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Dry drainage: A sustainable solution to waterlogging and salinity problems in irrigation areas?

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ABSTRACT

Estimates of the global extent of irrigation-induced soil salinity vary, but there is widespread agreement that the twin menaces of waterlogging and salinisation represent serious threats to the sustainability of irrigated agriculture in many arid and semi-arid regions. In certain circumstances, the conventional drainage solution may be questionable due to economic and/or environmental limitations and "*dry drainage*" has been postulated as an alternative. It involves the allocation of areas of fallow land, which operate as evaporative sinks drawing a stable flux of water and salt from irrigated areas. An evaluation of the merit of this approach requires answers to three key questions: (i) What is the limiting crop intensity? (ii) What is the limiting watertable depth? (iii) What is the long-term impact of salt accumulation in the drainage sink area? A simulation model was developed to investigate these questions for a dry-drainage system with a wheat–cotton cropping pattern using published data for the Lower Indus Basin in Pakistan, where shallow saline watertables, intensive irrigation, high evaporative demand and natural dry drainage exist. The simulation results showed that dry drainage could satisfy the necessary water and salt balance when the cropped area and sink area were approximately equal and watertable depth was around 1.5 m. The long-term impact of salt accumulation on the performance of the system was also considered.

1. Introduction

The introduction of irrigation in arid and semi-arid environments inevitably leads to watertable rise and often to problems of waterlogging and salinisation. Hoffman and Durnford (1999) reported how these twin problems have developed worldwide since recorded history, and the speed with which they are advancing at present. Ghassemi et al. (1995) reviewed various estimates of the global extent of salinisation of land and water resources and concluded that, of the total of 230 million ha of irrigated land around the world, some 45 million ha suffer from severe irrigation-induced salinity problems.

Conventional wisdom holds that the best solution to dealing with the twin menace of salinity and waterlogging, is to maintain a net flux of salt away from the rootzone and to control the watertable by means of artificial drainage. There is a widespread acceptance that irrigation without drainage is not sustainable, but it is necessary to consider also whether conventional technical fixes are themselves sustainable. While this approach may be suitable for local circumstances, within large contiguous irrigation systems significant economic and environmental limitations may arise (van Schilfgaarde, 1994; Kijne et al., 1998; Ayars and Tanji, 1999; Smedema, 2000; Saysel et al., 2002; Sonuga et al., 2002).

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In recent years, the assumption that irrigation is a public good has become questionable and there has been growing recognition of the importance of farmer participation. Poor performance in many large-scale irrigation schemes has been attributed to the failure of public sector management, a significant factor being the inability to provide adequately for the cost of operation and maintenance. The problem is even more severe in public drainage schemes (Gowing and Wyseure, 1992), as drainage does not generate more income, but simply aims to protect existing income, so farmers are reluctant to pay much to support such schemes. Economic sustain ability is therefore open to question.

Concern over environmental sustainability arises from the need to dispose off saline drainage effluent from irrigated land. Problems include (i) availability of main/public drains, (ii) high cost involved in connecting individual farm drainage systems to the public drain, (iii) resistance by neighbouring land owners to drainage effluent passing across their fields, (iv) environmental concerns, (v) salt loading of rivers and (vi) availability of drainage sinks in closed basins.

In recent years, there have been attempts to identify solutions, which will work within environmental constraints and will also be economically viable (Hanson, 1989; Gowing and Wyseure, 1992; Asghar, 1996; Sharma and Tyagi, 2004). Improved on-farm water management combined with disposal by means of evaporation ponds is seen as the optimal strategy, but with some environmental risks. Subirrigation facilities for watertable management with some limitations have been discussed by Skaggs (1999) and Fouss et al. (1999a,b). Another alternative is the control of the water level with irrigation management. A shallow watertable can be considered as a valuable resource for meeting part of the crop requirement for water (Ragab and Amer, 1986) and studies have shown that salt-tolerant crops (e.g., cotton, alfalfa and barley) are capable of extracting significant quantities of water from groundwater (Ayars and Schoneman, 1986). Therefore, shallow groundwater may be used as a resource when the salt content of the water does not lead to unmanageable rates of salinisation (Qadir and Oster, 2004). However, in arid and semi-arid regions, the evaporative demand and the salinity of groundwater may be high and the upward evaporative flux from a saline watertable may result in the accumulation of salt to a very high concentration at or near the soil surface. This can occur seasonally on fallow fields or continuously on unirrigated (abandoned) land.

The beneficial use of this process to control salinity by means of managed evaporative sink areas within a "dry-drainage" scheme was first proposed by Gowing and Wyseure (1992).

1.1. *Concept of dry drainage*

There is a tendency to view drainage in terms of controlling watertable depth, and therefore, to be misled by the notion of a "critical depth" for salinity control. In fact, salinity control depends upon establishing a time-averaged net downward flux through the rootzone, therefore, it is the water balance that is important (Smedema, 1990). Disturbance of the natural balance by introducing irrigation causes a rising watertable, where natural drainage sinks cannot cope with the increase in groundwater recharge (Gowing and Wyseure, 1992).

Within a given area, if inflow (rainwater excess, field application losses, watercourse and/or canal seepage losses) balances outflow (supply to crops from watertable, evaporation from uncropped areas, artificial and/or natural drainage sinks), then the watertable will be stable. If the uncropped area is large enough and evaporation from this area is fast enough, then the necessary balance can be achieved without artificial drainage. This is the concept of dry drainage. It means that part of the available land is set-aside as a sink for excess groundwater and for salt transported with the groundwater. The groundwater system provides the pathway for the movement of the excess water from the irrigated land to the fallow land (Fig. 1).

