
Initial groundwater density (kg/m^3)	1,005.04
Initial water table elevation (m)	9.5
Applied recharge (mm/d)	8
Applied recharge concentration (mg/l)	1500; (1000; 700)
Applied recharge density (kg/m^3)	1001.5, (1000.7; 1000.49)
Actual evapotranspiration, ET, rate (mm/d)	6.2
Extinction depth (m)	10
Saturated hydraulic conductivity, K, (m/d)	0.8
Aquifer bottom layer hydraulic conductivity (m/d)	1 × 10-7
Total porosity	0.3
Effective porosity	0.2
Specific yield	0.2
Specific storativity (m-1)	1 × 10-6
Longitudinal dispersivity, α_L, (m)	1
Transverse dispersivity, α_T, (m)	0.1
Molecular diffusion coefficient, D* (m^2/d)	5 × 10-5
Drain elevation (m)	8
Drain spacing (m)	30, 60, 90, 150, 200 and 250
Drain conductance (m^2/d)	3,000
Drain cell (m)	0.2 m per side

() values used in assessing irrigation water quality effect on drainage flow and leaching and the diffusion coefficient, D* (0.08, 0.03, 0.015 and 10^{-5} m^2/d).

It was noted that the saturated hydraulic conductivity, K, had a significant effect ($P \leq 0.05$) on the watertable elevation but had no effect on the salt concentration in both the discharged water and in the aquifer. It was observed that when K $\leq$ 0.2 m/d, the watertable level in the drain tended to rise above the drains and subsequently caused the watertable to rise above the soil surface, suggesting that, in the application of the SEAWAT model, the K should be more than 0.2 m/d.

The longitudinal dispersivity, α_L, had little effect on the discharged salt load, total salt load remaining in the aquifer and watertable elevation (Langevin, 2001). However, it had a significant effect on the salt concentration within the root zone (< 2.0 m below soil surface). Increasing α_L to a range (0.1–0.5) multiplied by the length of the model domain cell, tended to change the shape of the salt concentration contours within the root zone layer but for α_L values outside that range, the salt concentration contours remained unchanged with time. This confirmed the observation in the literature that the proportionality constant of the relation between the α_L and the distance travelled by the solute should be less than one (Gelhar, 1984). As the diffusion coefficient, D*, increased, the salt concentration remaining in the root zone also increased but showed no change with time when D* > 0.08 m^2/d. The changing shape of the salt concentration contours was clearly evident when the diffusion coefficient, D*, was < 0.015 m^2/d. Also investigated were drain conductance, CD, and drain cell (cell housing the drain) dimensions, and it was noted that each parameter had significant effect on the watertable. To maintain the watertables below the soil surface for low hydraulic conductivity, the CD needed to exceed 500 m^2/d and the drain cell size also should be greater than 0.1 m.

No evapotranspiration included in the model

Watertable depth and drain discharge characteristics. Drain spacing affected the watertable depth but had minimal effect on the quantity and quality of the discharged water. The steady state watertable depth for drain spacings of 30 m, 60 m and 90 m were 1.54, 1.13 and 0.61 m, respectively. Watertable depths for spacings more than 90 m reached the land surface, indicating that for only watertable control, drain spacings should not exceed 90 m, contrary to the view that spacings less than 20 m effectively controlled the watertable below the land surface for conventional drain spacing (Carter & Camp, 1994).

At steady state, all the drains yielded the same drain discharge rate that equalled the applied recharge rate (8 mm/d), suggesting that drain spacing had no effect on the discharge and this demonstrated that the model had correctly achieved mass balance. Fig. 1 shows the salt concentration in the drain discharges over time for the different spacings. The discharge concentrations decreased exponentially with time for all drain spacings but remained higher than the applied recharge concentration (1500 mg/l) even after 10 years. The higher discharge concentration above that of the applied recharge concentration emanated from deep within the aquifer indicating that not all the ‘leachable salt’ were drained out by 10 years of leaching for all the spacings. ‘Leachable

