ELSEVIER
Agricultural Water Management 39 (1999) 135–151
Agricultural water management

A flood history weighted index of average root-zone salinity for assessing flood impacts on health of vegetation on a saline floodplain

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Abstract

Native *Eucalyptus* woodlands on the floodplains of the lower River Murray, Australia are dying because of increased soil salinity associated with shallower watertables and reduced flooding. There is need for a simple salinity index, related to vegetation health, which can be used within a geographic information system (GIS) to evaluate the potential impacts across the floodplain of management options which aim to decrease soil salinity. Management options include increasing the frequency and duration of floods by releasing additional environmental flows from upstream storages or lowering the watertable by groundwater pumping. This paper extends a simple root-zone salt and water balance model which represents the salinisation process as a moving salt front (MSF) [Jolly, I.D., Walker G.R., Thorburn P.J., 1993. J. Hydrol. 150, 589–614; Thorburn, P.J., Walker, G.R., Jolly, I.D., 1995. Plant and Soil 175, 1–11], to develop a flood history weighted net discharge salinity index (WINDS-Index) which relates to vegetation health. The MSF model, based on steady state groundwater discharge theory incorporating water uptake by vegetation, is evaluated against simulations made using a fully dynamic soil-vegetation-atmosphere model (WAVES). These simulations evaluated the impact of groundwater pumping and flooding options [Slavich, P.G., Walker, G.R., Jolly, I.D., Hatton, T.J., Dawes, W.R., 1999. Agric. Water Manage. 39, 241–261]. The dominant features of the WAVES simulations were adequately reproduced using the moving front model, provided the discharge rate was limited to a potential canopy transpiration rate. The WINDS-Index reflects the impact of flooding history on the long term average soil water salinity for soils with varying hydraulic properties, watertable depth and watertable salinity. The WINDS-Index is strongly dependent on the relative inundation time, defined as the ratio of the duration of inundation to the duration between floods, of successive flood events and has application as a management tool within a GIS. The watertable depth for long term control of root-zone salinity is defined using the concept of a critical salt balance criterion which incorporates

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PII: S0378-3774(98)00075-4

the relative inundation time and soil hydraulic properties.

Keywords: Salinity; Flood; Model; Eucalyptus; Watertable

1. Introduction

The salinity-induced dieback of native Eucalyptus woodlands on the Chowilla floodplain of South Australia (140°, 52′E; 33°, 59′S) is typical of that occurring on the floodplains of the lower River Murray. Constructed weirs have raised the base flow river level and the watertable under adjacent floodplains, whilst management of flood flows and water diversions has reduced the frequency of medium-sized floods (Margules et al., 1990). Regional groundwater discharges principally through the base of the river. Because the river is artificially maintained at a relatively high level, the inflowing regional groundwater has caused the watertable to rise in order to maintain the discharge to the river. The watertables under the floodplain and the river are well connected hydraulically such that fluctuating river levels associated with floods influence the groundwater pressure under the floodplain causing the watertable to fluctuate in concert with the river level. These factors have increased the rate of soil salinisation and caused the health of the vegetation, comprising mainly of *Eucalyptus largiflorens* (black box) woodland, to decline. The health decline is greatest on the higher parts of the floodplain which are less frequently flooded, and where groundwater salinity is high. A study was established to assist the evaluation of management proposals, which include groundwater pumping to lower the watertable and/or strategic releases of water from upstream storages to increase the duration and/or frequency of floods.

Vegetation management in shallow watertable environments requires an understanding of the interaction between the physical and biological factors which determine the rate of root-zone salinisation. Groundwater discharge by deep rooted vegetation increases the rate of salinisation of the root-zone. Field tree water use studies on *Eucalyptus camaldulensis* and *E. largiflorens* on the Chowilla floodplain has shown that these trees transpire at relatively low rates (0.3–2 mm day^{-1}) throughout the year (Thorburn et al., 1993). This study used stable isotopes of water (^{2}H and ^{18}O) in soil water and xylem to establish that a large proportion of the water transpired during dry periods was derived from groundwater.

