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NUMERICAL MODELLING IN IMPROVING SUBSURFACE DRAINAGE SYSTEM FOR SALT CONCENTRATION CONTROL

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ABSTRACT

The study demonstrates that three-dimensional variable-density groundwater flow models such as the SEAWAT model can be effectively used for design of subsurface drainage systems for controlling salt concentration in the root zone on salt affected irrigated land. The SEAWAT model was used to optimize subsurface drainage design to ensure that the salt concentration of the groundwater at the base of the root zone does not exceed pre determined levels instead of the conventional approach of maintaining the groundwater at a predetermined water table level. The study was carried out on Mankessim Irrigation Project site in Ghana of initial shallow water table depth of 0.5 m and salt concentration of 6800 mg/l with assumed impermeable layer at 10 m deep and impermeable field boundaries. The simulated mid-drain head matched well with the measured especially when calibrated and the longitudinal dispersivity lied between 10 and 50 % of the main cell length, the drain conductance was greater than 500 m^2/d and drain cell dimension was at least twice the diameter of the drain. Using the model, spacings were designed to be used as design criteria for subsurface drainage system to reduce the water table depth from 0.5 m to 0.8 m from the soil surface and maintain concentrations of 6000; 5000; and 4000 mg/l at the base of the root zone. The results showed that over a wide range of irrigation water quality and aquifer hydraulic conductivity, the optimum drain spacing using SEAWAT model was wider by between 3 and 50 % and the amount of drain discharge reduced by 1 and 27 % than were calculated using conventional (Hooghoudt) design equations. It was concluded that Three-Dimensional Variable-Density Groundwater Flow models are better for designing effective drainage systems than conventional drain spacing design equations such as Hooghoudt.

Keywords: groundwater, subsurface, drainage, salt concentration, water table, root zone.

INTRODUCTION

In semiarid and arid irrigated regions, waterlogging coupled with soil salinity is a serious problem (Sharma *et al*., 2000). Without proper drainage system, salts tend to accumulate in the upper soil profile, especially when intense evapotranspiration is associated with insufficient leaching (Yeo, 1999). According to experimental evidence, subsurface drainage is the essential intervention necessary to maintain a suitable growing environment for crops (Sharma and Gupta, 2005). However, the efficiency of subsurface drainage systems in controlling salinity is a matter of debate.

When irrigated soils become saline, the widely used method for controlling salinity is the conventional method of keeping the water table below a critical level to control capillary rise (FAO, 1997). This is a proven approach but the problem is it discharges large volumes water which is often of similar quality as the irrigation water. It is therefore inherently wasteful of water. Therefore a drainage system that focuses more on salt control than water table control is worth considering especially in arid and semiarid regions.

The looming world water scarcity has prompted the need for the introduction of sustainable water management programmes on irrigation schemes (Cosgrove and Rijsberman, 2000). The optimization of such management can be realised by drainage systems that can reduce the need for leaching by discharging less water in order to maximize the contribution of soil water replenishment through capillary rise and control capillary salinization. According to various studies, the design criteria of conventional drainage system are too conservative and can be modified (Ritzema *et al*. 2007). In Pakistan, field monitoring programmes and computer simulations indicate that the field drainage design discharge rate could be reduced from an initial value of 3.5 mm/d to 1.5 mm/d (Wolters, 2000) to get the same results. There is therefore considerable potential to increase water use efficiency and reduce wastage of scarce water. This could be achieved if the drainage system was designed using a model that can simulate variable-density groundwater flow (Guo and Langevin, 2002).

There are several models available to study the movement of water and salt in the soil profile (Ali *et al*., 2000). Most of these models have been developed to design subsurface drainage system by using the conventional drainage equations that mostly consider only the need to achieve a specific water table depth that ensures minimal movement of salt into the crop zone (Ritzema, 1994). The conventional approach is to apply the design drainage equation to calculate a drain depth and spacing that will provide a design discharge rate for a specific water table depth (Guitjens *et al.,* 1997). As a result, drainage is often from depths well below the root zone thereby removing salt from greater depths within the soil profile. Christen and Ayars (2001) noted however that removing salt from such depths within the soil profile does not assist in maintaining a root zone salt balance since these approaches only consider the gross amount of water removed, and do not consider the flow path and the quantities of salt left in the soil profile. This has called for the need to revisit drainage design criteria that would target more towards salt control rather than water table management especially in combination with improved irrigation design.

The objective of this study is to use a variable density numerical groundwater model to design drain spacings that can maintain desired salt concentration at the base of the root zone with less discharge water as compared with conventional drainage design equation.

In reality, the recharge to and discharge from groundwater vary with time. In order to solve these unsteady-state problems, a numerical groundwater model that uses gridded system to discretise the model region into a mesh of cells needs to be considered. The discretization allows better handling of hydrological parameters in terms of their spatial and temporal variability (Harbaugh *et al*., 2000). Numerical groundwater models provide an opportunity to capture the full range of all influencing parameters, many of which are seasonally variable and interact with each other. One such groundwater model is SEAWAT (Guo and Langevin, 2002). The SEAWAT model is a 3-dimensional numerical groundwater model that simulates variable-density groundwater flow and solute flow in the porous media. Unlike the SEAWAT model, many groundwater flow models are constant-density flow models and therefore the flow equations used are based on fluid volume conservation. These models are then used purposely to control water tables. However, Bear (1997) points out that the use of an equation based on volume balance is inappropriate when fluid density gradients are present. To simulate groundwater flow in an environment with the aquifer having higher concentration of salt than the primary source of aquifer recharge, the assumption of constant density is not valid (Langevin, 2001).

Theory of SEAWAT model

The SEAWAT model (Langevin *et al*., 2003) combines a modified version of MODFLOW model (McDonald and Harbaugh, 1988) and MT3DMS (Modular 3-Dimensional Transport of Multi-Species) model (Zhen and Wang, 1999) into a single programme to solve the coupled groundwater flow and solute (salt) transport equations.