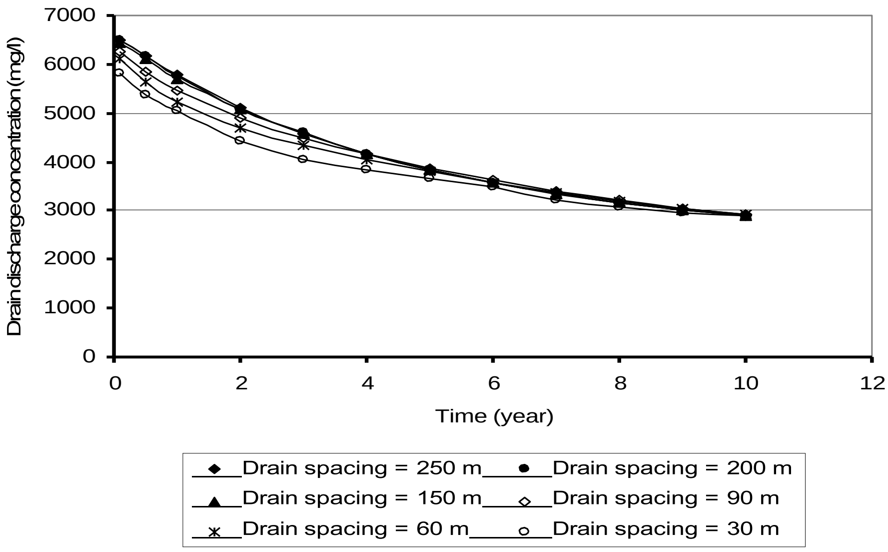

Fig. 1. Leached salt concentrations over time for different drain spacings when evapotranspiration not considered

salt' is the salt required to be leached from the aquifer in order to maintain a constant salt in the aquifer that is similar to both the salts in the applied recharge (or net recharge) and the drain discharge. The drain discharge concentration increased marginally with spacing up to about 5 years, thereafter, all spacings discharged the same concentrations (Fig. 1). This indicates that spacing had no effect on drain discharge concentration when there was no evapotranspiration. However, the initial marginal increase with spacing could be attributed to the mixing of applied recharge and the aquifer water which increased with spacing.

Salt remaining in the aquifer and leached salt. Table 2 shows temporal changes in aquifer salt and the percentage of the initial aquifer salt leached for different drain spacings. Irrespective of the drain spacings, more than 30% of the initial aquifer salt was leached, during 1 year of drainage and by Year 5 about 70% had been leached notwithstanding the 43,800 kg/ha/year of salt from the applied recharge. This caused a rapid decline of the initial aquifer salt during that period for all drain spacings. This can be attributed to the greater differences between the applied recharge salt and the initial aquifer salt. After 10 years, all the spacings had leached the same amount of salt, which was over 75% of the initial salt in the aquifer, suggesting that greater portion of the respective 'leachable salts' had been leached. The leachable salt for drain spacing of 30 m was 80.3% of the initial aquifer salt, and 79.8%, 79.3%, and 78.6% for drain spacings of 60 m, 90 m and greater than 90 m, respectively. This indicates that with no evapotranspiration, the same amount of salt is leached irrespective of the drain spacings. The relationship between the total salt leached and the salt applied is shown in Table 3. All spacings leached over 3 times more salt than

TABLE 2
Simulated salt remaining in aquifer, leached salt and 'leachable' salt when no ET was included in model

Drain spacing (m)	*Salt in aquifer (kg/ha)*			*Leached salt as a percentage of *initial aquifer salt (%)*			*'Leachable' salt (kg/ha)*
	1 year	*5 years*	*10 years*	*1 year*	*5 years*	*10 years*	
30	194,191	85,986	69,420	31	69	75	225,420
60	189,456	83,114	61,931	33	70	78	224,190
90	183,697	74,704	60,956	35	73	78	222,630
150	177,324	78,943	68,352	37	72	76	220,800
200	175,303	77,886	67,293	38	72	76	220,800
250	175,900	78,432	67,084	37	72	76	220,800

*Initial salt in the aquifer = 280,800 kg/ha

TABLE 3
Relationship between total leached salt and salt in the applied recharge when no ET was included in model

	Total leached salt (kg/ha)			*Leached salt/*Applied recharge salt (dimensionless)*		
Drain spacing (m)	*1 year*	*5 years*	*10 years*	*1 year*	*5 years*	*10 years*
30	131,194	414,310	650,167	3.0	1.9	1.5
60	135,148	416,689	656,872	3.1	1.9	1.5
90	140,901	425,094	657,842	3.2	1.9	1.5
150	147,266	420,847	650,439	3.4	1.9	1.5
200	149,271	421,889	651,481	3.4	1.9	1.5
250	148,665	421,422	651,681	3.4	1.9	1.5

*Applied recharged salt = 43,800 kg/ha/year

was applied up to Year 1, then declining to 1.9 times and to 1.5 times more salt than the applied by Year 10. The excess salts was more likely derived from deep in the aquifer since the concentrations at the base of the root zone were static and were the same for all the drain spacings (Fig. 2). The same salt amount in the drain discharge for all the spacings shows that when there was no evapotranspiration, spacing had no effect on the discharged salt concentration.