There is evidence that some parts of the Indus Basin in Pakistan have already benefited from dry-drainage systems and the practical significance of this mechanism has been recognised for some time (Middleton et al., 1966). It has also received some attention in field studies in Australia

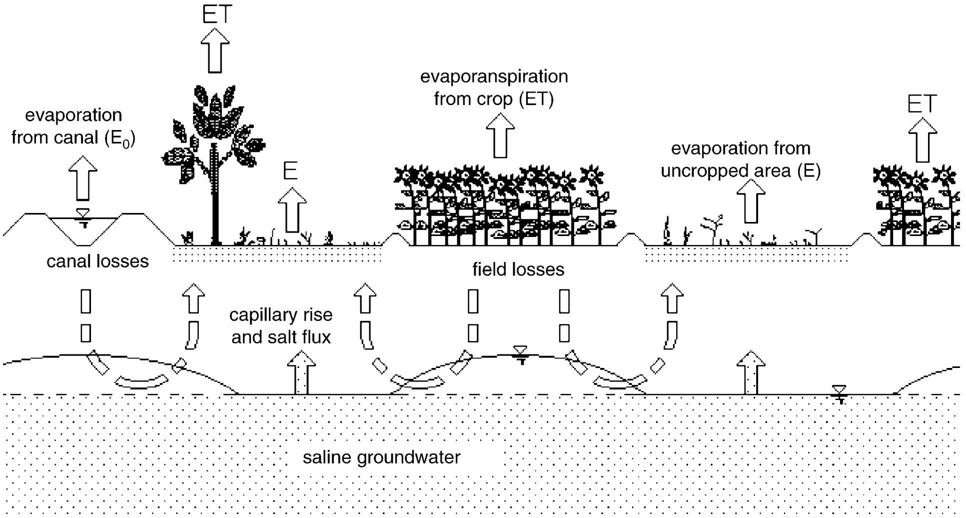

Fig. 1 – Schematic section of a dry-drainage system.

(Greenwood et al., 1992, 1994) and is recognised by West African Rice Development Association (WARDA, 1997) as a sound method to control salinity in rice-growing areas of West Africa. An initial theoretical assessment for conditions typical of the Lower Indus Basin in Pakistan (Gowing and Wyseure, 1992) confirmed previous observations that dry drainage could be effective if the areas of irrigated crop and evaporative sink were approximately equal. Asghar (1996) developed a physically based dynamic simulation model for quantifying the dry-drainage system. More recently, Khouri (1998) discussed the role and principles for the design and management of a dry-drainage scheme along with numerical studies on a hypothetical field-scale example.

1.2. *Objective of the study*

Khouri (1998) used the SUTRA model (Voss, 1984), which describes the transport of water as a liquid through the entire soil profile. The restriction to liquid phase movement may be acceptable in the cropped area during the irrigation season, but it cannot be applied to the fallow area or to the cropped area during a fallow period. In arid and semi-arid regions, the evaporative demand is usually greater than the ability of the soil to conduct water in the liquid phase and a liquid–vapour phase discontinuity, known as the evaporation front (EF), occurs at some depth between the soil surface and the watertable in the fallow area or during the fallow period (Menenti, 1984; Bastiaanssen et al., 1989; Asghar, 1996; Gowing and Asghar, 1996; Konukcu et al., 2004; Rose et al., 2005; Gowing et al., in press). Above an EF, a gradient of vapour pressure near the soil surface causes upward movement of water as vapour. Under such conditions, Richards' equation (which applies to the movement of soil water in the liquid phase) and simulation models based on Richards' equation (such as SUTRA) cannot be applied to the entire soil profile. Both phases, liquid and vapour in series, must be taken into account to describe the upward movement of water and evaporation from a watertable (Gowing et al., in press). In addition, Khouri (1998) did not calculate the salt balance of the cropped and fallow areas, which is the key factor for dry drainage to be successful.

Although Asghar (1996) developed a theory based on such two-phase flow to describe the water and salt balance of both cropped and fallow areas, the procedure for locating the depth of the EF imposes limitations on the general applicability of his model and also requires substantial parameterisation. The model, being numerical transient-state, locates the EF from the simulated matric potential at the EF. Numerical models become numerically unstable at a sudden discontinuity in the matric potential profile (Smith, 1965; Wang and Anderson, 1982) as experienced at an EF (Menenti, 1984; Bastiaanssen et al., 1989; Gowing et al., in press) so that alternative approaches are needed to overcome the limitations of these models.

Therefore, the objectives of this study are: (i) to develop a model to describe the water and salt balances of both cropped and fallow areas for a successful dry-drainage system, and (ii) to use the model to simulate the performance of a hypothetical dry-drainage system for conditions representative of the Lower Indus Basin in Pakistan.

2. Approach to simulating the dry-drainage system

As shown in Fig. 1, a single dry-drainage unit has two parts, the irrigated area and the fallow area. Both parts should be carefully designed and managed in terms of salt and water balance for the dry drainage to be successful.

2.1. *Behaviour of the irrigated area*

In arid and semi-arid areas, evapotranspiration exceeds precipitation and this water deficit should be covered by irrigation to achieve a satisfactory yield. The application of irrigation water means an input of salts because irrigation water, even if of excellent quality, is a source of soluble salts. If soil salinisation is to be avoided, these salts have to be leached out by deliberate over-irrigation percolating to the subsoil. The leaching requirement to provide the salt balance of the rootzone may be calculated (van Hoorn and van Alphen, 1994) by:

$$R^x = (\mathrm{ET} - P)\frac{C_i}{f_i\left(\frac{\theta_s}{\theta_{fc}}C_e - C_i\right)} \tag{1}$$

where R^x is the leaching requirement (mm); ET the evapotranspiration (mm); P the effective precipitation (mm); C_i the salt concentration of the irrigation water (g/l); C_e the salt concentration of saturated soil paste, i.e. the maximum permissible value for a given crop type (g/l); θ_s the saturation water content of soil (m^3/m^3); θ_{fc} the soil water content at field capacity (m^3/m^3); and f_i is the leaching efficiency coefficient. The total irrigation, I (mm), is then:

$$I = \mathrm{ET} - P + R^x \tag{2}$$

Note that (i) for any given crop type and irrigation schedule, there must be no point in the irrigated area that experiences a net outflow of water at the land surface, and therefore, a tendency to salinise; (ii) capillary rise from below the irrigated area during the irrigation season is neglected; (iii) all water percolating from the irrigated area during the irrigation season is assumed to evaporate from the fallow field; (iv) capillary rise and subsequent salinisation during the fallow period in the irrigated field is taken into account. Therefore, the irrigation schedule should be designed to maintain the salt balance during the whole year. Salt accumulation and leaching requirement of the irrigated area during the fallow period is computed as in the fallow field.