The groundwater discharge rate, and hence, soil salinisation rate, can be modelled using varying degrees of model complexity. The least complex models assume that steady state conditions apply, (i.e. that the matric potential profile is constant), and that soil hydraulic properties are uniform with depth. The steady state assumption implies that the watertable depth is constant and that there are no changes in soil water content from rainfall. With these assumptions the potential groundwater discharge from the soil surface can be modelled using soil hydraulic properties only (Gardener, 1958; Warrick, 1988). Warrick (1988) showed that the maximum upward water flux from a given watertable depth could be represented using a simple power function whose coefficients depended on soil hydraulic parameters. Steady state groundwater discharge theory has been extended to consider a moving salt front (MSF) which is driven upwards by transpiration of groundwater (Jolly et al., 1993) and downwards by floods. Thorburn et al. (1995) extended the MSF model to include the effect of groundwater salinity on plant uptake and used it to estimate the time scale for complete salinisation of soils on the Chowilla floodplain.

A feature of the groundwater hydrology of the Chowilla floodplain is that the watertable depth fluctuates several meters with changes in river level. Numerical process model may be employed to evaluate vertical groundwater discharge under non-steady conditions associated with fluctuating watertables and seasonal changes in climate, transpiration and soil moisture. WAVES (Water and Vegetation Energy Solute model; Dawes and Hatton, 1993; Slavich et al., 1998) is a one dimensional soil-plant-atmosphere model which uses daily climatic and watertable data to estimate canopy transpiration, canopy carbon assimilation in relation to predicted changes in soil water content and soil chloride (salinity). It employs a numerical solution to the Richard's equation for unsteady soil moisture flow, the convective dispersion equation for chloride movement, and the 'big leaf' Penman–Monteith equation for evapotranspiration. WAVES requires input of watertable depth as the lower boundary and hence makes no attempt to simulate two or three dimensional flow processes.

The WAVES model has been used to evaluate the impact of changes in management on vegetation health and salinisation rate at a number of reference sites on the floodplain (Slavich et al., 1999). The WAVES simulations were made using the Broadbridge and White (1988) model to describe soil hydraulic properties because convergence and stability of the numerical methods is guaranteed, facilitating its application over long time scales and a wide range of water contents. The management scenarios were evaluated using simulations run for a 24 year period (1970–1994) which included surface flood events and a daily fluctuating watertable.

The WAVES model may also be used to evaluate the conditions for which the assumptions of the simpler steady state MSF model are satisfied. Because of it's simplicity, the MSF model has parameters which can be spatially represented within a GIS and hence has the potential to be used at the floodplain scale. A GIS of the Chowilla floodplain (200 km^2) comprising of surface elevation, watertable depth, watertable salinty and soil type has been used to show that vegetation health correlated with the frequency of flooding (Overton et al., 1994).

The aim of this paper is to evaluate the assumptions of the steady state MSF model using the transient numerical process model WAVES. We also further extend the MSF model by combining limiting vegetation characteristics, soil hydraulic properties and flood history to develop a salinity index which is indicative of vegetation health and has parameters which can be feasibly represented within a GIS of the flood plain. We express the soil hydraulic parameters of the MSF model as functions of the soil hydraulic parameters of Broadbridge and White (1988) so that long term simulations with a fluctuating watertable can be compared with similar simulations conducted using WAVES. The model is used to define long term flooding regimes, characterised by flood frequency and duration, and watertable regimes, characterised by depth and salinity, which are necessary to maintain root-zone salinity within a tolerable range.

2. Theory

This analysis extends and integrates that of Jolly et al. (1993) and Thorburn et al. (1995). The conceptual model assumes that: (i) between floods the groundwater discharge by vegetation leads to the development of an upward moving salt front; (ii) during floods the salt front is leached downwards; (iii) the rate of uptake of soil water is limited by a maximum threshold soil water salinity (C_t) and a maximum transpiration per unit leaf area (T_L m (m leaf)$^{-2}$ day^{-1} and the leaf area index (LAI); (iv) the availability of soil water in the root-zone for uptake is determined by the average soil water salinity of the potential root-zone; (v) groundwater discharges laterally to the river after floods (vi) the root-zone where water uptake occurs is above the watertable. The simplified form of the solute profile described by the model is represented schematically in Fig. 1. The governing equations which accommodate these assumptions are developed as follows.