Mid-drain salt concentration distribution at the base of the root zone. Fig. 3 shows the distribution of the mid-drain salt concentration at 1.5 m below the soil surface for different drain spacings. There was a rapid exponential fall of the concentration and became stable after more or less in Year 2 for all the drain spacings. It was noted that the stabilized concentration was the same as the recharge concentration, indicating that the initial salt in the rooting depth was flushed

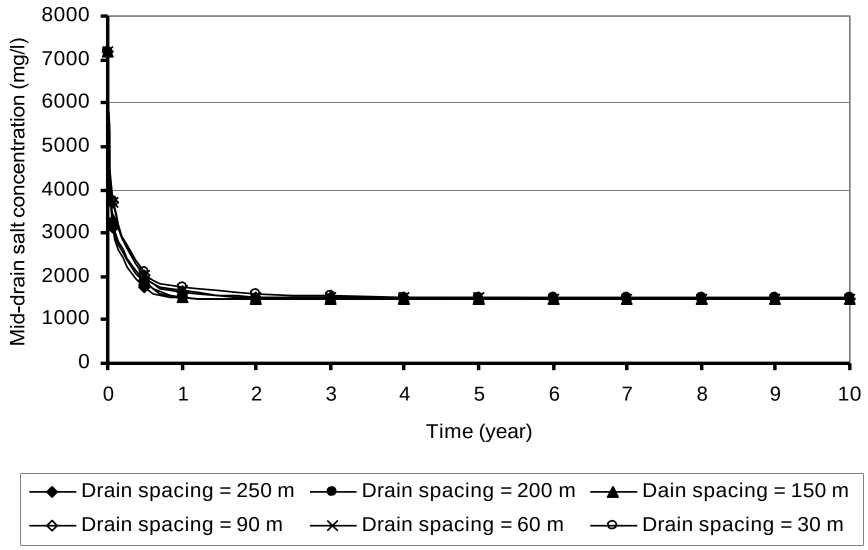

Fig. 2. Mid-drain salt concentration at 1.5 m below surface for different drain spacings when evapotranspiration not considered