2.2. *Behaviour of the fallow area*

In investigating the sustainability of a dry-drainage system, we need to predict accurately the rate of evaporation and salt accumulation in the fallow area. The capillary flux in the unsaturated zone above a watertable can be estimated with the aid of various available models under steady-state (Gardner, 1958) and under transient-state conditions (Hayhoe and de Jong, 1982 (SWASIM model); Voss, 1984 (SUTRA model); Wagenet and Hutson, 1989 (LEACH model); Vanclooster et al., 1995 (WAVE model); van Dam et al., 1997 (SWAP model); Ragab, 2002 (SALTMED model)). However, all these models describe the transport of water in the liquid phase through the entire soil profile and cannot be used to predict the evaporative flux from the fallow area for the reason explained earlier.

Gowing et al. (in press) developed a pseudo steady-state model, modifying the well-known Gardner (1958) model, to predict the rate of evaporation from the soil surface, particularly from the surface of bare soil. They successfully simulated the daily evaporation rate from saline and non-saline soils containing shallow watertables for periods of 80 days under high evaporative demands of up to 24 mm/day. Although the Gardner (1958) model (which takes only liquid phase into account) computes the rate of evaporation from a watertable when the water content of the surface soil decreases monotonically to a limiting value, the model of Gowing et al. (in press), which considers water movement as liquid and vapour in series, provides a solution for all surface conditions from saturation to air dryness and provides more accurate results (Gowing et al., in press). Therefore, this model will be used to compute the rate of evaporation from the fallow area.

Gowing et al. (in press) first locate the depth of EF and then calculate the rate of evaporation. When evaporation occurs after an equilibrium soil–water profile has been established above a constant watertable, they distinguish three stages in the progression of the EF: (i) no EF exists, (ii) the EF moves downwards, and (iii) the EF is stationary. In the first stage, because the soil is sufficiently wet, evaporation occurs from the soil surface and the EF is at the surface. In the second stage, because the rate of evaporation due to the external evaporative conditions is greater than the upward flow from groundwater, the topsoil becomes very dry and the depth of the EF increases progressively. In the steady-state, evaporation from the soil surface is equal to the groundwater contribution and the depth of the EF remains constant (Rose et al., 2005).

Stage 1: Because no EF exists in the soil, the liquid flow equation applies to the entire profile and the evaporation rate, E, from the soil surface is calculated by the modified Penman equation for unsaturated soil (Staple, 1974) as:

$$E = \frac{h\Delta(R_n - G)/\lambda + \gamma E_a}{h\Delta + \gamma} \tag{3}$$

where E is the evaporation from the soil surface (mm/day); h the relative humidity of the soil water, which has two components in saline conditions ($h = h_m \cdot h_0$), attributable to matric (h_m) and osmotic (h_o) forces; Δ the proportionality constant (kPa/K) equal to de/dT, where e is the actual vapour pressure (kPa) and T is temperature (K); R_n the net radiation (W/m^2); λ the latent heat of vaporisation of water (J/kg); γ the psychrometric constant (m/K); and E_a is the drying power of the atmosphere (mm/day). The calculation procedure for h is described by Philip and de Vries (1957). Δ and γ are computed as explained by Burman and Pochop (1994). The aerodynamic term, E_a, is calculated as (Staple, 1974):

$$E_a = f(u)(h\,e_{sat} - e) \tag{4}$$

where e_{sat} is the saturated vapour pressure at the temperature of the atmosphere. The wind function, $f(u)$, is given by 0.35 (0.5 + 0.54 u), where u is the average wind speed (m/s) at 2 m height.

The water flux as liquid is now calculated for the first stage. Because a steady flux is assumed during a time increment, the steady-state equation describing vertical liquid flow from a watertable is:

$$q_1 = K\left[\frac{d\psi_m}{dz} - 1\right] \tag{5}$$

so that

$$z = \int \frac{d\psi_m}{1 + q_1/K} \tag{6}$$

Eq. (6) can be integrated for any relationship between hydraulic conductivity, K, and matric potential, ψ_m. Gardner (1958) gave $K(\psi_m)$ as:

$$K(\psi_m) = \left[\frac{a}{b + \psi_m^n}\right] \tag{7}$$

where a, b and n are constants related to the soil texture. Gardner (1958) evaluated analytical solutions of the integral (Eq. (6)) using Eq. (7), with b set equal to zero, for values of n equal to 1, 3/2, 2, 3 and 4.

In each time increment during the first stage, the water loss from the soil profile, $\Delta\theta$, is calculated as:

$$\Delta\theta = (E - q_1)\,\Delta t \tag{8}$$

In the first time step, Δt_1, the water content at the soil surface is the initial water content, θ_i. The water content in the surface compartment at the start of the second time increment, θ_{t2}, is computed as:

$$\theta_{t2} = \left(\theta_i - \frac{\Delta\theta_{t1}}{d}\right) \tag{9}$$

where d is the thickness of the compartment (m) from which water is removed during the first stage. If θ_{t2} is greater than θ_e, the same procedure is repeated for successive time increments. When the water content in the compartment decreases to θ_e, the first stage is complete. At the end of this stage, the depth of the EF is $z_e = d$.

Stage 2: Both liquid flux below the EF and vapour flux above the EF. Because the evaporative demand is high, the rate at which water moves through the soil profile up to the EF becomes limiting. Gardner (1958) assumed that this limiting value occurred when the water content was below the wilting point but within the range of validity of Eq. (7). In this condition, the maximum liquid flux can be calculated for any given watertable depth, z_w, (Gardner, 1958) as:

$$q_{lim} = \frac{A}{z_w^n} \tag{10}$$

where $A = 3.77a$ for $n = 3/2$, $A = 2.46a$ for $n = 2$, $A = 1.76a$ for $n = 3$, and $A = 1.52a$ for $n = 4$, and a is the constant in Eq. (7).

