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An analytical model for predicting water table dynamics during drainage and evaporation

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Abstract

Water table dynamics in tile-drained fields have been thoroughly investigated by numerous researchers. Recent studies have highlighted the importance of incorporating the effects of evaporation into the design of such drainage systems. In tropical areas, evaporation plays a particularly crucial role in lowering the water table in finely textured soils. In this paper, water table dynamics are investigated for the case of coupled drainage and evaporation. A simple analytical model that determines the relative contribution of the drainage component to the draw down of the water table is proposed. The model's estimates compare reasonably well to field data, as well as those derived from numerical simulations conducted for various evaporation rates and soil types. When presented in a non-dimensional form, the model's results can provide a quick estimate of the relative contribution of drainage to lowering the water table, which is highly relevant to the hydrology of acid sulphate soils. Crown Copyright © 2002 Published by Elsevier Science B.V. All rights reserved.

Keywords: Drainage; Evaporation; Acid sulfate soils; Water table

1. Introduction

Surface and sub-surface drainage systems are installed in agricultural land to prevent water logging, which is a common phenomenon where water tables are located at shallow depths. The drainage problem has been tackled using analytical approaches, numerical approaches and stochastic approaches these are review and presented in Skaggs and van Schilfgaarde (1999).

For soils where the water table is near the soil surface evaporation from a bare soil and evapotranspiration will be similar, while the rate of water transport from the water table is able to meet the atmospheric demand. For the purposes of this study we have considered the two to be equivalent and will only use the term evaporation to cover both processes. In tropical and sub-tropical regions, neglecting the effect of evaporation and/or evapotranspiration could lead to erroneous drain design. Youngs et al. (1989) extended the analysis of Youngs (1985) to include drains as well as evaporation. Wenyan et al. (1994) also proposed a model for the calculation of drain spacing that accounts for the effect of evaporation but uses different drainage and evaporation models. Cook et al. (2000) demonstrated that in fine-textured acid sulphate soils grown to sugar cane where drains are widely spaced, the water table

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behaviour midway between the drains is almost solely controlled by evaporation. Their study investigated the effect of drainage on acid discharge from acid sulfate soils.

In acid sulfate soils (ASS) it has been argued that drains have lowered the water table and this has lead directly to pyrite oxidation and release of acidic water into the surrounding environment and causing damage (White et al., 1995). The results of Cook et al. (2000) showed that water table reduction may not be due to soil-water flow to drains, but is more probably due to removal of surface water reducing the period of inundation (White et al., 1995).

In this paper, an analytical model that describes the water table behaviour under the combined effects of drainage and evaporation is proposed. The model couples the drainage model of Youngs (1985) to the evaporation model of Averiyanov (see Wenyan et al., 1994). This model has some similarities to the model proposed by (Youngs et al., 1989) for prediction of water table behaviour in flat landscapes. Results are compared with measurements and numerical estimates obtained from HYDRUS-2D (Simunek et al., 1999). The analysis will show that the contribution of the drainage component to the draw-down of the water table midway between the drains, ΔH, is easily estimated from a drainage dimensions, soil hydraulic conductivity and evaporation rate.

2. Theory

The groundwater flux to drains is described by Youngs (1985):

$$q = K\left(\frac{H_D - H}{D}\right)^a \tag{1}$$

where q is the flux to drains ($\mathrm{L\,T^{-1}}$), K the saturated hydraulic conductivity ($\mathrm{L\,T^{-1}}$), H_D the depth to the drains (L), D the half-drain spacing (L), H the water table depth mid-way between the drains at time t (L), and a is the parameter related to the equivalent depth, which determines the extent of the flow occurring below H_D. For a drain placed on an impermeable layer $a = 2$ and for infinite depth $a = 1.36$ (Youngs, 1985).