2.1. Estimating the groundwater discharge rate

The maximum steady state vertical groundwater discharge rate for a given watertable depth and soil hydraulic properties can be estimated by integrating Darcy's equation, i.e.

$$Z_w = \int_{-\infty}^{0} \frac{d\psi}{1 + q/K(\psi)} \tag{1}$$

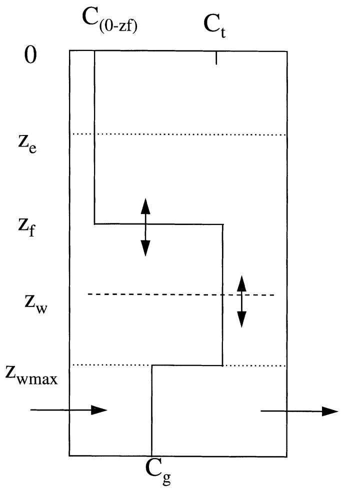

Fig. 1. Schematic representation of salinity profile and associated symbols. Note double ended arrows indicate varying positions of watertable depth (Z_w) and salt front (Z_f). Single ended arrows indicate lateral groundwater flow. C_g is the groundwater salinity; $C_{(0-zf)}$ is the average soil water salinity above the solute front; C_t is the maximum soil water salinity which roots can extract water from; Z_{wmax} is the maximum depth the watertable falls to during long dry periods; Z_e is a critical soil depth which needs to remain salt free for vegetation survival during long dry periods and coincides with the depth from which vegetation extracts groundwater during long dry periods.

where Z_w is the watertable depth (positive downwards), ψ is soil matric potential (m), q is the maximum rate of groundwater discharge (m/day^{-1}) and $K(\psi)$ is the unsaturated hydraulic conductivity function.

The solution to Eq. (1) can be approximated as a power function which relates the upward water flux to the watertable depth (Gardener, 1958; Warrick, 1988; Salvucci, 1993) and whose coefficients depend on combined soil hydraulic parameters. To account for groundwater water extraction by roots above highly saline soil water near the watertable, Jolly et al. (1993) expressed the power function in terms of the distance between the watertable depth and the depth of the salt front (Z_f) which was assumed to be the depth of uptake of groundwater (Z_e) i.e.,

$$q = A(Z_w - Z_f)^p \tag{2}$$

where Z_f is the depth of the salt front assumed to be the depth of groundwater extraction by roots, A and p are coefficients which depend on combined soil hydraulic parameters.

Approximate relationships between the coefficients of Eq. (2) and the hydraulic parameters of the Broadbridge and White (1988) moisture characteristic and unsaturated hydraulic conductivity model (BW) were developed as (see Fig. 2 and Appendix A)

$$p = \frac{-1.9}{(C-1)^{0.177}} \tag{3}$$

$$A = \frac{K_s}{a_0 \lambda^p} \tag{4}$$

for $Z_w - Z_f > \lambda$ where λ is the matric potential scaler (see Appendix A). As the depth of the watertable (Z_w) approaches $Z_f + \lambda$ the discharge rate will approach a maximum which is either the saturated hydraulic conductivity or, if the soil is relatively permeable and the

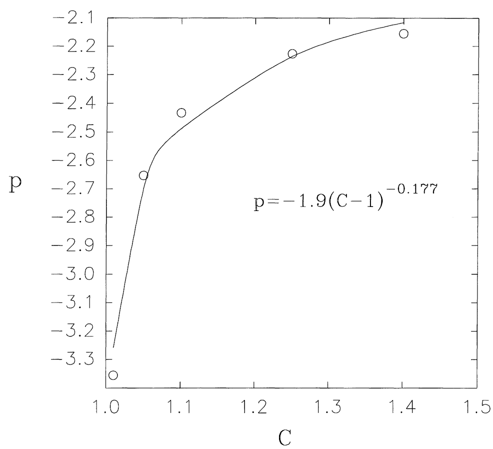

Fig. 2. The dependence of the exponent (p) of the power function relating the watertable depth and the groundwater discharge rate on the C parameter of the Broadbridge White soil hydraulic model. ○ fitted values from Fig. A.1. ——— represents fitted curve Eq. (3).

leaf area low, the transpiration capacity of the canopy leaf area. Hence the discharge rate can be limited by the soil hydraulic properties, which we define as soil limited discharge, or canopy characteristics which we define as canopy limited discharge.