The governing equation for variable-density flow in terms of equivalent freshwater head as used in SEAWAT is thus (Guo and Langevin, 2002):

$$\frac{\partial}{\partial x}\left\{\rho K_x\left(\frac{\partial h_f}{\partial x}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial Z}{\partial x}\right)\right\}+\frac{\partial}{\partial y}\left\{\rho K_y\left(\frac{\partial h_f}{\partial y}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial Z}{\partial y}\right)\right\}+\frac{\partial}{\partial z}\left\{\rho K_z\left(\frac{\partial h_f}{\partial z}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial Z}{\partial z}\right)\right\}=\rho S_f\frac{\partial h_f}{\partial t}+\theta\frac{\partial \rho}{\partial C}\frac{\partial C}{\partial t}-\rho_s q_s$$

where,
ρ = density of saline aquifer water (kgm^{-3}); ρ_f = density of freshwater (kgm^{-3}); h_f = equivalent freshwater head (m); Z = elevation at the measurement point (m); S_f = specific yield, in terms of freshwater head (m^{-1}); C = salt concentration that affect aquifer water (kgm^{-3}); ρ_s = source/sink water density (kgm^{-3}) and q_s = source/sink volumetric flow rate per unit volume of aquifer (d^{-1})

According to Langevin (2001), temperature has no effect on the variation of the water density and therefore it is not considered when running SEAWAT. The detailed derivations of the variable-density groundwater flow equation can be found in Guo and Langevin (2002).

The SEAWAT models the contribution of the saturated zone to evapotranspiration by a sliding scale from full extraction when the water table is at the soil surface, falling to a depth where the upflux from the water table approximately ceases, known as extinction depth. A computational adjustment was needed to enable the model to produce the desired groundwater contribution to evapotranspiration rates to meet crop water demand.

METHODOLOGY

Study site

The study was conducted on Mankessim Irrigation Project at Barfikrom/Mankessim in the Central Region of Ghana. The project is located on latitude 15^{o}18' -15^o 20' N and longitude 1^o 02' - 1^o 04' W. The project was started in 1974 and completed in 1978 by Ghana Irrigation Development Authority (GIDA) with the intention to improve the economic levels of the farmers by sustaining vegetable growth (GIDA, 2001). The project had potential area of 260 ha but only 17 ha were developed. The average slope of the field is approximately 0.2 %. The site has as head-works, an earth dam designed for gravity and sprinkler irrigation system with a river as its main source (GIDA, 2008). The project had been almost abandoned by GIDA since 1998 leaving only few individual farmers who are still cultivating various vegetables such as okro, water melon and garden eggs randomly on some parts of the field. The farmers therefore irrigate their farms without any control and regulations, even though the project has no subsurface irrigation systems. However, the Government of Ghana has expressed interest to revive the project towards the achievement of the millennium development goals in the country (MOFA, 2009). The climate of the site is coastal savannah with an average annual rainfall of 1100 mm (Ghana Meteorological Service, 2008).

Field data selection

The data collected were based on parameters required by the model. Three drainage plots representing 3 main different aquifer saturated hydraulic conductivities of 0.51 m/d, 0.8 m/d and 1.22 m/d identified on the field were selected. The size of each plot for the study was 100 m x 100 m even though the total field covered different horizontal hydraulic conductivities. These hydraulic conductivities were determined by auger-hole method (Amoozegar and Wilson, 1999). Data collected in the

ARPN Journal of Engineering and Applied Sciences

field included water table depth, water table salinity and irrigation water rate and salinity, and soil porosity. There was no sign of impermeable layer within the 5 m profile dug in the field and therefore assumed that the bedrock was 10 m below the soil surface. Subsurface drainage laterals were constructed on each aquifer by installing 3 slotted PVC plain pipes at a slope of 0.01 % in a gravel envelope at 2 m deep and 35 m parallel to each other. Each pipe was of 0.11 m internal diameter and 100 m long. The laying of the drains was not based on any drainage design but was intended to cover an appreciable portion of each aquifer in order to drain as much water as possible and to reduce the water table depth from 0.5 m to a depth greater than 1.5 m below soil surface. The laterals were connected to the open drain collectors already existed at the end of the field. The initial water table depth was determined by piezometers randomly installed on the field before installation of the drains. They farmers were then monitored to irrigate at a rate of 8 mm/day though the irrigation at times was supplemented by rainfall especially during the rainy season. Four piezometers were installed adjacent each drain to monitor and measure water table height on the drains (drain head), and five piezometers along the midway between any two drains to monitor and measure mid-drain water table height (mid-drain head). The heads were measured when they had been monitored till they became relatively stable or a number of relatively constant measurements were taken. This occurred about 320 to 350 days of drainage. The model was then run for that number of days that the field heads became stable. The average crop ET at the irrigation site was obtained from the Regional Directorate of Ministry of Food and Agriculture, Central Region (personal communications).

In addition to the field data collected, each aquifer was discretized into equal finite-difference grid of cells with 100 rows by 100 columns by 10 layers giving each main grid cell dimension of 1 m by 1 m by 1 m. In layer 2, (2 m below soil surface) the row of cells that housed the drains (drain cells) were subdivided into square cells (0.2 m per side) to more accurately approximate lateral flow of water and salt at the upper part of the aquifer. To prevent flow into or from the model domain, no flow boundaries were assigned along boundaries. The bed of each aquifer which lied 10 m below soil surface was represented as an impermeable barrier (no flow boundary) with a hydraulic conductivity of 1 x 10^{-7} m/d, an approach used by Swain *et al.,* 1996. The longitudinal dispersivity was estimated using the formula by Gelhar, (1986) and Xu and Eckstein (1995), the transverse dispersivity by Bear and Verruijt (1990), molecular diffusion coefficient using formula by Berner (1980) and Shen and Chen (2007), the drain conductance was determined using the equation by McDonald and Harbaugh, (1988), and the specific yield giving the same value as effective porosity as suggested by Lavingen (2001). Table-1 summarizes the main input data used for the model simulations.

The study could be divided into three parts. In the first part the SEAWAT model was verified and some parameters adjusted to suit its usage on irrigated field by running it for water table heights midway between drains (mid-drain heads) at the different hydraulic conductivities (1.22 m/d; 0.8 m/d; and 0.51 m/d) corresponding to each plot and compared the simulated mid-drain heads with the measured drain-heads. This is because the model is mostly used for saltwater intrusion in coastal aquifers (Langevin, 2001) and very little is known of its usage on irrigated field.