The evaporative flux is described by Averiyanov (see Wenyan et al., 1994):

$$\begin{aligned} E &= E_o, & H &\le H_a \\ E &= E_o\left(1 - \frac{H - H_a}{H_m - H_a}\right)^n, & H_a &< H < H_m \\ E &= 0, & H &\ge H_m \end{aligned} \tag{2}$$

where E and E_o are the actual and potential evaporative fluxes ($\mathrm{L\,T^{-1}}$), respectively, H_a the water table depth below which the actual evaporative flux falls below potential (L), H_m the water table depth below which the evaporative flux approaches zero (L) (will be discussed in Section 3), and n is the shape factor for the evaporative flux.

H_a is defined by Gardner (1958):

$$H_a = \left(\frac{c_1 c_2}{E_o}\right)^{1/\beta} \tag{3}$$

where c_1, c_2, and β are fitting parameters that relate to the following hydraulic conductivity function (Gardner, 1958):

$$k = \frac{c_1}{|\psi|^\beta + c_3} \tag{4}$$

where k is the unsaturated hydraulic conductivity, c_3 a fitting parameter (L), and ψ is the matric potential (L). The value of c_2 for various values of β is given in Gardner (1958). There are various other models for relating H_a to E_o, these are discussed in more detail by Thorburn et al. (1992).

The variation of the water table depth as a function of time is described by:

$$S\frac{\mathrm{d}H}{\mathrm{d}t} = q + E \tag{5}$$

where S is the specific yield ($\mathrm{L^3\,L^{-3}}$).

Separating the variables in Eq. (5) and integration over the limits of $t = 0$ to t, and $H = H_o$ to H gives:

$$\frac{1}{S}\int_0^t \mathrm{d}t = \int_{H_o}^{H} \frac{\mathrm{d}H}{q + E} \tag{6}$$

where H_o is the initial water table depth mid-way between the drains.

Substitution of Eqs. (1) and (2) into Eq. (6) allows an analytical solution to be obtained for the special case where $a = 2$, and $n = 1$:

$H \le H_a$

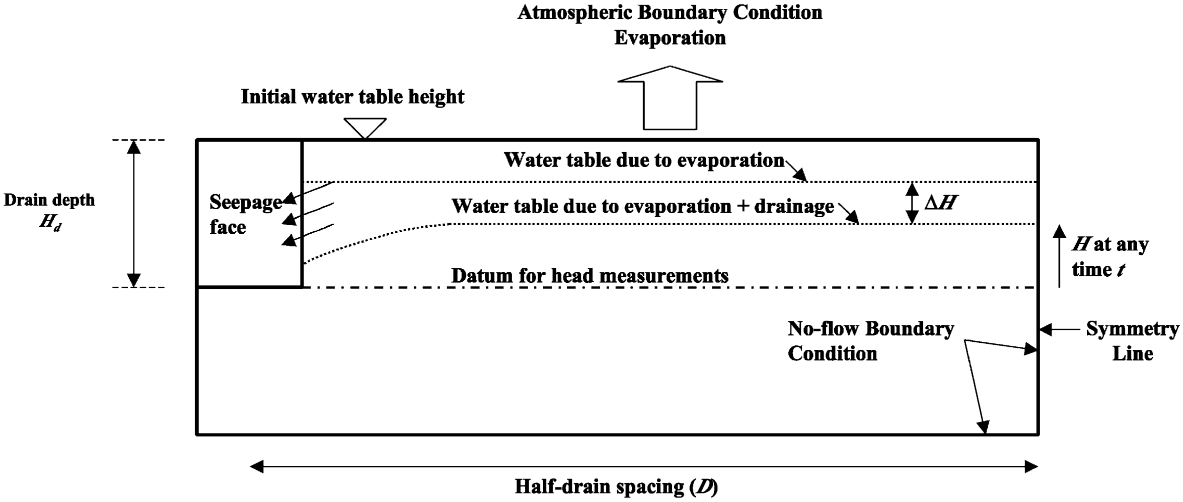

Fig. 1. Schematic diagram of domain and boundary conditions for numerical and analytical modelling.

$$t = \frac{DS}{\sqrt{KE_o}}\left[\tan^{-1}\frac{(H'_D - H'_o)}{\sqrt{E_o/K}} - \tan^{-1}\frac{(H'_D - H')}{\sqrt{E_o/K}}\right], \tag{7}$$