Eq. (10) can be used to describe the maximum liquid flux from a watertable in the steady-state when the EF lies at or very close to the surface. However, when the EF moves deeper, the depth of the watertable from the EF, $z_w - z_e$, should be used instead of z_w in Eq. (10). Hence, we modify Eq. (10) to:

$$q_1 = \frac{A}{(z_w - z_e)^n} \tag{11}$$

and use Eq. (10) to calculate the liquid flux below the EF. As before, the water content at the EF, θ_e, is assumed to be the limiting water content.

For the vapour flux, q_v (kg/m^2 s), above the EF, a Fickian equation is used (Gardner, 1958):

$$q_v = \frac{D_v(e_{sat} - e)}{z_e} \tag{12}$$

where D_v is the coefficient of diffusion of water vapour through the soil (m^2/s) which may be calculated following Rose (1963).

The depth of the EF after the first time increment, z_{et2}, in the second stage is calculated as:

$$z_{et2} = d + \Delta z_{et1} \tag{13}$$

where

$$\Delta z_{et1} = \frac{d(\Delta\theta)}{\theta_i - \theta_e} \tag{14}$$

Note that θ_i in Eq. (13) is the initial water content of the soil layer just beneath the EF.

The water loss from the soil profile in this stage, $\Delta\theta$, is given by $\Delta\theta = (q_v - q_1)\,\Delta t$. This procedure is repeated until the vapour flux becomes equal to the liquid flux, i.e. a steady-state is reached.

Stage 3: In this stage, the steady-state, the liquid and vapour fluxes, Eqs. (11) and (12), are equal and the depth of the EF remains constant. In order to calculate E for different soil textures, the values of θ_e and the hydraulic properties of the particular soils should be known. The model is fully described and validated in Gowing et al. (in press).

Salt accumulation: The capillary flux from a saline watertable leads to the concentration of these salts at or near the soil surface (Hassan and Ghaibeh, 1977; Rose et al., 2005). The concentration profile which develops with time depends upon both the upward evaporative flux of water, which concentrates salts, at the surface, and the diffusive–dispersive flux, which tends to move salts downward against the upward flux of water. Elrick et al. (1994) described the spatial and temporal distribution of the concentration subject to the conditions of steady-state evaporation from a shallow watertable. They offered two equations to compute solute concentration profiles using a constant water-content profile and a depth-dependent water-content profile. We use the simpler constant water-content model, which gives an approximate but sufficiently accurate concentration profile for our simulations, as:

$$C(z,t) = C_i + \Delta C(z,t) \tag{15}$$

$$\begin{aligned} \Delta C(z,t) \\ = C_i\Bigg(\upsilon\left(\frac{1}{\pi D}\right)^{0.5}\left\{\exp\left[\frac{-(z+\upsilon t)^2}{4Dt}\right]\right\} - 0.5\left\{\mathrm{erfc}\left[\frac{z+\upsilon t}{2(Dt)^{0.5}}\right]\right\} \\ + 0.5\left(1 - \frac{\upsilon z}{D} + \frac{\upsilon^2 z}{D}\right)\exp\left(\frac{\upsilon z}{D}\right)\left\{\mathrm{efrc}\left[\frac{z+\upsilon t}{2(Dt)^{0.5}}\right]\right\}\Bigg) \end{aligned} \tag{16}$$

where $\Delta C(z, t)$ is the change in the salt concentration (g/l) as a function of depth, z (m) and time, t (s); C_i the initial salt concentration (g/l); υ the upward evaporative flux (m/s), calculated using Eq. (3) during the first stage and Eq. (11) during the second and third stages (Gowing et al., in press); and D is the dispersion coefficient (m^2/s), which may be computed following the procedure given by Elrick et al. (1994).

Leaching process: In the leaching process, the soil profile or the rootzone can be considered as a single reservoir or a series of one-dimensional reservoirs with bypass (van Hoorn and van Alphen, 1994). The latter assumption will be used to describe both (i) the leaching requirement of the cropped area after a fallow period and (ii) the salinity profile of fallow area after an effective rainfall.

In the series of reservoirs with bypass, each reservoir receives the outflow from the overlying one. If the initial salt concentrations of the successive layers are different, the following equations are obtained for numerical solution (van Hoorn and van Alphen, 1994):

$$aC_i + bC_{s1} = (a+b)C_{x1} \tag{17}$$

where a is the depth of influent water (mm); b the depth of soil water in layer 1 (mm); C_i the salt concentration of influent water (g/l); C_{s1} the salt concentration of the soil water in layer 1(g/l); and C_{x1} is the salt concentration of the soil solution of layer 1 after mixing (g/l).

If the water retained in layer 1 is equal to c (mm), an amount $(a - c)$ with a concentration C_{x1} percolates into layer 2 and mixes with its moisture. The concentration of the soil solution of layer 2 after being mixed, C_{x2}, is calculated in the same way:

$$(a-c)C_{x1} + dC_{s2} = (a-c+d)C_{x2} \tag{18}$$

where d is the amount of soil water in layer 2. Successive layers can be treated in the same way.

2.3. *Parameters for dry-drainage system test case*

The dry-drainage system was simulated for the Lower Indus Basin in Pakistan, where shallow saline watertables, intensive irrigation and high evaporative demand exist. Almost one-third of its available cultivated land has already been abandoned due to waterlogging and salinity (Gowing and Wyseure, 1992). Average climatologic data and soil properties were adopted from Asghar (1996) (Table 1) and estimates of evapotranspiration, ET, from Gowing and Wyseure (1992) (Table 2).

In Table 2, the total irrigation amount I and leaching requirements R^x are calculated assuming 85% irrigation application efficiency (e_i) and 80% leaching efficiency (f_i). Salinity of the irrigation water, C_i, is 0.7 g/l (1 dS/m) (Gowing and Wyseure, 1992; Asghar, 1996) whereas the salinity of the drainage water, C_s, is 2.8 g/l (4 dS/m) for a given crop pattern (Maas and Hoffman, 1977). Asghar (1996) indicated that the observed groundwater salinity of the region is about three times greater than that of irrigation water, 2.1 g/l at 1.78 m depth and 10 times greater 7.0 g/1 or 10 dS/m at 10–45 m depths. We assumed the maximum value of 7.0 g/l throughout our simulation of the salt accumulation in the groundwater over time in the sink area.