2.2. Root-zone salt balance model

The floodplain is characterised by a semi-arid climate (average rainfall 260 mm year^{-1}; pan evaporation approximately 2000 mm year^{-1}) and periodic floods which leach salt to the river. Most simply, we can represent the duration between floods (t_d) as groundwater discharge periods when salinity of the unsaturated zone increases and the flood duration (t_s) as leaching periods when the salinity decreases. Following Jolly et al. (1993) and Thorburn et al. (1995) the soil salinity profile can be represented as two layers characterised by a less saline depth of soil overlying a high salinity layer in the continuously moist capillary fringe near the watertable. We assume that the saline layer is too saline for water extraction by the vegetation. Hence, salinisation and leaching processes are represented by a moving salt front. Between floods evaporation and root water extraction occurring from the less saline soil causes the front to move slowly upwards whilst during floods the front is displaced downwards relatively rapidly. Hence, the average salinity of the soil water above a constant reference watertable depth depends on the depth of the salt front from the surface i.e.

$$C_{(0-Z_{\mathrm{wmax}})} = C_t\left(1 - \frac{Z_{\mathrm{f}}}{Z_{\mathrm{wmax}}}\right) + C_{(0-Z_{\mathrm{f}})}\frac{Z_{\mathrm{f}}}{Z_{\mathrm{wmax}}} \tag{5}$$

where Z_{wmax} is a constant reference depth set to the maximum depth of the watertable; $C_{(0-\mathrm{zwmax})}$ is the average soil water salinity from the surface to this depth; Z_{f} is the depth of the salt front, i.e. the boundary between the two soil layers; $\mathrm{C}_{(0-\mathrm{zf})}$ is the average soil water salinity above the salt front. If the groundwater salinity (C_{g}) is greater than, C_{t} then C_{g} should be substituted for C_{t} in the above equation.

Between floods the salinisation rate of the unsaturated zone is determined by the discharge rate and groundwater salinity, i.e.

$$Z_{\mathrm{wmax}}\theta_{\mathrm{d}(0-\mathrm{Zwmax})}\frac{\mathrm{d}C_{(0-Z_{\mathrm{wmax}})}}{\mathrm{dt}} = qC_{\mathrm{g}} \tag{6}$$

where C_{g} is the groundwater salinity; $\theta_{\mathrm{d}(0-\mathrm{zw})}$ is the average soil water content (m^3 m^{-3}) during the discharge period; and q is the groundwater discharge rate for a given watertable depth Eq. (2).

During floods the leaching rate is assumed to depend on K_{s} and the displacement of groundwater from the root-zone. Hence,

$$Z_{\mathrm{wmax}}\theta_{\mathrm{s}(0-Z_{\mathrm{wmax}})}\frac{\mathrm{d}C_{(0-Z_{\mathrm{wmax}})}}{\mathrm{dt}} = -K_{\mathrm{s}}C_{\mathrm{g}} \tag{7}$$

where $\theta_{\mathrm{s}(0-\mathrm{zw})}$ is the average soil water content (m^3 m^{-3}) during the recharge period. The salinity of the flood water is assumed to be negligible.

The survival of the vegetation during the long dry periods depends on maintaining the salt front (Z_{f}) below a critical depth where roots extract most of their groundwater (Z_{e}).

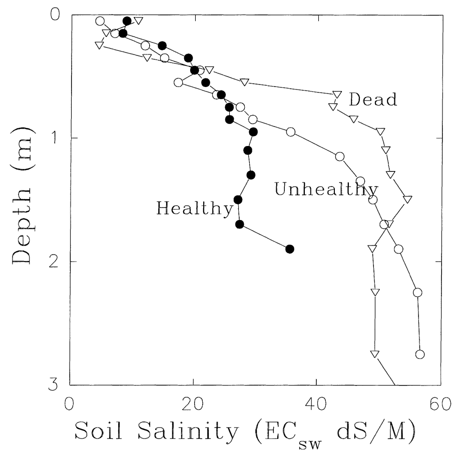

Fig. 3. Profiles of soil water salinity measured beneath black box trees with varying health. EC_{sw} is electrical conductivity of soil water.