$H_a < H < H_D$

$$t = T_a + \frac{2SH_e}{E_o\gamma}\left[\tan^{-1}\frac{\frac{2K}{E_o}\left[H'_e\left(H'_D - H'_a\right)\right] + 1}{\gamma} - \tan^{-1}\frac{\frac{2K}{E_o}\left[H'_e\left(H'_D - H'\right)\right] + 1}{\gamma}\right] \tag{8}$$

where $H_e = H_m - H_a$, $H'_e = H_e/D$, $H'_D = H_D/D$, $H'_a = H_a/D$, $H' = H/D$, $H'_m = H_m/D$, T_a is obtained by substituting $H = H_a$ in Eq. (7), and

$$\gamma = \left\{\frac{4KH'_e}{E_o}(H'_m - H'_D) - 1\right\}^{1/2} \tag{9}$$

Eq. (8) is only valid if:

$$H'_e(H'_m - H'_D) > \frac{E_o}{4K} \tag{10}$$

Eq. (10) may be solved iteratively to determine the minimum value of H_m that maintains the validity of Eq. (8).

The time required for the water table to reach the drain level, T_{Hd}, can be obtained by substituting $H = H_D$ in Eq. (8). At time T_{Hd}, and in the absence of drainage, evaporation alone would lower the water table to a depth H_{ev} (Appendix A):

$$H_{ev} = H_m - H_e\exp\left(-\frac{E_oT_{Hd} - SH_a}{SH_e}\right) \tag{11}$$

The contribution of the drainage component to the drawdown of the water table at the mid-point between the drains, ΔH (Fig. 1), is given by:

$$\Delta H = H_D - H_{ev} \tag{12}$$

When $H_a \geq H_D$, Eq. (7) is applicable and Eqs. (8) and (11) simplify to:

$$T_{Hd} = \frac{DS}{\sqrt{KE_o}}\tan^{-1}\left(\frac{H'_D - H'_o}{\sqrt{E_o/K}}\right) \tag{13}$$

and

$$H_{ev} = \frac{T_{Hd}E_o}{S} = D\sqrt{E_o/K}\tan^{-1}\left(\frac{H'_D - H'_o}{\sqrt{E_o/K}}\right) \tag{14}$$

Substitution of Eq. (14) in Eq. (12) results in a

Table 1
Soil hydraulic parameters

	S ($m^3\ m^{-3}$)	K (m day^{-1})	van Genuchten model		Gardner model			
			α (m^{-1})	n	c_1 ($m^2\ s^{-1}$)	c_2 (m^{β})	c_3 (m)	β
Sand loam	0.123	1	7.5	1.89	4.05×10^{-5}	1.5	5.5×10^{-5}	4.2
Silt loam	0.034	0.1	2	1.41	6.79×10^{-4}	1.83	1.06×10^{-2}	2.9
Clay loam	0.011	0.01	1.9	1.31	4×10^{-5}	2	1.4×10^{-2}	2.55
Pimpama soil	0.04	0.33						

non-dimensional form of Eq. (12):

$$\frac{\Delta H}{H_D} = 1 - \frac{\sqrt{E_o/K}}{H'_D}\tan^{-1}\left(\frac{H'_D - H'_o}{\sqrt{E_o/K}}\right) \quad (15)$$

It is worth noting that S is eliminated in Eq. (15), which means that ΔH is only dependent on H_D, D, E_o and K. It will only be when $H_D \gg H_a$ and $E_o \ll q(H_a)$ that values of ΔH obtained from Eq. (15) will be significantly different from those obtained with Eq. (12). The water table height is fairly constant after a short distance from the drain (Kirkham, 1958) when D is large, so ΔH will apply to most of such a drained field.

Youngs et al. (1989) also obtained Eq. (6) but solved it as piecewise steady state with a daily time step. Their solution used a different evaporation function based on the exponential hydraulic conductivity function (Gardner, 1958). However, the use of this function for the hydraulic conductivity over a wide range of matric potential as occurs when soil limited evaporation occurs from a water table is not recommended (Gardner, 1958; Philip, 1985; Cook, 1991).