A sandy clay loam soil prevails in the region (Asghar, 1996). The data for $\psi(\theta)$ and $K(\psi_m)$ were taken from Rijtema (1969) and the van Genuchten (1980) and Gardner (1958) models, respectively, were fitted. The curve-fitting parameters are summarised in Table 3. The watertable is shallow over much of the area with a large part within 1.5 m of the surface

Table 1 – Average climatologic data in the study area (Asghar, 1996)

	Months											
	January	February	March	April	May	June	July	August	September	October	November	December
T (°C)	13.0	16.7	22.5	28.1	33.3	33.6	31.4	30.3	28.9	26.1	20.0	15.3
h_a (%)	57	51	36	27	28	45	67	72	62	44	41	56
P (mm)	23	18	13	8	13	74	180	173	117	10	3	10
N (day)	2	2	1	1	2	4	8	8	4	1	1	1

T: mean daily temperature; h_a: mean relative humidity of air; P: montly mean precipitation; and N: number of rain days.

Table 2 – Average evapotranspiration (Gowing and Wyseure, 1992)

	Month											
	January	February	March	April	May	June	July	August	September	October	November	December
ET_0 (mm)	64	82	140	183	243	262	214	198	177	136	81	61
Wheat–cotton												
ET (mm)	60	90	98	75	49	144	225	218	177	109	75	34
I^x (mm)	59	96	113	89	48	93	60	60	80	132	96	32
R^x (mm)	10	17	20	16	8	16	11	11	14	23	17	16
I (mm)	69	113	133	105	56	109	71	71	94	155	113	48
Sugarcane												
ET (mm)	61	74	126	174	243	262	203	168	150	129	81	61
I^x (mm)	38	56	113	166	230	188	23	−5	33	119	78	51
R^x (mm)	10	15	31	46	63	52	6	−1	9	33	21	14
I (mm)	48	71	144	212	293	240	29	−6	42	152	99	65
Orchards												
ET (mm)	64	82	140	183	243	262	214	198	177	136	81	61
I^x (mm)	41	64	127	175	231	188	34	25	60	126	78	51
R^x (mm)	4	6	13	18	23	19	3	3	6	13	8	5
I (mm)	45	70	140	193	253	207	37	28	66	139	86	56
Weighted mean												
ET (mm)	66	88	104	84	65	152	219	209	163	103	76	38
I^x (mm)	43	70	91	76	52	78	39	36	46	93	73	28
R^x (mm)	12	19	25	21	14	21	11	10	13	26	20	8
I (mm)	55	89	116	97	66	99	50	46	59	119	93	36

ET_0: reference evapotranspiration; ET: evapotranspiration for wheat and cotton; I^x: irrigation without leaching ($I^x = ET - P$); I: total irrigation amount ($I = I^x + R^x$) and R^x: leaching requirement with 80% leaching efficiency + field losses of 15%.

(Gowing and Wyseure, 1992). Therefore, simulation results are presented for the watertable depth of 1.5, 1.0 and 2.0 m. Similarly, although the simulations were done for the predominant wheat–cotton cropping pattern, sugarcane and orchard are also considered.

Monthly average P is distributed within a given month over equal periods taking the number of rains into consideration. For instance, monthly average P in January is 74 mm and the number of rains is 4. So, 74/4 = 18.5 mm rain is assumed to fall on the 4th, 11th, 19th and 26th days of January.

Table 3 – The parameters for soil hydraulic properties, $\psi_m(\theta)$ (van Genuchten, 1980)

θ_r (m^3/m^3)	θ_s (m^3/m^3)	θ_{fc} (m^3/m^3)	α (l/m)	n	m	R^2
$\psi_m(\theta)$ parameters						
0.005	0.44	0.32	1.48	1.208	0.172	0.99

a (m)	b (m)	$a/b = K_s$ (m/s)	n	R^2
K (ψ_m) parameters				
0.0109	0.0462	0.236	2.25	0.98

R^2: coefficient of determination; θ_r: residual water content; θ_s: saturated water content; θ_{fc}: water content at field capacity; K_s: saturated hydraulic conductivity; α, m, n, a and b, curve-fitting parameters.

3. Results and discussion

3.1. *Water and salt balance of the cropped area*

The amount of water (leaching + irrigation losses) percolating from the cropped area for each month during a year is given in Table 2. The maximum and minimum percolation occurred in October (27 mm) and December (7 mm), respectively. Given that the drainable pore space, μ, of the soil (i.e. saturation water content minus field capacity) is 0.12 m^3/m^3, the rise in the watertable below the cropped area ranges between 5.8 and 22.5 cm. This range is considered sufficient to provide the hydraulic head to drive the necessary flux from source (cropped) to sink (fallow) areas. The evaporation from the fallow area lowers the watertable depth, which also increases the head and enhances the flux. This maximum watertable rise of 22.5 cm will not lead to yield reduction in the cropped area if the initial watertable depth is 1.5 m in the cropped area (Rijtema, 1969; van Hoorn, 1979).

Because the irrigation is designed to maintain the salt balance of the rootzone of the cropped area and there is no fallow period to lead to salt accumulation, no additional equations for salt equilibrium and storage are applied.

3.2. *Water and salt balance of the fallow area*

Fig. 2a shows the daily evaporation from the soil surface over a year for the average watertable depth of 1.5 assuming an equilibrium water content above this watertable at the start of our calculation in October, the beginning of the dry season. (Note that the calculation started from October but is presented from January.) A relatively high evaporation rate on the first day (day 273), about 8 mm/day, decreased to 2.1 mm/day within the first 7 days because the evaporative demand of the atmosphere exceeded the ability of the soil to conduct water so causing the soil surface to dry. The evaporation rate then fluctuated minimally above this value during the dry season following small amounts of precipitation. Daily evaporation increased suddenly when the rainy season began and then fluctuated widely between the potential and limiting rates during the rainy season.