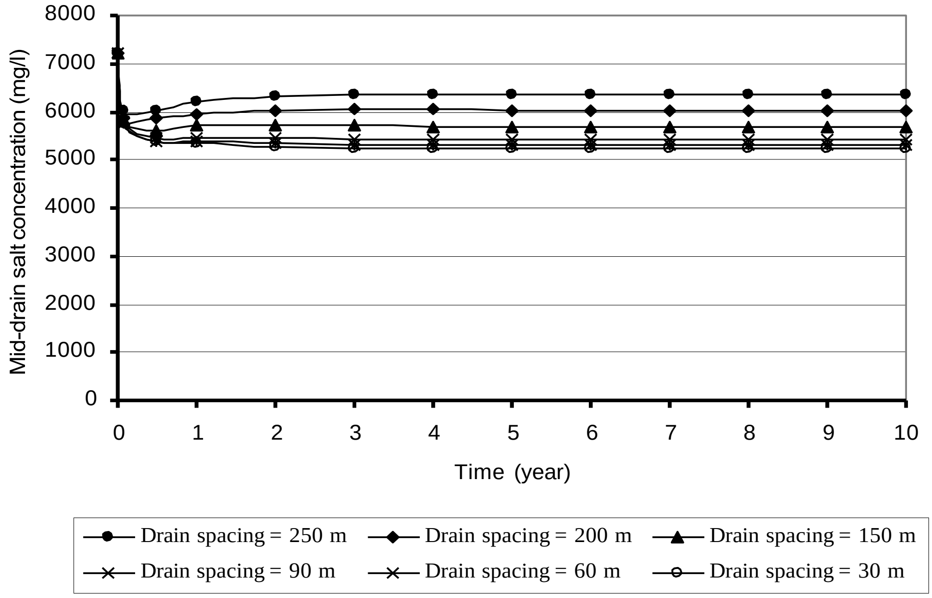

Fig. 3. Mid-drain salt concentration at 1.5 m below soil surface for different

out within 2 years of drainage irrespective of length of the drain spacing. The rapid aquifer concentration fall could be attributed to the large concentration gradient between aquifer concentration and the applied recharge concentration. Notwithstanding the applied recharge concentration of 1,500 mg/l, for all the drain spacings, the initial aquifer concentration of 7,200 mg/l fell rapidly by about 75% by Year 2, then to about 80% by 5 years and remained constant (Fig. 2) at a concentration level equal to the concentration of the applied recharge. This suggests that all spacings could maintain the same salt concentration level at the base of the root zone, although at different watertable depths. This is an indication that the salt concentration at the base of the root zone could depend on the salt concentration of the applied recharge but not necessarily the effect of drain spacing. Therefore, when evapotranspiration was not included, the salt concentration in the rooting zone could be controlled using any drain spacing.

Evapotranspiration included in the model

The effect of drain spacing on watertable and drain discharge. The SEAWAT model was used to investigate the influence of evapotranspiration on the effects of drain spacing on watertable, the concentration of recharge that entered the groundwater (net recharge concentration), groundwater contribution to the evapotranspiration and the drain discharge characteristics. Generally watertable depths decreased with increasing drain spacing similar to the no evapotranspiration case except that the depths were greater for the corresponding spacings. At steady state of the watertable drawdown remained approximately constant (i.e. the rate of applied recharge approximately matched the sum of the drain discharge and evapotranspiration rates). The watertable depth, initially at 0.5 m below the soil surface (9.50 m elevation), fell to 1.72 m for 30 m drain spacing but rose to 0.42 m for 250 m drain spacing (Table 4). Watertable depths for spacings of 150 m, 200 m and 250 m, which rose to the soil surface when there was no evapotranspiration, remained below the surface when there was evapotranspiration indicating the capability of evapotranspiration to drawdown watertable (Heupermann, 2002). In addition, as spacing increased more water was evapotranspired from the shallow watertable and this increased water use efficiency and the salt concentration at the base of the root zone.

Salt remaining in the aquifer salt and leached salt. Table 5 shows the salt remaining in the aquifer, the leached salt as a percentage of the initial aquifer salt and 'leachable salt' for different drain spacings. The salt remaining in the aquifer at all times increased with increasing drain spacing (Table 5). This is primarily caused by the increase in evapotranspiration rate and the subsequent decrease in drain discharge with small amounts of salt when the spacings were increasing (Christen & Ayars, 2001). At wider spacings, the salt concentration at the base of the root zone increased which in turn led to a decrease in the quantum of leachable salt. The 'leachable' salts, ranged from 32% to 13% of the initial aquifer salt (280,800 kg/ha) for drain spacings of 30 m and 250, respectively. However, the leached salts accounted for over 70% of the respective 'leachable' salts for all the drain spacing for 10 years of drainage.

The relationship between the total leached salt and the applied salt for different drain spacings is shown in Table 6. The total

TABLE 4

Simulated groundwater contribution to evapotranspiration, ETg, water table depth and net recharge characteristics for different spacings

Drain spacing (m)	*ETg (mm/d)*	*Drain discharge rate (mm/d)*	*Water table depth at steady state (m)*	*Net recharge concentration (mg/l)*	*Net recharge density (kg/m3)*
30	5.70	2.30	1.72	5,217	1,003.65
60	5.73	2.27	1.61	5,286	1,003.70
90	5.76	2.24	1.47	5,357	1,003.75
150	5.85	2.15	1.12	5,581	1,003.91
200	6.01	1.99	0.77	6,030	1,004.22
250	6.07	1.93	0.42	6,218	1,004.35