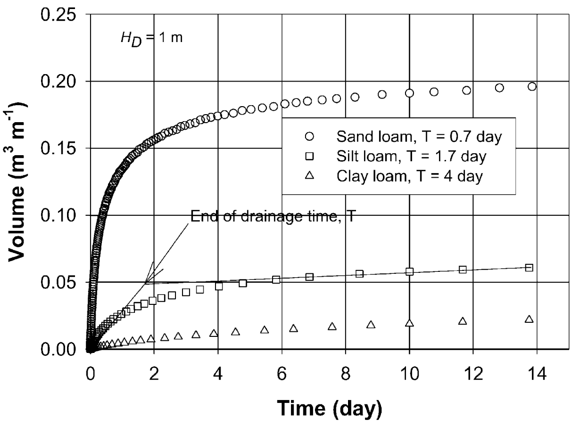

Fig. 2. Simulated volume drained from $1\times1\times1\ m^3$ block of soil for three different soils.

3. Methods

The validity of the model is demonstrated for three soils, namely, sand loam, silt loam, and clay loam, thus covering a wide range of soil types using numerical modelling and field data. The numerical modelling was performed using HYDRUS-2D (Simunek et al., 1999), which solves the Richards' equation using finite element methods. The domain and boundary conditions used in the modelling are shown in Fig. 1. Data for the three soils came from the database supplied with HYDRUS-2D which is based on Carsel and Parrish (1988). The relevant soil hydraulic properties for these three numeric soils and the field soil are shown in Table 1.

The field data were obtained from a drained acid sulphate soil site located at Pimpama, in Southeast Queensland, Australia. Details on the field soil and experimental set-up are found in Cook et al. (2000). The water table height mid-point between the drains ($D = 67$ m) was monitored with the aid of PVC dip wells, 50 mm in diameter and 1500 mm long slotted to within 300 mm of the soil surface. A pressure transducer (dataflow model 984a) was placed in the tube and automatically logged every 10 min. These data were smoothed using a moving average.

To compare the numerical and analytical results a value of specific yield was required. This was estimated numerically by conducting a drainage simulation on a one-dimensional saturated soil column measuring $1\times1\times1\ m^3$. An average specific yield is obtained at the end of drainage, and is equal to the change in water content of the drained soil (Dos

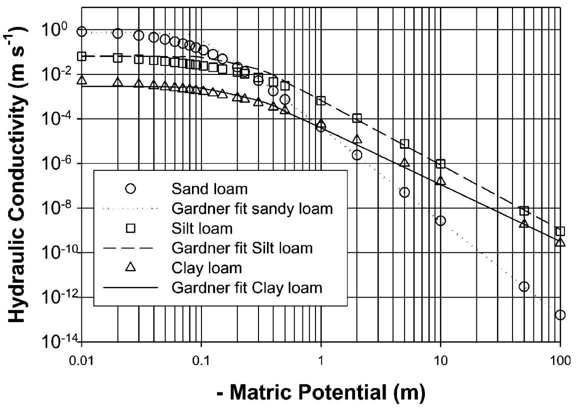

Fig. 3. Hydraulic conductivity variation with matric potential. The data points are from the hydraulic conductivity data for the three soils obtained from HYDRUS-2D and the lines are a best fit using the Gardner (1958) function (Eq. (4)).

Santos Junior and Youngs, 1969). The cessation of drainage is assumed to occur at a time where the two tangents to the drainage curves intersect (Fig. 2). The estimated specific yield for the three soil types is listed in Table 1.

Estimates of H_a and H_m are required for the soils. H_a is estimated using Eq. (3), which contains the hydraulic conductivity parameters of Gardner's (1958) model. The unsaturated hydraulic conductivity function for the three soils is shown in Fig. 3. The van Genuchten (1980) model parameters for these soils are listed in Table 1. The Gardner model was fitted to the data shown in Fig. 3 and the estimated parameters are listed in Table 1. Parameters c_1 and m of Eq. (4) and c_2 (Gardner, 1958) are used to calculate H_a via Eq. (3).