Using Gardner's model (Gardner, 1958; Rijtema, 1969), the steady rate of evaporation during the dry period was calculated at 2.8 mm/day, 33% larger than 2.1 mm/day calculated using the model of Gowing et al. (in press). Over a year, the Gardner (1958) model predicts 175 mm more cumulative evaporation than that of Gowing et al. (in press).

The cumulative evaporation from the fallow area should balance the total of precipitation and percolating water from the cropped area for dry drainage to be a success. The cumulative evaporation from the fallow area was 1054 mm/year (Fig. 2b) while the sum of precipitation (643 mm/year) and percolating water from the cropped area (198 mm/year) amounted to 841 mm/year. This means that the fallow area is capable of sustaining the required water balance for the success of the system. Under the simulated conditions, the cropped area may be larger than the fallow area by a factor of 1.25 (i.e. 1054/841). Gowing and Wyseure (1992) suggested approximately equal areas whereas Khouri (1998) stated that, for an excavation of 30 cm deep in the fallow area to accelerate the upward flux, a ratio of areas of cultivated to uncultivated land of less than 2 satisfied the leaching requirement. This ratio will be further discussed together with the salt balance of fallow area.

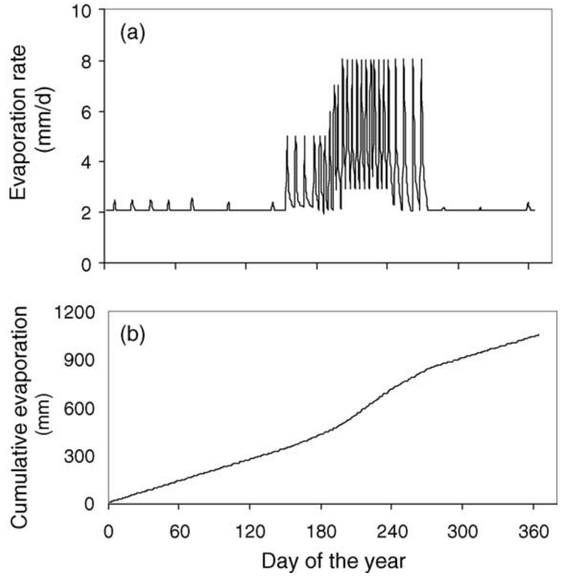

Fig. 2 – (a) Evaporation rate and (b) cumulative evaporation from the surface of the fallow area during a year.

The main concern of the management of the fallow area in a dry-drainage scheme is how to increase, or at least maintain, the evaporation rate from the bare soil surface. The rate of evaporation determines the salt accumulation at the soil surface, which in turn influences the rate of evaporation (Hassan and Ghaibeh, 1977; Khouri, 1998). In this part, we discuss the salt accumulation at the soil surface in the dry period (from the beginning of October to the end of May) and the leaching process during the rainy season (from the beginning of June to the end of September).

Salt accumulation in the soil profile of the fallow field was calculated from Eqs. (15) and (16) during the dry season. The initial salt concentration of the soil was assumed to be 7.0 g/l, (i. e. that of the groundwater) and a uniform average water-content profile for a given month was taken. The salt-concentration profile was calculated monthly. The salt and water profiles at the end of the previous month were used as the initial conditions for the next month. The parameter υ was taken as the average evaporative flux (Fig. 2) for a given month, converting the unit into m/s. Dispersion coefficients, D, of 9.6×10^{-8} and 1.19×10^{-7} m^2/s were used for the equilibrium water-content profile in the first month and for subsequent profiles during the following months, respectively.

Fig. 3 shows the calculated salt concentration profiles at four different times during the dry period. At the end of the dry season, approximately the top 60 cm of soil had become saline. Leaching was calculated using Eqs. (17) and (18) during the rainy season. To do this, the soil profile was divided into five layers, each 30 cm deep, and the average salt and water contents of these layers were calculated from the salt and water-content profiles at the end of the dry season. Figs. 4 and 5 show the average and end of dry season water- and salt-content profiles, respectively.

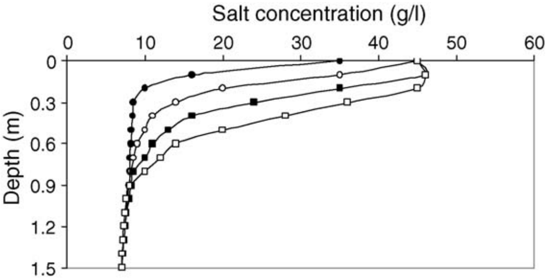

Fig. 3 – Profiles of salt concentration of the fallow area at four different times during the dry season. (●) 30 November, (○) 31 January, (■) 31 March and (□) 31 May.

After each rain, the water and salinity profiles were recalculated. Fig. 6 shows the calculated salt concentration of each soil layer. The amount of evaporation during the period between two rainfalls was allowed for in calculating the next water-content profile. Although the rainy season started in June, the amount of precipitation during this month was not sufficient to replenish the water content to field capacity so no percolation and therefore no leaching occurred. At the end of July, a considerable amount of salt from the 0–30 cm soil layer was leached into the 30–60 cm layer but there was no leaching below 60 cm. During August and September, leaching occurred in all soil layers; however, salt does not accumulate in the soil profile during the year.

Having carefully considered the water and salt balance of both irrigated and fallow areas, the remaining salt in the soil profile of the fallow area at the end of the year may be leached if this leaching requirement is not too large, as practised in West Africa (WARDA, 1997). In our case, 120 mm water is needed to bring the salt profile at the end of the first year to the concentration of groundwater, 7 g/l. Re-checking the water balance of the fallow land, the inflow (961 mm) needed, which is the sum of percolating water from the irrigated area (198 mm), total precipitation (643 mm) and leaching requirement of the fallow area (120 mm), is still smaller than the outflow, which is the cumulative evaporation from the fallow area (1054 mm). In this case, the ratio of cropped to fallow area becomes 1054/961 = 1.10, i.e. the irrigated area may be approximately 10% larger than the cropped area, which is virtually the same as proposed by Gowing and Wyseure (1992), Asghar (1996) and Khouri (1998). Note that this ratio will change with climate, soil type, watertable depth, irrigation amount, groundwater quality and crop type.