The second part involved running the model to design drain spacings at drain depth of 2 m that would reduce the water table depth from 0.5 m to 0.8 m below soil surface and maintain different salt concentrations of 6000 mg/l; and 5000 mg/l; and 4000 mg/l at the base of the root zone if the dimension of each drainage plot were extended to 1000 m by 1000 m and under different groundwater contribution to evapotranspiration rates, ET_g, of 8; 7; 6; 5; 4; 3; 2; and 1 mm/d. With the calibrated parameters and other field data, the design drain spacings were simulated by varying the applied recharge concentrations and the spacings till the desired concentration at the base of the root zone and water table depth of 0.8 m were obtained for each groundwater contribution to evapotranspiration rate. This was repeated on all the drainage plots. The 0.8 m water table depth was adopted because it was beyond the reach of vegetable rooting depth and could provide a healthy vegetable growing environment.

The third part involved comparing the simulated drain spacings and drain discharges for salt concentrations of 6000 mg/l; 5000 mg/l and 4000 mg/l at the base of the root with corresponding calculated values of conventional (Hooghoudt) drainage design equations - a combination of Hooghoudt steady state equation (Ritzema, 1994), and the following equations:

$LF = \frac{Ci}{Cn}$ (van Hoorn and van Alphen, 1994) and

$AW = \frac{ET}{1 - LF}$ (FAO, 1985)

where, *LF* is leaching fraction; *Ci* is applied water (recharge) salt concentration; *Cn* salt concentration at the base of the root zone; *AW* is applied water (recharge) and *ET* evapotranspiration.

RESULTS AND DISCUSSIONS

Verification and calibration of SEAWAT model on irrigated field

The model was calibrated by systematically adjusting the drain conductance, drain cell dimension, porosity and longitudinal dispersivity which appeared to be sensitive to the model, to achieve an acceptable match between average values of measured mid-drain water table heights (mid-drain heads) and the corresponding values simulated by the model. Adjusted values of model parameters were constrained to lie within the range of values obtained in the field. Table-1 shows simulated mid-

ARPN Journal of Engineering and Applied Sciences

drain heads for different drain cells of 0.1 m, 0.2 m and 0.5 m per side using different drain conductances: 500; 1000; 1500; and 3000 m^2/d and the corresponding measured mid-drain head on each aquifer. Both the measured and the simulated mid-drain heads changed with changing spatial hydraulic conductivity. This confirms the observation by Palacios-Vélez *et al*. (2004) of the critical role played by hydraulic conductivity in controlling water table by subsurface drainage system. The similar trend of mid-drain head changes with changing the saturated hydraulic conductivity for both measured and simulated suggested that the model could be used for subsurface drainage system design model on irrigated field.

Table-1. Simulated and measured mid-drain heads of the different aquifers.

Saturated hydraulic conductivity (m/d)	**Dain cell dimension** (m/side)	**Drain conductance, CD** (m^2/d)				**Measured mid-drain head** (cm)
		500	**1000**	**1500**	**3000**	
		Simulated mid-drain head (cm)	**Simulated mid-drain head** (cm)	**Simulated mid-drain head** (cm)	**Simulated mid-drain head** (cm)	
0.51	0.1	77.4	77.1	77.0	77.8	79.0
	0.2	73.2	72.9	72.8	72.7	
	0.5	71.0	71.7	70.9	70.8	
0.80	0.1	58.7	58.5	58.4	58.2	60.2
	0.2	56.2	55.8	55.7	55.6	
	0.5	54.9	54.6	54.5	54.4	
1.22	0.1	40.7	40.4	40.3	40.2	41.7
	0.2	38.7	38.4	38.1	38.1	
	0.5	37.2	36.9	36.8	36.6	

Generally the simulated mid-drain heads for the different drain cell dimensions correlated well ($R^2 = 0.998$) with the measured mid-drain heads. However, the 0.1m drain cells was discounted because maintaining all other parameters and adjusting drain cell dimension to 0.1 m per side, the simulation produced drain head value almost same as the mid-drain head whilst the measured produced relatively no drain head on all the aquifers. This suggested that drain cell dimension needed to be bigger than the diameter of the drains. Similar phenomenon was observed on each aquifer when the drain conductance was adjusted to 500 m^2/d and all the other parameters were maintained. Drain conductance describes the drain's ability to transmit water and therefore a drain conductance of 500 m^2/d might not be sufficient to transmit enough water thereby resulting to the formation of water table height on the drains (drain head). The drain conductance of 500 m^2/d was also discounted.

Table-2 show the simulated mid-drain heads for different porosities, drain conductances and longitudinal dispersivities, α_L and for the aquifer with hydraulic conductivity of 0.8 m/d. The simulated values compared well with the measured in all cases with the percentage difference ranging between 10.7 % and 8.9 %. Though there were marginal differences in percentage difference, the longitudinal dispersivity, $\alpha_{L,}$ of 0.01 m generally had relatively higher difference and was therefore discounted. Similar trend was observed between the simulated and measured heads for the other drainage plots. Though when the α_L was adjusted to 1.0 m, the simulated mid-drain head matched well with the measured, the α_L value of 1.0 m was discounted based on the studies by Gelhar, (1986) and Xu and Eckstein, (1995) that the constant

ARPN Journal of Engineering and Applied Sciences

Table-2. Simulated mid-drain heads of different longitudinal dispersivities, drain conductances and effective porosities and measured mid-drain head for 0.8 m/d hydraulic conductivity aquifer.

Drain conductance (m^2/d)	**Effective porosity** (%)	**Longitudinal dispersivity, α_L** (m)				**Measured mid-drain head** (cm)
		0.01	**0.1**	**0.5**	**1.0**	
		Simulated mid-drain head (cm)	**Simulated mid-drain head** (cm)	**Simulated mid-drain head** (cm)	**Simulated mid-drain head** (cm)	
1000	10	55.0	55.8	56.0	55.7	60.2
	20	54.9	55.7	55.9	55.6	
	30	54.8	55.6	55.8	55.5	
1500	10	54.9	55.7	55.9	55.5	
	20	54.8	55.5	55.8	55.4	
	30	54.2	55.4	55.7	55.3	
3000	10	54.3	55.6	55.8	55.5	
	20	54.2	55.4	55.7	55.3	
	30	54.0	55.3	55.6	55.2	

of proportionality of the relation between longitudinal dispersivity, α_L, and distance covered by solute (model domain cell length) should always be less than one. This suggested that for the model to perform well on irrigated field the longitudinal dispersivity, α_L need to lie between 10 % and 100 % of the main grid cell length. For the different effective porosities (10%, 20% and 30%) used the simulated mid-drain head matched well with the measured on all the drainage plots.