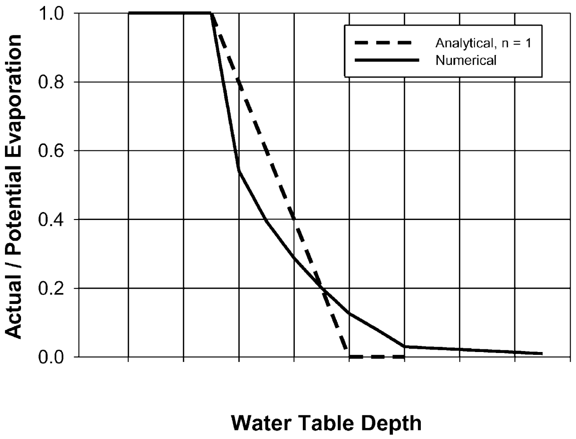

Fig. 4. E/E_o verses H for analytical model (Eq. (2)) with $n = 1$, compared with a typical response from the numerical model.

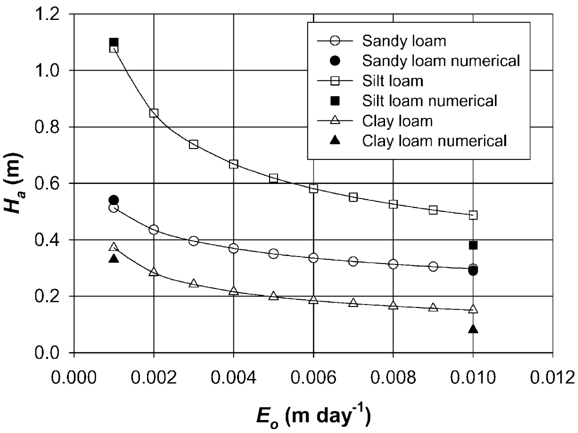

Fig. 5. Estimates of H_a from numerical modelling for three soils (solid symbols) and estimated using Eq. (3) (open symbols).

The proposed model is not very sensitive to variations in H_m. Assuming $H_m = 10H_a$ produced good results except for special cases of very narrow drain spacings (D) of less than 5 m. Under such conditions, the drainage effects are dominant and hence cause the actual evaporative flux to drop dramatically, thus leading to smaller values for H_m as defined by Eq. (10).

4. Results and discussion

The results show with $n = 1$ the resulting evaporation rate calculated with Eq. (2) is not very different from that found with the numerical model (Fig. 4). The deviation is not likely to be very different between the two models so long as H_a is similar, as too early or too late a reduction in the potential evaporation rate is likely to have more of an effect on water table behaviour as the higher evaporation rate will cause a too rapid or too slow a response in the water table behaviour.

The proposed model is tested using numerical methods. Rassam and Williams (1999) have used numerical techniques to estimate the critical evaporation rate of mine tailings. A similar approach is adopted here to test estimates of H_a obtained from Eq. (3). A 1-dimensional soil column with surface

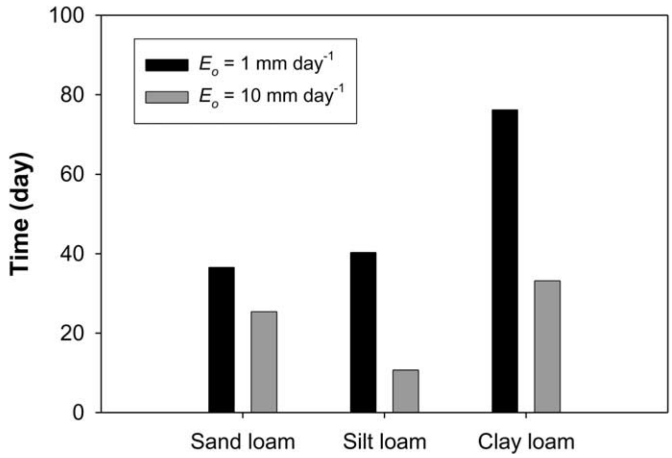

Fig. 6. Time to reach the drain depth for two contrasting rates of E_o for three different soils.