ETg = groundwater contribution to evapotranspiration rate

TABLE 5

Salt remaining in aquifer, leached salt and 'leachable' salt when ET applied

Drain spacing (m)	*Salt in aquifer (kg/ha)*			*Leached salt as a percentage of *initial aquifer salt*			*'Leachable' salt (kg/ha)*
	1 year	*5 years*	*10 years*	*1 year*	*5 years*	*10 years*	
30	267,200	233,425	215,232	4.8	16.9	23.3	90,067
60	267,325	235,364	217,915	4.8	16.2	22.4	86,381
90	267,884	237,444	220,826	4.6	15.2	21.4	82,270
150	269,870	243,808	229,375	3.9	13.2	18.3	70,061
200	273,223	254,792	244,868	2.7	9.2	12.8	48,887
250	274,859	260,792	253,248	2.1	7.1	9.8	37,428

*Initial salt in the aquifer = 280,800 kg/ha

TABLE 6

Relation between total leached salt and salt in the applied recharge

	Total leached salt (kg/ha)			*Total leached salt/*Applied recharge salt (dimensionless)*		
Drain spacing (m)	*1 year*	*5 years*	*10 years*	*1 year*	*5 years*	*10 years*
30	57,400	266,375	503,568	1.31	1.22	1.15
60	57,275	264,436	500,885	1.30	1.21	1.14
90	56,716	262,356	497,975	1.29	1.20	1.14
150	54,730	255,992	489,425	1.25	1.17	1.12
200	51,378	245,008	473,932	1.17	1.12	1.08
250	49,876	239,408	465,623	1.14	1.09	1.06

*Applied recharge salt load = 43,800 kg/ha/year leached salt which decreased with increasing drain spacing could be attributed to less water being discharged as a result of more water loss through evapotranspiration for wider drain spacings. All spacings removed more salt than the salt in the recharge by 10 years, indicating that none of the spacings had completely leached the corresponding 'leachable' salts by that period.

Mid-drain salt concentration dynamics at the base of the root zone. The mid-drain salt concentration levels at the base of the root zone (1.5 m depth) for different drain spacings are shown in Fig. 4. For all spacings, notwithstanding the recharge concentration of 1500 mg/l, there was rapid fall of aquifer concentration within the first 0.08 year (30 days) (Fig. 3) and then it either increased or continued to fall depending on the spacing before becoming stabilised (Fig. 3). The initial rapid fall of the salt concentration in the aquifer was due to relatively less concentrated applied recharge (or net recharge) which diluted the salt at the watertable causing more salt leaching at the beginning of the drainage. The later increase (rise) in salt concentration at the base of the root zone (Fig. 3) was because, when the recharge initially entered the aquifer, salt concentration gradient (which was more pronounced at wider spacing) was created at the root zone, which gradually reduced through diffusion from high salt concentration beneath the watertable till the salt concentration stabilised. For all spacings, the salt concentration at the corresponding watertables became stable by Year 3 but at different levels.

At 250 m drain spacing, notwithstanding the recharge concentrations, the salt concentration retained at the base of the root zone was about 14% lower than the initial aquifer concentration. The 200 m and 150 m spacings followed similar patterns and retained concentration levels less than the initial aquifer concentration by about 16% and 22%, respectively. The 90 m spacing retained concentration of about 25% lower than the initial aquifer concentration. The concentrations for spacings 60 and 30 m retained salt concentration levels of 27% and 28%, respectively, lower than the initial aquifer concentration by Year 2, indicating that spacings 60 and 30 m retained almost similar concentrations at the base of the root zone.

It was, however, noted that after 3 years of drainage, the drain discharge concentrations for all spacings were over 99% of their respective 'leachable' concentrations. The leachable concentrations for spacings 30, 60, 90, 150, 200 and 250 m being 1983, 1914, 1843, 1619, 1170 and 982 mg/l, respectively. Fig. 4 shows watertable depths and their corresponding mid-drain concentration levels at 1.5 m from soil surface for different spacings. The results indicated spacing influence on concentration at the base of the root zone when evapotranspiration was included. For example, with a recharge concentration of 1500 mg/l, the salt concentration at the base of the root zone could be changed from about 6037 mg/l to about 5311 mg/l whilst the watertable depth increased from 0.77 m to 1.61 m below the soil surface when spacing was reduced from 200 m to 90 m (Fig. 3). In general there was lower watertable depth and subsequent decrease of concentration at the base of the root zone with decrease in spacing (Ali *et al.*, 2000). This was because at the deeper watertable, less water was lost through evapotranspiration, resulting in a greater net recharge and, consequently, greater drain