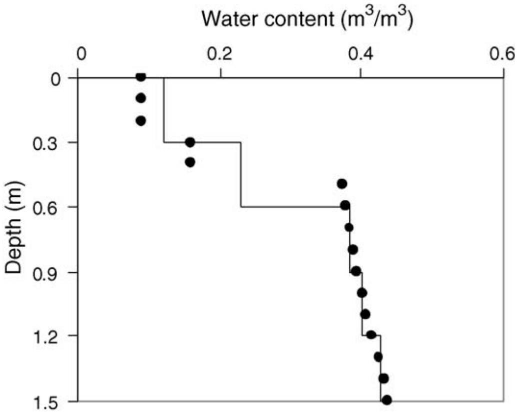

Fig. 4 – Average water content (—) of each soil layer in the fallow area calculated from the water-content profile at the end of the dry season (●).

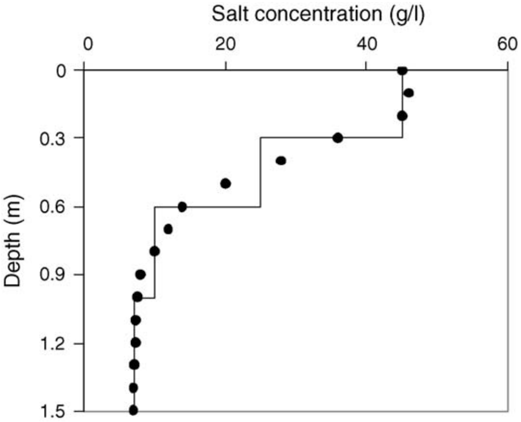

Fig. 5 – Average salt concentration (—) of each soil layer in the fallow area calculated from the salt concentration profile at the end of dry season (●).

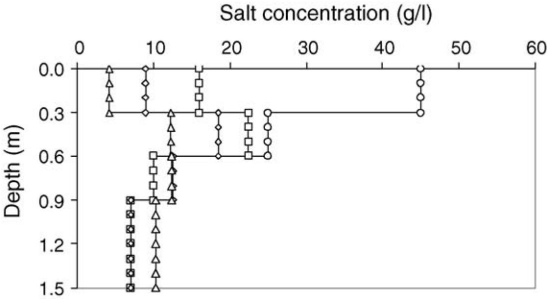

Fig. 6 – Profiles of the salt concentration in the fallow area at four different times during the rainy season: (○) initial, (□) 30 July, (◇) 31 August and (△) 30 September.

3.3. *Long-term behaviour of the fallow area*

The water and salt balances of the fallow area were simulated for a period of 30 years, (considered as the economic life of a conventional drainage system) to investigate the long-term behaviour of the system. Figs. 7 and 8 show the cumulative evaporation and salt concentration profile, respectively, at four different times during the simulation period, namely, at the end of 1, 10, 20 and 30 years.

The cumulative evaporation of 1054 mm in the first year decreased gradually to 991, 960 and 952 mm after 10, 20 and 30 years. The rate of decrease in annual cumulative evaporation was greater at the start but became negligible towards the end of the period. This was because the accumulated salt in the soil profile during the first year was not totally removed. Therefore, slightly more salt accumulation was calculated in the following year, which, in turn, decreased the rate of evapora-

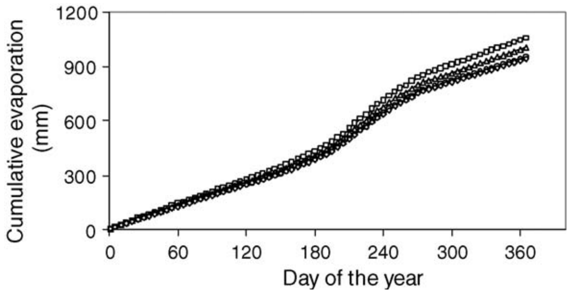

Fig. 7 – Annual cumulative evaporation from the fallow area at four different times of the simulation period: (□) 1 year, (△) 10 years, (○) 20 years and (◇) 30 years.

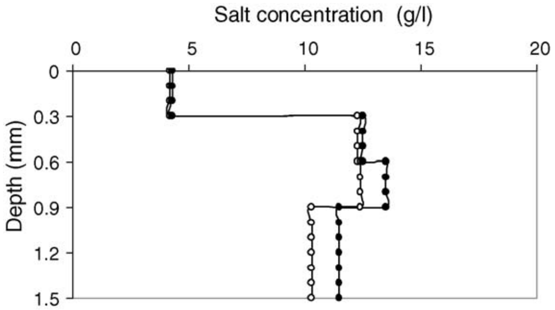

Fig. 9 – Profiles of the salt concentration in the fallow area at the end of the rainy season after the first (○) and the last (●), 30th year, of the simulation.

tion. Comparison of Figs. 7 and 8 reveals that decreases in the cumulative evaporation and increases in salt accumulation in the top layer of the soil are more distinct in the first decade than in the second and equilibrium is approached in the last decade.

Fig. 9 shows the salt-concentration profile of the fallow area at the end of the rainy season, i.e. after leaching, for years 1 and 30: the difference between them is negligibly small. The weighted mean salt concentration in the profiles were 9 and 10 g/l, respectively, for years 1 and 30, an increase of 30–40% on the initial or groundwater concentration of 7 g/l for the same water-content profile.

Note that the effect of salt accumulation on evaporation was included by modifying only the vapour flux because its effect on liquid flow may be neglected (Wagenet and Hutson, 1989; Konukcu et al., 2004). Salinity also has significant effects on soil physical properties and therefore on evaporation, especially in clay soils (van Hoorn and van Alphen, 1994), but it was not possible to take this into account. We also ignored any effect of salt accumulation on albedo.

3.4. *Effect of watertable depth and soil type*

The effect of the watertable depth on the sustainability of the dry-drainage system was also investigated. The simulation results for 1.0 and 2.0 m were compared to the results for the average watertable depth, 1.5 m.