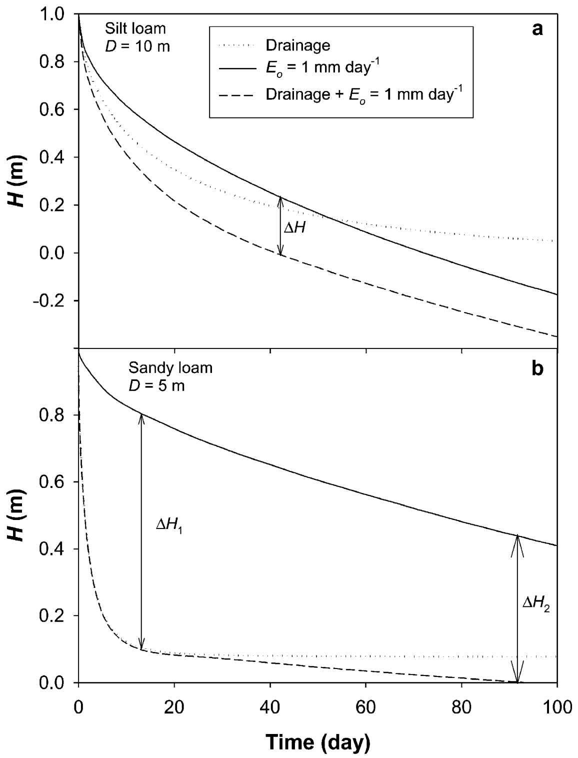

Fig. 7. Water table height (H) with time during evaporation and drainage as simulated with the HYDRUS-2D model for (a) silt loam and (b) sandy loam soils.

evaporation is simulated. The water table is lowered until the steady-state evaporative flux just falls below potential, which is the definition of H_a. The critical water table depth H_a (obtained from Eq. (3), Gardner's method) and the proposed model-estimates of H_a are in close agreement (Fig. 5). This suggests that the Gardner method gives acceptable estimates of H_a.

The soil that exhibited the highest H_a was the silt loam. This is attributable to a high air-entry potential (AEP) and a higher unsaturated hydraulic conductivity for matric potentials lower than the AEP compared to the other soils. The sandy loam has the next highest H_a with the clay loam having the lowest H_a. The AEP levels for the soils in this study occur at matric potentials between -0.2 and -1.0 m (Fig. 3). Hence steady state flow will be reached within this matric potential range, as the conductivity reduces rapidly at potentials less than this. Gardner (1958) indicated that the critical evaporation rate is approached while the matric potential at the soil surface is still relatively low. The evaporative flux from a soil surface is dependent upon external climatic conditions as well as soil's hydraulic properties and depth of the water table. If potential evaporation is increased for a fixed water table depth, the actual evaporative flux increases until a critical rate is reached beyond which the actual flux is no longer equal to the potential evaporation (Gardner, 1958). Similarly, for any potential evaporation rate there exists a critical water table depth, H_a, beyond which the actual evaporative flux is no longer equal to the potential rate.

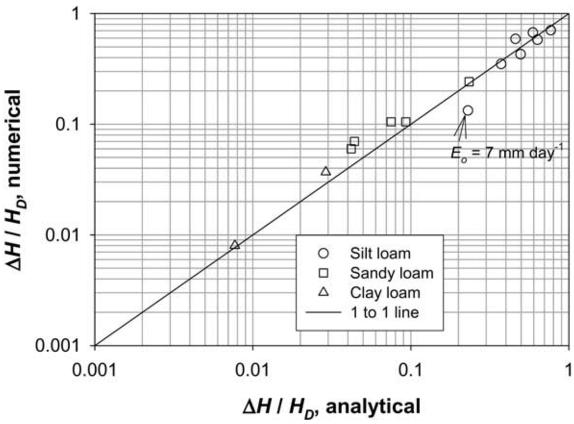

Fig. 8. Comparison of $\Delta H/H_D$ from HYDRUS-2D model and derived using Eq. (12) for three different soils.