Observations of salinity profiles occurring beneath healthy, unhealthy and dead trees (Fig. 3) suggests that the vegetation health can be maintained when the soil water salinity at approximately 1 m depth is below the maximum water salinity that the vegetation can take up (C_t). Isotope studies also suggest that the vegetation uses groundwater derived soil water during dry periods and that this groundwater is extracted from approximately 1 m (Jolly and Walker, 1996). If we assume that the vegetation extracts groundwater derived soil water from Z_e and that the soil is initially low in salt (i.e. $C_{(0-zf)}$ is negligible), then the maximum period between floods for vegetation survival (t_{dmax} for Z_f to approach z_e from z_{wtmax}) can be estimated by integration of Eq. (6) and combining with Eq. (5) to give:

$$t_{dmax} = C_t(1 - \frac{Z_e}{Z_{wmax}})\frac{Z_{wmax}\theta_{d(0-Z_w)}}{C_g\bar{q}} \tag{8}$$

If we assume the soil water salinity is the dominant factor affecting the long term average availability of soil water for uptake then a normalised (0–1) index of soil water availability (X_w), similar to that used in the WAVES modelling of Slavich et al. (1998, 1999), can be defined as

$$X_W = 1 - \frac{C_{(0-Z_{wmax})}}{C_{lmin}} \tag{9}$$

where C_{lmin} is the equivalent soil water salinity to the minimum leaf water potential (ψ_{lmin}) of the vegetation (the limit $0 \leq X_w \leq 1$ applies).

2.3. Salinity index based on flood history

The moving salt front approach can be extended to develop a weighted salinity index based on the average water availability resulting from a given flood history for the past t_{dmax} years. We can represent the flood history of the site as a series of discharge-recharge

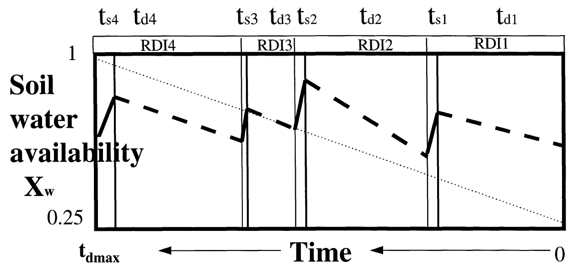

Fig. 4. Schematic of flood history concepts used to calculate the salinity index. Soil water availability is averaged across successive RDI. t_{di} is the duration of the ith discharge interval, t_{si} is the duration of the ith recharge interval.

or dry and flood periods (Fig. 4) and define the discharge and recharge salinity index (WINDS-Index), as

$$\mathrm{WINDS-Index} = \sum_{i=1}^{n_f} \overline{X_{\mathrm{W}i}} W_i \tag{10}$$

where n_{f} is the number of floods in the past t_{dmax} years, $X_{\mathrm{W}i}$ is the average root-zone soil water availability associated with the ith recharge–discharge interval (RDI), and W_i is a weighting coefficient (W_i sum to 1), termed the RDI weight, associated with the duration and age of the ith interval. The average root-zone salinity for the ith RDI used to calculate $X_{\mathrm{W}i}$ can be estimated by integrating and combining Eqs. (6) and (7) to give,

$$C_{(0-Z_{\mathrm{wmax}})_i} = C_{(0-Z_{\mathrm{wmax}})_{i-1}} + \frac{C_g}{Z_{\mathrm{wmax}}} \left(\frac{\bar{q}_i t_{di}}{\theta_{\mathrm{d}(0-Z_{\mathrm{wmax}})}} - \frac{K_s t_{si}}{\theta s_{(0-Z_{\mathrm{wmax}})}} \right) \tag{11}$$

where subscript i refers to the ith RDI, q_{i} is the average discharge rate for average watertable depth $Z_{\mathrm{w}i}$, t_{s} is the duration of inundation, t_{d} is the duration between floods, and Z_{wmax} is the maximum watertable depth. We set a negligible lower limit on $C_{(0-\mathrm{Zwmax})}$ to avoid possible computation of a negative salinity.The weighting factor for each RDI is given by