The cumulative evaporation from the fallow area was 1168 and 702 mm/year, for 1.0 and 2.0 m watertable depths, respectively, against 1054 mm/year for 1.5 m depth. At the end of the dry season, the salt concentration of the soil water reached 125 g/l, deposited mainly in the top 30 cm and to 25 g/l, deposited in the top 90 cm for 1.0 and 2.0 m watertable depths, respectively. Note that 60 cm topsoil became saline and the concentration reached 45 g/l for 1.5 m deep watertable.

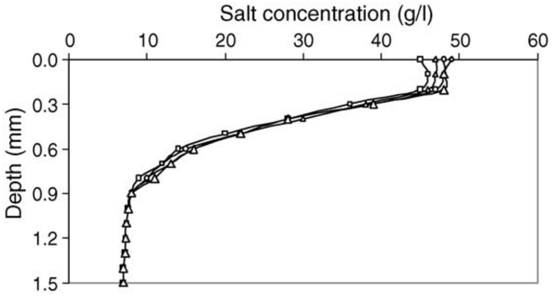

Fig. 8 – Profiles of salt concentration in the fallow area at four different times of the simulation period: (□) 1 year, (△) 10 years, (○) 20 years and (◇) 30 years.

The ratio of crop to the fallow area under different watertable depths is summarised in Table 4. A shallow depth (1.0 m) increases the evaporation rate and decreases the size of the sink area but leads to salt accumulation to an unmanageable extent in the fallow area. It may also limit crop production due to shallow and saline watertable (van Hoorn, 1979). If the remaining salt is to be leached, 375 mm water is needed, which, in turn, increases the size of the sink area. In contrast, a deep watertable (2.0 m) cannot provide sufficient upward water flux in the fallow area to sustain the necessary water balance. In other words, the ratios of cropped to sink area to maintain the necessary balance becomes considerably smaller when compared to that of 1.5 m watertable depth. However, no leaching is required at the end of the season since the precipitation is sufficient to leach the accumulated salt in a small amount. Therefore, where dry drainage is used, a watertable depth of 1.5 m can be considered optimal in terms of both crop production and surface evaporation for an average cultivated soil.

Soil texture also significantly affects the rate of evaporation and the ratio of cropped to fallow areas. The coarser the texture, the larger would be the sink area and the higher the silt content, the smaller the sink area for the same watertable depth.

The assessment was made assuming the crop water requirement was fully satisfied. However, the ratio of the areas will also change if the irrigation schedules changes (e.g. under deficit irrigation). The smaller the irrigation amount, the smaller will be the abandoned area. But, in this case, the salt balance of the irrigated area should be managed carefully taking possible capillary rise from saline groundwater into account.

3.5. *Effect of cropping pattern*

Replacing wheat–cotton with other cereal crops followed by cotton will not change the simulation results. The ratios of cropped to sink areas were also simulated for sugarcane (12

Table 4 – The ratio of cropped to fallow areas for different watertable depths and wheat–cotton crop pattern in the Lower Indus Basin in Pakistan with different options

Watertable depth (m)	Cropped area/fallow area			
	No leaching of fallow field		Leaching of fallow field	
	$f_i = 1$; $e_i = 1$	$f_i = 0.85$; $e_i = 0.80$	$f_i = 1$; $e_i = 1$	$f_i = 0.85$; $e_i = 0.80$
1.0	1.60	1.39	1.13	0.96
1.5	1.47	1.25	1.26	1.10
2.0	0.83	0.71	Not required	Not required

f_i: leaching efficiency coefficient; e_i: irrigation efficiency coefficient (cumulative evaporation from the fallow area, $\sum E = 1168$, 1054 and 702 mm/year for 1.0, 1.5 and 2.0 m watertable depths).

Table 5 – The ratio of cropped to fallow areas for different crop patterns in the Lower Indus Basin in Pakistan with different options at 1.5 m watertable depth

Crop pattern	Cropped area/fallow area			
	No leaching of fallow field		Leaching of fallow field	
	$f_i = 1$; $e_i = 1$	$f_i = 0.85$; $e_i = 0.80$	$f_i = 1$; $e_i = 1$	$f_i = 0.85$; $e_i = 0.80$
Wheat–cotton	1.47	1.25	1.26	1.10
Sugarcane	1.40	1.07	1.21	0.95
Orchards	1.38	1.03	1.20	0.92
Weighted mean	1.47	1.25	1.26	1.10

f_i: leaching efficiency coefficient; e_i: irrigation efficiency coefficient ($\sum E = 1361$, 1732, 1841, 1367 mm/year for wheat–cotton, sugarcane, orchards and weighted mean of all crops, respectively, adopted from Gowing and Wyseure, 1992).

months), orchards (12 months) and the weighted mean of all crops (12 months) for the same watertable depth (1.5 m), groundwater salinity (7 g/l), climatic conditions and soil type (sandy clay loam). The ET values for these crops were obtained from Gowing and Wyseure (1992). Table 5 summarises the calculated ratio for these crops with four different options: (i) no leaching of fallow area with $f_i = 1$ and $e_i = 1$; (ii) no leaching of fallow area with $f_i = 0.85$ and $e_i = 0.80$; (iii) leaching of fallow area with $f_i = 1$ and $e_i = 1$; (iv) leaching of fallow area with $f_i = 0.85$ and $e_i = 0.80$.

4. Conclusion

Performance of a dry-drainage system with different cropping patterns and watertable depths was simulated for conditions representing the Lower Indus Basin in Pakistan, where shallow saline groundwater, intensive irrigation and high evaporative demand exist. The results show that about 50% of the potentially irrigable land should be assigned for use as the evaporative sink.

There is a need for field trials to validate the simulation approach and to investigate the influence of salt capping and the effects of vegetation, possibly a halophytic tree plantation to remove salt, in the sink area.

In addition, there is a need to investigate the attitude of farmers and their ability to manage the system. It might appear that allocation of 50% of potentially irrigable land to use as an evaporative sink would be unattractive, but in circumstances where irrigation water is limited and conventional drainage solutions are costly, then dry drainage may represent a viable alternative.

As a potential solution to problems of salinity and waterlogging induced by irrigation, dry drainage merits further research, both theoretical and practical.

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