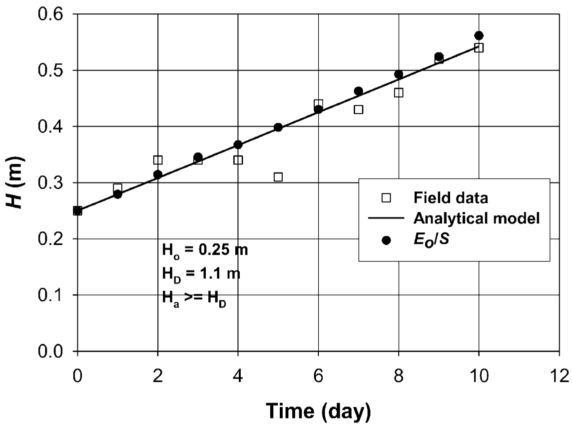

Fig. 10. Comparison of measured water table height (H) with time with analytical model and evaporation only.

A number of numerical simulations were also conducted to investigate the transient water table draw down. The imposed boundary conditions are shown in Fig. 1. The time required for the water table to reach the drain level was investigated for two evaporation rates of 1 and 10 mm/day, which should cover the normal range of evaporation. The simulations showed that the three soil types exhibited different trends under low and high evaporation rates. Fig. 6 shows that under a low evaporation rate, the finer the soil the longer the time to reach the drain level. However, under a high evaporation rate, the silt loam exhibits the quickest draw down. This demonstrates that under low evaporation rates, the saturated hydraulic conductivity of the soil dominates the water table dynamics. In contrast, the unsaturated hydraulic conductivity is dominant under high evaporation rates.

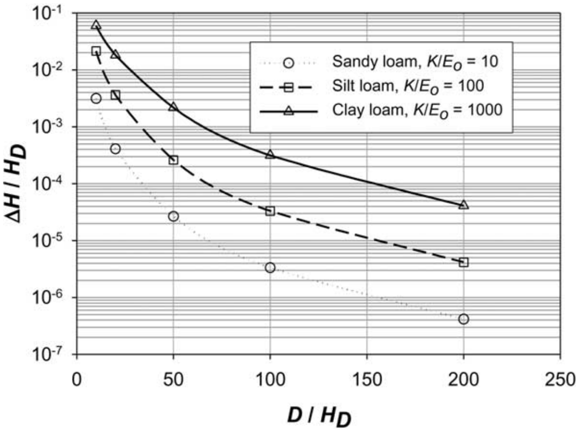

Fig. 9. Non-dimensional plot of $\Delta H/H_D$ with D/H_D for three values for K/E_o, derived using Eq. (15).

The relative contribution of drainage and evaporation components to the water table draw down is shown in Fig. 7. Shortly into the simulation, the evaporation plus drainage and evaporation lines run parallel to each other for the silt loam soil (Fig. 7a), which deems the definition of ΔH valid at any time thereafter. In contrast, for an extreme case where the drainage component is dominant (sandy soil and narrow drain spacing) a totally different trend occurs (Fig. 8b). Under such favourable drainage conditions, the water table drops very quickly to 0.1 H_D then comes to halt (Fig. 7b, drainage only). Due to the extremely low hydraulic conductivity of the drained coarse-grained soil, the evaporation component takes a long time to further lower the water table to the drain level. Hence, there is a big discrepancy between ΔH_1 and ΔH_2 (Fig. 7b). Since the drainage curve flattens at $0.1H_D$, it is concluded that the true estimate of ΔH is equal to ΔH_1.

The ΔH obtained from the proposed analytical model (Eq. (12)) agrees reasonably well with that derived from the numerical model for a wide range of soils (Fig. 8). Only in the extreme case of a coarse-textured soil with a relatively high evaporation rate, does the analytical model fail to match the numerical estimate. The proposed analytical model should give reasonable estimates of the relative contribution to water table behaviour of drainage in high evaporation environments.

The model results using Eq. (15) are presented in a non-dimensional form in Fig. 9. It is evident that the contribution of the drainage component is significant only in coarse-grained soils ($K/E_o = 1000$). For medium- to fine-grained soils ($K/E_o = 100$, $K/E_o = 10$), drainage accounts for less than 10% of the total drawdown of the water table. This highlights the importance of evaporation in water table dynamics of such soils. For example if $H_D = 1$ m and $D/H_D = 10$ ($D = 10$ m) then ΔH would be respectively 0.6, 0.2 and 0.03 m for $K/E_o = 1000, 100, 10$. For values of D greater than this ΔH will be less than the above values.