$$W_i = \frac{v_i}{\sum_{i=1}^{n_f} vi} \tag{12}$$

$$v_i = \left(\frac{t_{si} + t_{di}}{t_{\mathrm{dmax}}} \right) \left(1 - \frac{\Delta t_{\mathrm{L}i}}{t_{\mathrm{dmax}}} \right) \tag{13}$$

where Δt_{Li} is the number of days from the present day to the last day of the ith RDI. The salinity index decreases as root-zone salinity increases and approaches 0 as the discharge period approaches t_{dmax}. $C_{(0\text{-Zwmax})}$ approaches the maximum average soil water salinity ie ($C_{\mathrm{t}}(1-Z_{\mathrm{e}}/Z_{\mathrm{wmax}})$ as time approaches t_{dmax}. The first term bracketed in Eq. (12) assigns a weight proportional to the ratio of the duration of the RDI to the maximum duration for survival between floods whilst the second term linearly scales this weight according to the how long ago the RDI occurred. Hence the greatest weight is assigned to recent long RDIs.

Table 1
Soil and vegetation parameter used in moving front model

Parameter	Site 1	Site 6
K_s (m day^{-1})	0.006	0.002
λ (m)	0.3	0.7
C	1.04	1.1
$\theta_{s(0\text{-zw})}$	0.36	0.45
$\theta_{d(0\text{-zw})}$	0.18	0.22
C_g (dsm^{-1})	55	18
Z_{max} (m)	4	4
C_{lmin} (dsm^{-1})	55	55
C_t(dsm^{-1})	40	40
T_L(mm day^{-1} LAI^{-1}	1.5	1.5

3. Evaluation of moving salt front model and salinity index

3.1. Simulation methodology

The simplifying assumptions associated with the moving salt front model and salinity index were evaluated by comparing simulations against the WAVES simulations presented by Slavich et al. (1999) which evaluated the potential impact of proposed management options on soil water availability and canopy growth. The comparisons were made for two sites (Sites 1 and 6) on the floodplain with contrasting soil hydraulic properties and watertable salinity, but similar elevations and hence, watertable depth and flooding history (Table 1). The water availability of the root-zone was calculated daily using the MSF model assuming a quasi-steady state, from estimates of historical daily watertable depth and flood occurrence for a 25 year simulation period (1970–1994) (Table 2, SIM1 and SIM4). We also compared the models for an additional simulation which assumed Site 1 was 1 m lower elevation on the flood plain and hence, was more frequently flooded and had a watertable 1 m shallower (Table 2, SIM7). In each simulation a constant leaf area index of 0.25 was set to limit the potential groundwater discharge rate via the canopy.

Table 2
Watertable and flooding regimes used for model comparisons

Simulation	Flood regime	Watertable depth range (m)	RIT	Site
SIM1	H	1–4	0.0207	1
SIM2	PE	1–4	0.0240	1
SIM3	H	2–5	0.0207	1
SIM4	H	1–4	0.0207	6
SIM5	PE	1–4	0.0240	6
SIM6	H	2–5	0.0207	6
SIM7	F	0–3	0.117	1

H is with historical flows, PE is with enhanced flood peak flows, F is with frequent flooding, RIT is relative inundation time 1970–1994 (t_s/t_d)

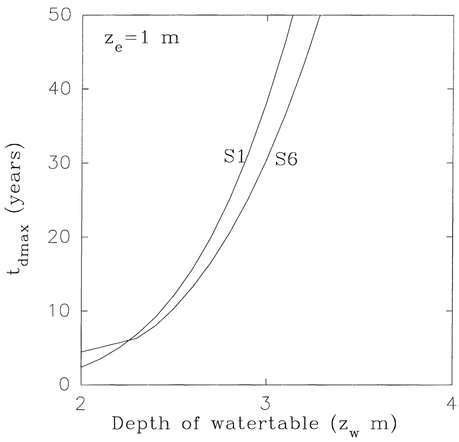

Fig. 5. Dependence of t_{dmax} on watertable depth at two sites (Sites 1 and 6).

3.2. Simulation results

The maximum duration between floods (t_{dmax}) is very sensitive to the watertable depth (Fig. 5) at relatively large Z_w. We limited the maximum t_{dmax} to 25 years because WAVES simulations (Fig. 6(a)) suggested that the maximum period that a growth response to a large individual flood may persist, is of this order.