Table-3 lists the calibrated parameters and their corresponding range of values considered acceptable for the model.

Table-3. Calibrated model parameters and their corresponding range of values.

Model parameter	**Range of values**
Effective porosity	10 - 30 %
Drain cell dimensions	(0.2 - 0.5) m horizontal and (0.2- 0.5) m vertical
Drain conductance	1000 - 3000 m^2/d
Longitudinal dispersivity	(0.1 - 0.5) L_s*

*L_s is length of horizontal side of the model cell

Drain spacing design

The drain spacings designed were intended for the use in different conditions with different available water for irrigation, and also different climatic conditions and hence different contributions of ground water the evpotranspiration to maintain different salt concentrations ranging from 4000 mg/l to 6000 mg/l at the base of the root zone corresponding to the different conditions. Figures 1, 2 and 3 show the relationship between design drain spacing, groundwater contribution to evapotranspiration rate, ET_g, and applied recharge concentration to maintain the desired concentrations at the root zone for different aquifer hydraulic conductivities. Each group of curves are presented such that each corresponds to the desired concentration that was maintained at the base of the root zone. It was noted that the desired concentrations were maintained at the base of the root zone with the drain spacings yielding different drain discharges irrespective of ET_g on all the aquifers. Thus no two drain spacings yielded the same drain discharge either for a given ET_g or applied recharge concentration. Figure-4 shows the relationship of the drain spacing and the corresponding drain discharges for the different aquifer hydraulic conductivities. From Figure-4, the drain discharge of any drain spacing can be read off. Figures 1, 2, and 3 can be used as 'salt concentration control' design spacing graphs and Figure-4 can be said to be a 'drain discharge' spacing design graph thus the graphs could be served as subsurface drainage design chart. It must be stated though that in view of spatial variability of hydraulic conductivity; sloping surface and usually less than 10 m aquifer depth for most irrigated fields with water moving between different areas by gravity, the design graphs should be used with prudence.

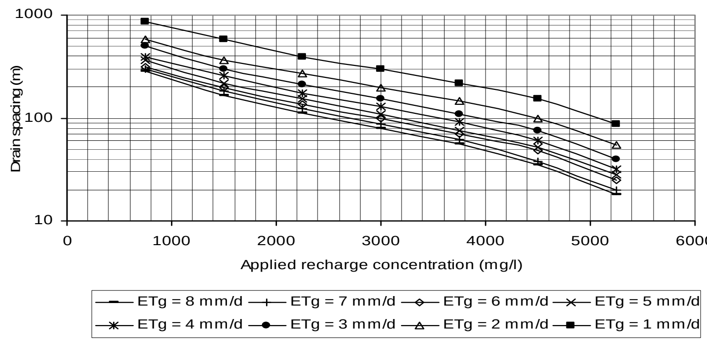
Figures 1(a), 2(a) and 3(a) present drain spacings and the corresponding drain discharges that maintained salt concentrations of 6000 mg/l at the base of the root zone and at a water table depth of 0.8 m for different groundwater contribution to evpotranspiration rates. It was found that the concentration of the applied recharge could be increased with decreased drain spacing and increasing applied recharge (and drain discharge) to maintain the desired concentration of 6000 mg/l at the base of the root zone. Further decreasing drain spacing and more applied recharge (and more drain discharge) was necessary when the evapotranspiration rate is higher. For example, for the aquifer having hydraulic conductivity of 0.8 m/d, applied

VOL. 9, NO. 11, NOVEMBER 2014 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

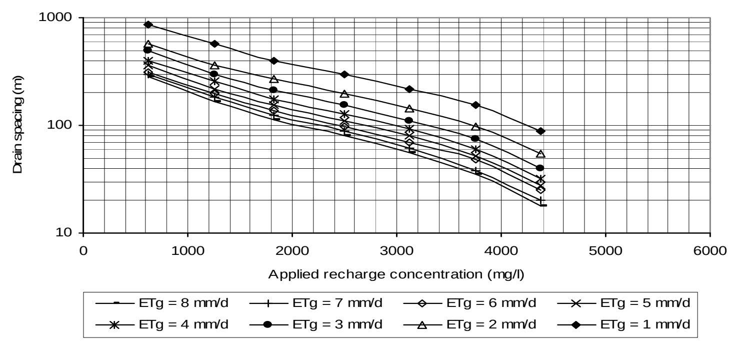
recharge concentrations of 750 mg/l and 3000mg/l necessitated drain spacings of 395 m and 128 m respectively (Figure-1a) with corresponding applied recharges of 4.6 mm/d (and drain discharge of 0.6 mm/d) and 7.6 mm/d (and drain discharge of 3.6 mm/d) (Figure-4) to maintain concentration of 6000 mg/l at the base of the root zone when the groundwater contribution to evapotranspiration rate was 4 mm/d. For the same aquifer type, the same applied concentrations correspondingly necessitated drain spacings of 282 m and 80 m with applied recharges of 9.0 mm/d and 15.1 mm/d respectively to maintain concentration of 6000 mg/l at the base of the root zone when groundwater contribution rate was 8 mm/d. This emphasises the need not to use lower quality water for irrigation in areas of high evapotranspiration rate.

Comparison of SEAWAT and conventional design spacing and drain discharges

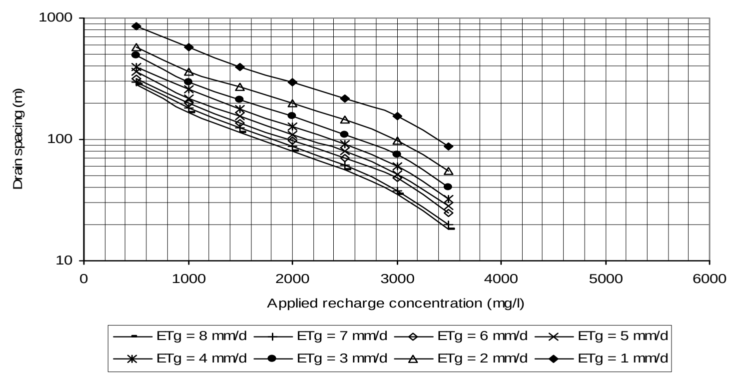
With the field data, drain spacings and drain discharges that could maintain the desired salt concentrations of 6000 mg/l, 5000 mg/l and 4000 mg/l were calculated using Hooghoudt steady-state equation (conventional method) for the



(a): Root zone base salt concentration of 6000 mg/l for different groundwater evapotranspiration rates.