Comparison between the time course of H predicted using Eq. (7) and H measured in the field experiment for a drainage event is good (Fig.10). At this site $H_a \geq H_D$ so that Eq. (7) is relevant. In solving the calculations using Eq. (7) an average value of E_o of 1.2 mm day^{-1} is used. The range in E_o values during the 10 days of drainage is from 1.5 to 0.9 mm day^{-1}. Also shown is the effect that evaporation only (E_o/S) would have cause in lowering the water table. There is little difference between the model and E_o/S results. These results demonstrate that the model's estimates agree well with the field observations and shows that for such wide drain spacings, the water table dynamics are mainly driven by evaporation. Hence for this soil groundwater flow to the drains is unlikely to have contributed greatly to exposure of pyrite and subsequently to the acidification of this soil.

In acid sulphate soils in South-East Queensland the drain spacing ($2D$) is generally 100–300 m. The drain depths are typically 1–2 m, which results in values of D/H_D from 25 to 150. Typical hydraulic conductivities for these soils are 0.4 m day^{-1} (Rassam et al., 2001) and potential evaporation rates vary from 2 to 10 mm day^{-1} (Cook, unpublished). This gives K/E_o values of 40–200. From these values of D/H_D and K/E_o, Eq. (15) would result in values of $\Delta H/H_D < 0.1$. Hence the drainage flux to widely spaced drains found in South-East Queensland may have not contributed to the exposure of pyrite and acidification of these soils due to groundwater flow to these drains. However, as Cook et al. (2000) have shown the major pathway for acid discharge from these soils is through groundwater discharge to the drains.

This study has shown that groundwater flow to drains is unlikely to be a mechanism for exposure of pyrite and led to formation of acidic conditions in these soils. However, the removal of surface water via the drainage system has reduced the period these soils were inundated. White et al. (1995) has estimated that the period of inundation has been reduced from 100 days to as little as 5 days in a similar area of acid sulfate soils in Northern New South Wales. This process is likely to have contributed significantly contributed to exposure of pyrite and the formation of acid in soils containing pyritic sediments.

5. Conclusions

Evaporation plays an important role in designing drains in tropical and sub-tropical areas especially in low conductivity soils. The simple analytical model presented in this paper estimates the relative contribution of drainage to the draw down of the water table when the coupled effects of evaporation and drainage are taken into consideration. It was shown that the drainage component accounted for less than 10% of the total draw down in the case of medium- to fine-textured soils. For a wide range of soils, estimates of ΔH obtained from the proposed analytical model agreed reasonably well with field observations as well those derived from numerical modelling. For low evaporation rates, it was shown numerically that the time the water table takes to reach the drain level mainly depends on the saturated hydraulic conductivity of the soil. However, for high evaporation rates the time is dependant on the unsaturated hydraulic conductivity of the soil. This demonstrates the importance of incorporating climatic effects as well as soil properties into the design of drainage systems.

In acid sulfate soils in South East Queensland ground water flow to the drains is unlikely to have significantly increased the exposure of pyritic sediments.

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Appendix A

The response of a water table to evaporation from a soil surface is given by Eq. (5) with $q = 0$, which results in:

$$-S\frac{dH}{dt} = E_o \quad (A1)$$

Separation of the variables and integration over the limits use in Eq. (6) for E given by Eq. (2) gives:

$H \le H_a$

$$t = \frac{SH}{E_o} \quad (A2)$$

$H_a < H < H_m$

$$t = \frac{-H_e S}{E_o}\ln\left(\frac{H_m - H}{H_e}\right) + \frac{H_a S}{E_o} \quad (A3)$$

Substitution of $t = T_{Hd}$, which is the time when the water table reaches the depth of the drain when both drainage and evaporation are occurring, and rearranging Eq. (A3) results in Eq. (11) in the text.

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