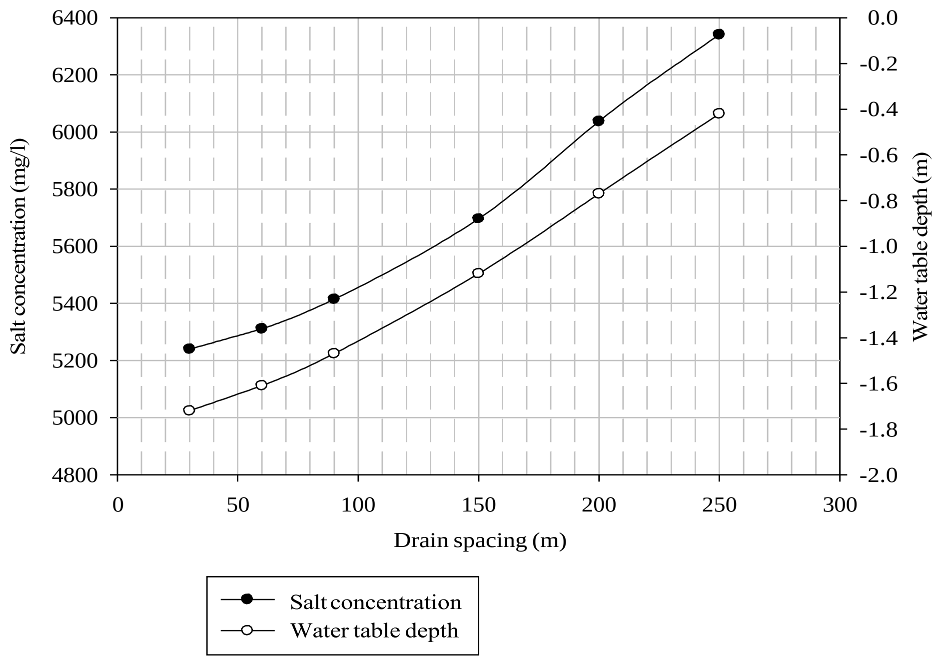

Fig. 4. Watertable depths and their corresponding salt concentration levels at base of rootzone after 5 year drainage

discharge rate and therefore less concentration within the root zone.

Salt dynamics within rooting zone for applied recharge concentrations of 1000 mg/l and 700 mg/l

To check the model for consistency of performance, two runs of the model were made using different applied recharge concentrations of 1000 and 700 mg/l but maintaining the applied recharge rate and the potential evapotranspration. The groundwater contribution to the evapotranspiration, ETg, the drain discharge rate and the watertable depths obtained for all spacings remained the same as the corresponding drain spacing as in the run when the applied recharge concentration was 1500 mg/l. The amount of aquifer salt leached increased with decreasing recharge concentration for all spacings. When the applied recharge concentration was 1000 mg/l, the leached aquifer salt ranged from over 6–8% of the initial aquifer salt in 1 year, about 23–29% of the initial aquifer salt in 5 years, and about 30–40% of the initial aquifer salt in 10 years for drain spacings of 250–300 m, respectively.

When the applied recharge concentration was 700 mg/l, the leached aquifer salt ranged from about 9 to 11% of the initial aquifer salt in 1 year, about 32–37% of the initial aquifer salt in 5 years, and about 44–50% of the initial aquifer salt in 10 years for drain spacings 250 to 30 m, respectively. The results of the two simulations showed that more salt is leached when the applied recharge is less saline (FAO, 1994).

However, for all the drain spacings in both situations, the leached aquifer salts were over 15%, 50%, and 70% of their respective 'leachable' salts in 1, 5, and 10 years, respectively, same percentage as were observed when the concentration of the applied recharge water was 1500 mg/l. This clearly demonstrates that the model was working correctly.