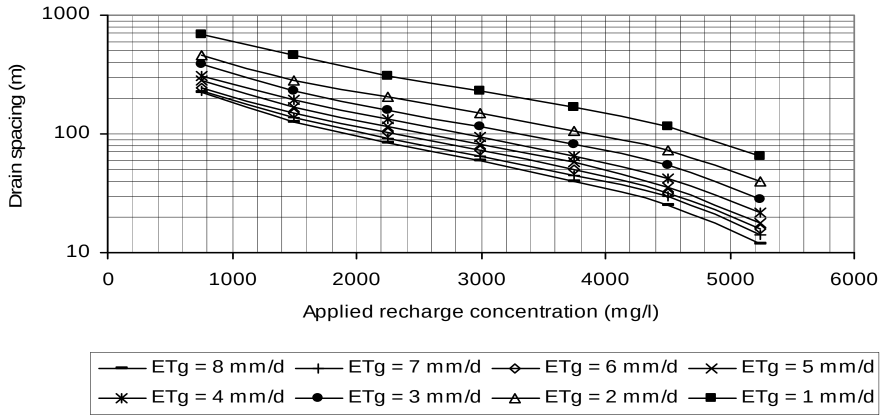
(b): Root zone base salt concentration of 5000 mg/l for different groundwater evapotranspiration rates.



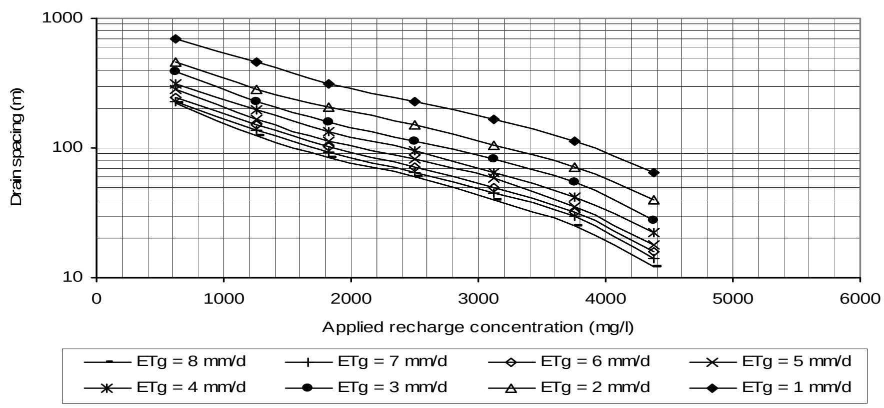
(c): Root zone base salt concentration of 4000 mg/l for different groundwater evapotranspiration rates.

Figure-1. Design drain spacing for Aquifer K = 0.8 m/d to maintain the desired concentration at the base of the root zone.

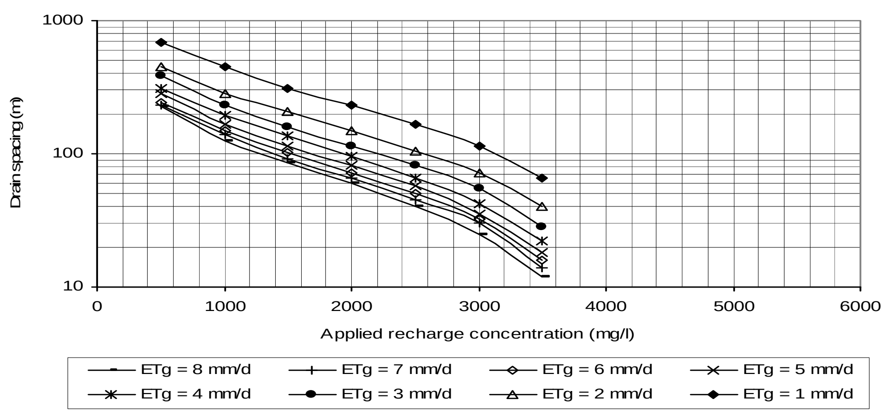
VOL. 9, NO. 11, NOVEMBER 2014 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences



(a): Root zone base salt concentration of 6000 mg/l for different groundwater evapotranspiration rates.



(b): Root zone base salt concentration of 5000 m/g/l for different groundwater evapotranspiration rates.



(c): Root zone base salt concentration of 4000 mg/l for different groundwater evapotranspiration rates.

Figure-2. Design drain spacing for Aquifer K = 0.51 m/d to maintain the desired concentration at the base of the root zone.

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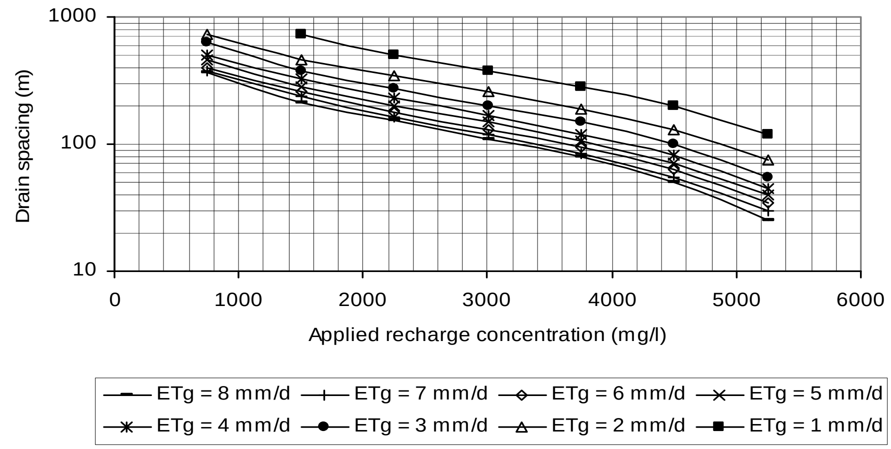
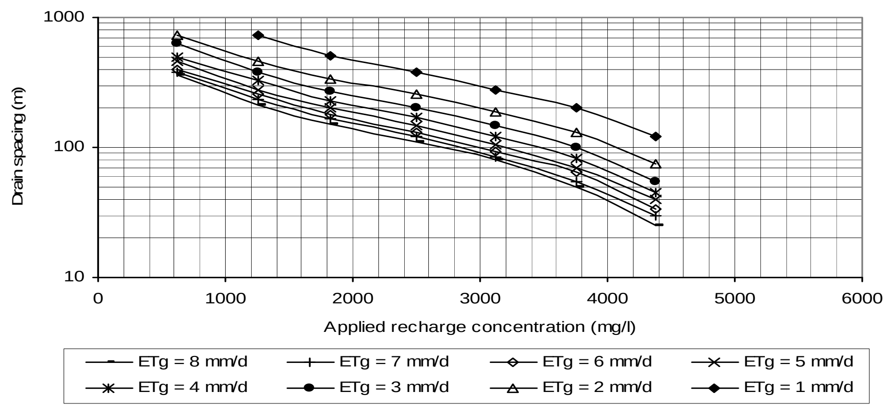
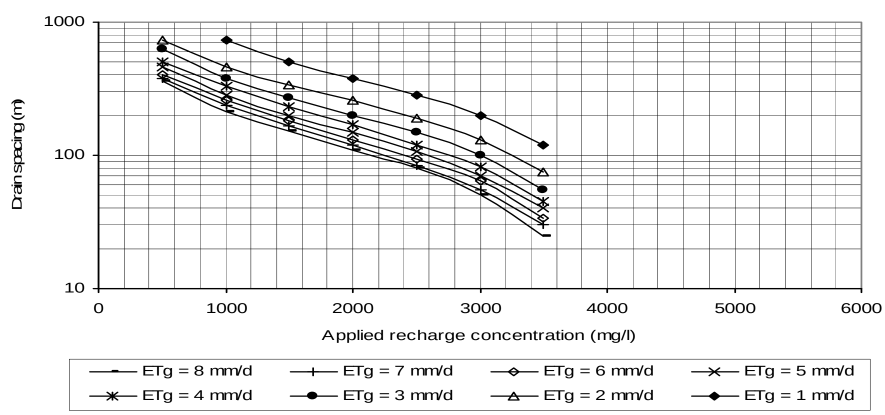


(a): Root zone base salt concentration of 6000 mg/l for different groundwater evapotranspiration rates.



(b): Root zone base salt concentration of 5000 mg/l for different groundwater evapotranspiration rates.



(c): Root zone base salt concentration of 4000 mg/l for different groundwater evapotranspiration rates.

Figure-3. Design drain spacing for Aquifer K = 1.22 m/d to maintain the desired concentration at the base of the root zone.

VOL. 9, NO. 11, NOVEMBER 2014 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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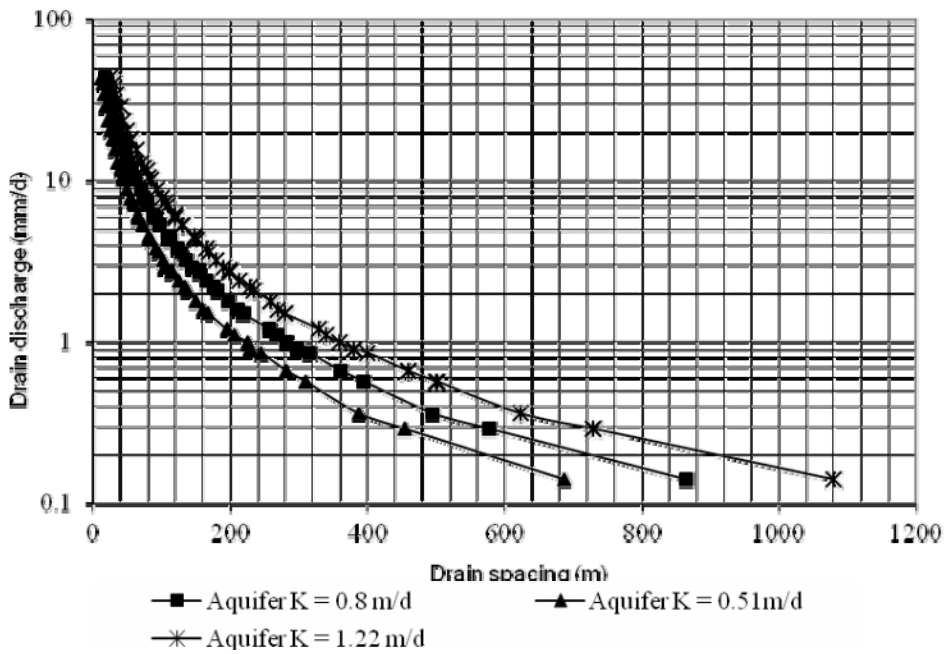

Figure-4. Relationship between design drain spacing and drain discharge for different aquifers.

different hydraulic conductivities and compared with the corresponding SEAWAT simulated values. Tables 4, 5, and 6 show model simulated and conventional (Hooghoudt calculated) design drain spacings, and percentage differences between the simulated and the conventional spacings required to maintain concentration of 6000 mg/l at the base of the root zone for the 3 aquifers respectively. The 'positive percentage difference' means that the model simulated spacing was wider than the conventional spacing. This suggests that SEAWT model could maintain the same desired salt concentration at the base of the root zone as the conventional method but with less number of drain laterals. Table-7 presents the simulated drain discharges, conventional (Hooghoudt calculated) drain discharges and percentage differences between the simulated and conventional drain discharges for the different aquifer hydraulic conductivities. The 'negative percentage difference' means the simulated drain discharge is less than the conventional drain discharge. The higher conventional drain discharge compared to the model simulated discharge could be attributed to the comparatively more number of drains needed by the conventional method to maintain the same salt concentration at the base of the root zone as that of the model because the rule of thumb is it that the more the number of drains the more drain discharges.

In comparing the model simulated and the conventional (Hooghoudt calculated) design drain spacings, it was found that in all situations, the model simulated design spacings are wider than the conventional (Hooghoudt calculated) spacings ranging from 3% to over 50 %. This means more economic savings when the model was used as a design tool for drain spacing. Generally, the savings are much more when the evapotranspiration rate is high than when the evapotranspiration rate is low.