Fig. 5 and 6 show the mid-drain salt concentrations at a depth of 1.5 m from the soil surface for recharge concentrations of 1000 mg/l and 700 mg/l, respectively, after 10 years of drainage. Even though in both

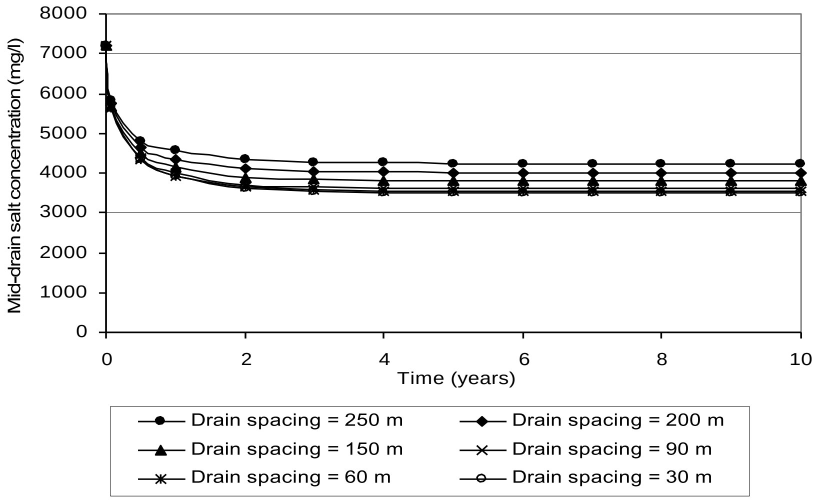

Fig. 5. Mid-drain salt concentration at 1.5 m depth for applied recharge concentration of 1000 mg/l

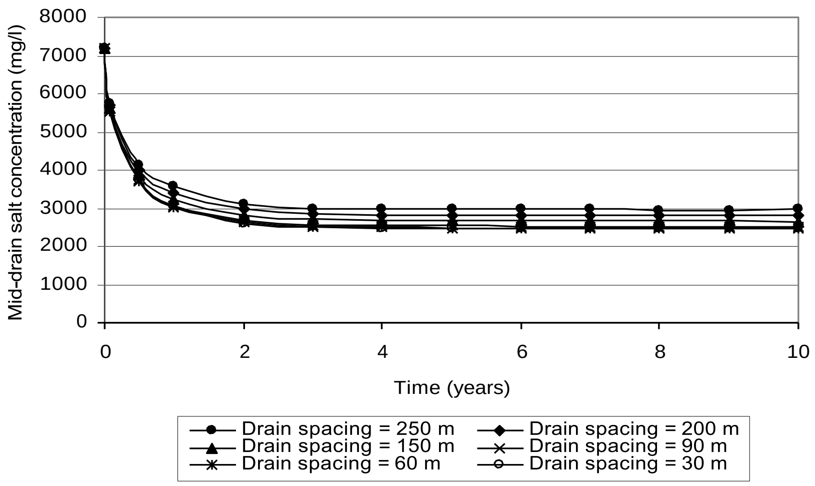

Fig. 6. Mid-drain salt concentration at 1.5 m depth for applied recharge concentration of 700 mg/l

cases, the salt concentration became stable after Year 3 for the same spacing, the salt concentrations retained at the base of the root zone were less for the applied recharge concentration of 700 mg/l than for the applied recharge concentration of 1000 mg/l. This indicates that the quality of the recharge had an effect on the salt concentration at the base of the root zone during drainage. In the case of an applied recharge concentration of 1000 mg/l, the 250 m drain spacing had a salt concentration of about 41% lower than the initial aquifer salt concentration (7200 mg/l) whilst the 200 m and 150 m drain spacings had 44% and 47%, respectively, lower than the initial. The 90 m, 60 m and 30 m drain spacings all had salt concentration levels of over 50% lower than the initial aquifer salt concentration.

With the applied recharge concentration of 700 mg/l, the concentration at the base of the root zone reduced even further. The concentration levels at the base of the root zone for all the spacings were over 60% lower than the original concentration level of the aquifer, and drain spacings 30, 60 and 90 m yielded the same concentration at the base of the root zone. This indicates that the influence of drain spacing on salt concentration at the base of the root zone reduced when the applied recharge is of lower salinity. The greater reduction of the initial aquifer salt concentration could be attributed to the larger difference between the aquifer salt concentration and the net recharge concentration.

In general, a drain spacing of 250 m is over eight times wider than a drain spacing 30 m but in terms of the concentration at the base of the root zone, the drain spacing of 250 m retained salt concentration of only 1.2 times more than that for the drain spacing of 30 m, irrespective of the applied recharge concentration. This indicates that, for any of the applied recharge concentrations, the salt concentration retained at the base of the root zone was not highly dictated by the drain spacings. This was because the potential evapotranspiration rate of 6.2 mm/d used was not large enough to make the salt concentration at the base of the root zone more sensitive to the drain spacings. This suggests that salt concentrations retained at the base of the root zone is a function of not only drain spacing, but also evapotranspiration rate and salt concentration in the applied recharge (water).