Comparing the model simulated and the conventional (Hooghoudt calculated) drain discharges, differences in drain discharges were all negative indicating that the simulated drain discharges were less than the conventional drain discharges (Table-7). This means there was drained water savings for the model design which ranged from 1 to 27 % in maintaining the desired concentration at the base of the root zone. In general the percentage differences were higher in areas of high evapotranspiration than areas of low evapotranspiration. Similarly, the differences were greater when the concentration in the applied recharges were high than when the concentration in the recharges were low (Table-7). This means more drainage water (and irrigation water) will be saved in areas of high evapotranspiration when the model is used as a tool for subsurface drainage system than the conventional drainage system and much more water savings could be achieved when the concentration in the applied recharge is high.

Table-4. Model simulated and Hooghoudt calculated spacing, and % difference between the spacings for aquifer K = 0.8 m/d.

***ETg rate:**	**8 mm/d**			**7 mm/d**			**6 mm/d**			**5 mm/d**			**4 mm/d**			**3 mm/d**			**2 mm/d**			**1 mm/d**		
Applied recharge conc. (mg/l)	**Drain spacing** (m)			**Drain spacing** (m)			**Drain spacing** (m)			**Drain spacing** (m)			**Drain spacing** (m)			**Drain spacing** (m)			**Drain spacing** (m)			**Drain spacing** (m)		
	Sim	**Cal**	**% diff**	**Sim**	**Cal**	**% diff**	**Sim**	**calc**	**% diff**	**Sim**	**Cal**	**% diff**	**Sim**	**Cal**	**% diff**	**Sim**	**Cal**	**% diff**	**Sim**	**Cal**	**% diff**	**Sim**	**Cal**	**% diff**
750	282	254	+11	298	270	+10	315	288	+9	362	335	+8	395	368	+7	496	466	+6	578	550	+5	865	839	+3
1500	165	142	+16	182	158	+15	198	173	+14	218	193	+13	258	229	+13	298	270	+10	362	335	+8	578	550	+5
2250	113	93	+22	124	103	+20	136	115	+18	155	131	+24	176	153	+15	212	186	+14	268	241	+11	395	368	+7
3000	80	64	+40	88	71	+24	98	80	+23	110	91	+21	128	106	+21	155	131	+18	198	184	+8	298	270	+10
3750	56	42	+33	62	47	+32	70	54	+30	76	62	+23	92	73	+26	110	91	+21	145	122	+19	218	193	+13
4500	35	26	+35	38	29	+31	48	32	+50	52	38	+37	60	46	+30	75	59	+27	98	80	+23	155	131	+18
5250	18	12	+50	20	14	+43	25	16	+56	28	19	+47	32	23	+39	40	29	+38	55	40	+38	88	71	+24

Sim is SEAWAT model simulated spacing. Cal. is calculated spacing from Hooghoudt steady state equation

Table-5. Model simulated and Hooghoudt calculated spacings, and % difference between the spacings for aquifer K = 0.51 m/d.

ET_g rate:	**8 mm/d**			**7 mm/d**			**6 mm/d**			**5 mm/d**			**4 mm/d**			**3 mm/d**			**2 mm/d**			**1 mm/d**		
Applied recharge conc. (mg/l)	**Drain spacing** (m)			**Drain spacing** (m)			**Drain spacing** (m)			**Drain spacing** (m)			**Drain spacing** (m)			**Drain spacing** (m)			**Drain spacing** (m)			**Drain spacing** (m)		
	Sim	**Cal**	**% diff**	**Sim**	**Cal**	**% diff**	**Sim**	**Cal**	**% diff**	**Sim**	**Cal**	**% diff**	**Sim**	**Cal**	**% diff**	**Sim**	**Cal**	**% diff**	**Sim**	**Cal**	**% diff**	**Sim**	**Cal**	**% diff**
750	225	192	+17	230	204	+13	245	218	+12	282	256	+10	310	282	+10	388	360	+8	455	427	+7	688	650	+6
1500	125	103	+21	138	115	+20	150	127	+18	168	143	+17	195	171	+14	230	204	+13	282	256	+10	455	427	+7
2250	85	68	+25	92	75	+23	102	84	+21	114	95	+20	135	111	+22	160	138	+16	206	181	+14	310	282	+10
3000	60	45	+33	65	50	+30	72	57	+26	82	65	+26	95	77	+23	114	95	+20	150	127	+18	230	204	+13
3750	40	29	+38	45	32	+40	50	36	+39	58	45	+29	65	52	+25	82	65	+26	105	89	+18	168	143	+17
4500	25	18	+39	30	20	+50	32	23	+39	35	27	+30	42	31	+35	55	40	+38	72	57	+26	114	95	+20
5250	12	9	+33	14	10	+40	16	11	+45	18	13	+38	22	15	+47	28	20	+40	40	28	+43	65	50	+30

*ET_g is groundwater contribution to evapotranspiration

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Table-6. Model simulated and Hooghoudt calculated spacings, and % difference between the spacings for aquifer K = 1.22 m/d.

***ET_g rate:**	**8 mm/d**			**7 mm/d**			**6 mm/d**			**5 mm/d**			**4 mm/d**			**3 mm/d**			**2 mm/d**			**1 mm/d**		
Applied recharge conc. (mg/l)	**Drain spacing** (m)			**Drain spacing** (m)			**Drain spacing** (m)			**Drain spacing** (m)			**Drain spacing** (m)			**Drain spacing** (m)			**Drain spacing** (m)			**Drain spacing** (m)		
	Sim	**Cal**	**% diff**	**Sim**	**Cal**	**% diff**	**Sim**	**Cal**	**% diff**	**Sim**	**Cal**	**% diff**	**Sim**	**Cal**	**% diff**	**Sim**	**Cal**	**% diff**	**Sim**	**Cal**	**% diff**	**Sim**	**Calc**	**% diff**
750	360	329	+9	380	348	+9	400	371	+8	460	430	+7	500	470	+6	624	592	+5	730	694	+5	1080	1051	+3
1500	214	187	+14	235	208	+13	260	227	+15	280	252	+11	330	298	+11	380	348	+9	460	430	+7	730	694	+5
2250	152	126	+21	165	139	+19	180	155	+16	200	174	+15	230	202	+14	270	243	+11	340	312	+9	502	470	+7
3000	110	88	+25	120	96	+25	130	107	+21	148	122	+21	170	144	+18	200	174	+15	260	227	+15	380	348	+9
3750	80	60	+33	84	66	+27	94	74	+27	106	85	+25	120	99	+21	148	122	+21	190	164	+16	280	252	+11
4500	50	36	+39	55	40	+38	64	46	+39	70	54	+30	82	65	+26	100	80	+25	130	107	+21	200	174	+15
5250	25	18	+39	30	20	+50	33	22	+50	40	27	+48	45	32	+41	55	40	+38	75	58	+29	120	96	+25

Table-7. Model simulated and Hooghoudt calculated drain discharges, and % difference between the discharges.