Discussion

Drain spacing equations have been traditionally used to design subsurface drainage systems to maintain watertable depths in irrigated land, low enough to prevent salinisation in the root zone by capillary rise. However, these design systems directly do not consider salt concentration control within the rooting zone. Correct choice of drain spacing can be a major contributor to resolving the problem of salt concentration at the base of the root zone. The influences of drain spacing of subsurface drainage system, the quality of the irrigation water (applied recharge) and the prevailing evapotranspiration and their interrelationships on the salt accumulation in the root zone were analysed by using the SEAWAT model, a variable-density numerical groundwater model.

The SEAWAT model simulation showed that when there was no evapotranspiration, both closely and widely spaced drains retained the same salt concentrations at the base of the root zone that were identical to the concentration in the applied recharge. This situation occurred because the volumes of discharges for the spacings were the same and, therefore, the same amount of leached salt resulted since discharge volume is directly related to the amount of leached salt (Christen & Ayars, 2001). This suggests that the concentrations at the base of the root zone depended on only the concentration in the applied recharge but not necessarily on the drain spacing when there was no evapotranspiration.

When evapotranspiration was included, the drain discharge decreased with increasing spacing with an associated rise in the watertable level. It was noted that as the drain spacing widened, the watertable rose, and this enhanced more water loss through evapotranspiration, thereby, reducing the net recharge which in turn drained out as the discharge. Since drain discharge volume relates to the amount of leached salt, with increasing spacing, less water was discharged and, subsequently, less leached salt, thereby, relatively higher salt was left in the aquifer, resulting in a higher concentration at the base of the root zone (Fig. 3). Different spacings had differing effects on watertable depths and concentration levels at the base of the root zone identical to the net recharge concentrations.

The difference was because different spacings resulted in different evapotranspirational water losses, necessitating different water of different salt concentrations percolating to the watertable (Cooper *et al*., 2006). Though the salt concentration at the root zone increased with spacing, the concentration increase was less marked for spacings less than 90 m. Thus, spacings of 30, 60 and 90 m retained relatively the same salt concentration at the base of the root zone. This was because there were marginal differences in evapotranspirational water losses for these spacings and, therefore, the same drained out concentrations. The watertable depths were relatively greater for all spacings than the corresponding spacings when evapotranspiration was not included (Heupermann, 2002) and that evapotranspiration is capable of lowering the watertable.

Conclusions and recommendations

The foregoing research illustrates that the model is capable of simulating both drainage flow and leaching in an irrigated field for different spacings. It was noted that when there was no evapotranspiration, which rarely occurs, the level of salt concentration was affected by the quality of water but not the drain spacing. However, when there was evapotranspiration, the level of salt concentration at the base of the root zone depended on both the drain spacing and the quality of the applied water. It is, therefore, suggested that a variable density numerical groundwater models such as SEAWAT can be effectively used to develop effective subsurface drainage designs that could maintain long lasting concentration at predetermined levels in the field.

To allow easy performance of the SEAWAT, a conceptual uniform flat field with impermeable boundaries was created and, hence, there was no topographic driven gradients affecting groundwater flow from higher to lower lying ground. Since in real irrigation schemes topographic driven flow is a major factor affecting salinity levels in the land, the above performance will be an underestimate of the potential in drainage designs based on SEAWAT. This is because SEAWAT is able to model lateral flow of water and salt throughout the aquifer, with drain spacing widening on higher ground, where lateral outflow reduces the need for drainage, while in lower lying areas where there is expected to be a net inflow of water and salts into the root zone from higher ground, SEAWAT could model higher drain densities to remove excess salinity. The overall performance of variable density numerical groundwater models for designing effective drainage systems must, therefore, be appreciably more effective than conventional drainage designs, which model very restricted boundary conditions between two drains. It can be concluded that the SEAWAT model is applicable on agricultural fields and, therefore, in future work, a real-time field work should be conducted to validate the model.

Acknowledgement

The authors would like to acknowledge the Commonwealth Scholarship and Fellowship Plan, United Kingdom, for the funds for this study.

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