ET_g rate:	**8 mm/d**			**7 mm/d**			**6 mm/d**			**5 mm/d**			**4 mm/d**			**3 mm/d**			**2 mm/d**			**1 mm/d**		
Applied recharge conc. (mg/l)	**Drain discharge** (mm/d)			**Drain discharge** (mm/d)			**Drain discharge** (mm/d)			**Drain discharge** (mm/d)			**Drain discharge** (mm/d)			**Drain discharge** (mm/d)			**Drain discharge** (mm/d)			**Drain discharge** (mm/d)		
	Sim	**Cal**	**% diff**	**Sim**	**Cal**	**% diff**	**Sim**	**Cal**	**% diff**	**Sim**	**Cal**	**% diff**	**Sim**	**Cal**	**% diff**	**Sim**	**Cal**	**% diff**	**Sim**	**Cal**	**% diff**	**Sim**	**Cal**	**% diff**
750	1.0	1.1	-10	0.9	1	-11	0.86	0.9	-5	0.66	0.7	-6	0.57	0.6	-5	0.36	0.4	-11	0.29	0.3	-3	0.14	0.14	0
1500	2.4	2.7	-13	2.1	2.3	-10	1.8	2	-11	1.5	1.7	-13	1.2	1.3	-8	0.9	1	-11	0.66	0.7	-6	0.29	0.3	-3
2250	4.3	4.8	-12	3.8	4.2	-11	3.2	3.6	-13	2.8	3	-11	2.2	2.4	-9	1.6	1.8	-13	1.1	1.2	-9	0.57	0.6	-5
3000	7.1	8	-14	6.2	7	-13	5.3	6	-13	4.5	5	-11	3.6	4	-11	2.7	3	-11	1.8	2	-11	0.9	1	-11
3750	11.7	13.3	-14	10.2	11.7	-15	8.8	10	-14	7.3	8.3	-14	5.9	6.7	-14	4.4	5	-14	2.9	3.3	-14	1.5	1.7	-13
4500	20.2	24	-19	18.2	21	-15	15.6	18	-15	13	15	-15	10.5	12	-14	7.8	9	-15	5.4	6	-11	2.7	3	-11
5250	44	56	-27	40	49	-23	34.5	42	-22	29	35	-21	23.4	28	-20	18	21	-17	12	14	-17	6.1	7	-15

Sim. is SEAWAT model simulated drain discharge. Cal. is calculated drain discharge from Hooghoudt steady state equation

*ET_g is groundwater contribution to evapotranspiration

DISCUSSIONS AND CONCLUSIONS

The simulated mid-drain heads compared well with the measured mid-drain heads and this suggested that SEAWAT could be used as subsurface drainage design model on irrigated fields. Conventional subsurface drainage system procedures for salt concentration control in the root zone rely on lowering the water table enough to prevent capillary rise of salt into the root zone. Christen and Ayars (2001), however, noted that this approach does not consider long term salt balance in the root zone associated with the depth and spacing of drains in a particular hydrologic setting. It is evident from the results that SEAWAT model could be used to design drain spacings to maintain the desired salt concentrations at the base of the root zone with lower drain discharges (and applied water) for different climatic and aquifer conditions.

The comparison of the SEAWAT simulated drain spacing to the conventional (calculated) drain spacings to maintain a concentration of 6000 mg/l at the base of the root zone shows that great economic savings may be achieved when the SEAWAT is used as a tool. This is because the simulated drain spacings (for all evapotranspiration rates and all aquifer hydraulic conductivities) are larger than the corresponding conventional (calculated) drain spacing, providing percentage differences ranging from 3 to over 50 % between the simulated and the conventional drain spacings. This is comparable to those obtained by other numerical approaches that considered evapotranspiration from the water table (Hathoot, 1980; Hathoot *et al*. 1992).

Again, comparing the simulated drain discharges to the conventional (calculated) drain discharges, all the percentage differences were negative indicating that the simulated discharges were less than the corresponding conventional drain discharges. This provided drain discharge savings ranging in the order of 3 to over 20 %.

It must be stated, however, that the neglect of the slight vertical hydraulic conductivity variations identified on the field was likely to have uncertainty and a source of error. Also, the fact that the field surface was relatively flat may not realistically represent the flow conditions occurring in the aquifer on sloping field. Therefore the design chart and the results should not be taken as absolute. Nevertheless there could be an overall reduction in drain discharge if subsurface drainage is installed based on SEAWAT designs and not conventional designs.

Since the field was relatively flat, there was not much topographic driven gradients' effecting groundwater flow from higher to lower lying ground. The simulated drain discharges could then be an underestimate of the potential drain discharges based on SEAWAT drainage design, since in most irrigation schemes topographic driven flow is a major factor affecting both water and salinity levels in the land. The numerical modelling technique clearly provided more effective designs on flat land which when extended onto sloping larger tracts of land where water is moving by gravity towards the low lying land, the SEAWAT will be much more effective than the conventional design.

The results indicated that the SEAWAT model was a valuable alternative to conventional design procedure for subsurface drainage design, especially in hot and dry regions to maintain salt concentration at the base of the root zone with lower applied water. The overall performance of variable density numerical groundwater models for designing cost effective drainage systems must therefore be appreciably more effective than conventional drainage designs which model very restricted boundary conditions between two drains. Again, the results showed that over a wide range of irrigation water concentrations and aquifer hydraulic conductivities, the optimum drain spacing using SEAWAT was, depending on modelled water quality and aquifer hydraulic conductivities, wider by between 3 and 50 % and the amount of drain discharges reduced by between 2 and 27 % than would be recommended using conventional design equations.

It is however recommended that the SEAWAT model is further validated using a real-time sloping irrigated field of over ten year conventional subsurface drainage system.

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