Both the models predicted similar broad trends in soil water availability over the 25 year simulation period for both flooding/watertable regimes (Fig. 6(a)–(c)). The main differences are that water availability was slightly higher in the WAVES simulation because it also includes the effects of rainfall and fluctuating watertable depth on soil matric potential. The discharge rate, indicated by the rate of decrease in water availability, was similar as the historical simulations at Sites 1 and 6 but was considerably over predicted for the SIM7 regime (Fig. 6(c)). This suggests the simplifying assumptions do not apply as well when the watertable is relatively shallow. The WAVES simulation also shows that some slow leaching also continues for some time after the floods whereas the moving salt front model assumes that the discharge only occurs after the flood. The effect of omitting the canopy area constraint on the discharge rate was evaluated for the simulation shown in Fig. 6(a). This decreased the water availability by approximately 0.2 for the post 1975 period (data not shown). A greater decrease would occur for the shallower watertable simulation represented in Fig. 6(c).

The effect of changing the watertable and/or flooding regime (Table 2) at each site on the RDI weighted salinity index, computed by weighting the floods since 1970, was assessed using the WAVES simulations (Table 2) presented by Slavich et al. (1999). For each simulation the average water availability and LAI for each recharge-discharge interval was used to calculated the RDI weighted salinity index and the associated RDI weighted average LAI. The WINDS-Index was closely related to the RDI weighted LAI for each simulation (Fig. 7) and hence, is proposed as index of vegetation health.

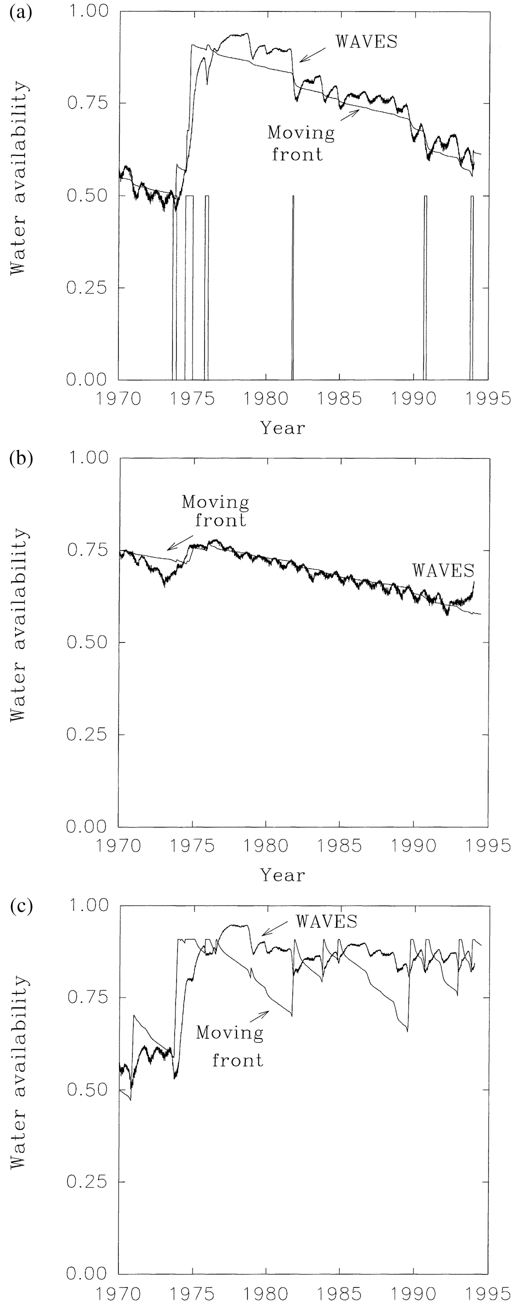

Fig. 6. Comparison of quasi-steady state moving front model with fully dynamic WAVES model for simulations at (a) Site 1 with historical watertable and flooding regime (SIM1) (b) Site 6 with historical watertable and flooding regime (SIM4) (c) Site 1 with shallow watertable and frequent flooding regime (SIM7). Histogram in Fig. 8(a) indicates years when the watertable was close to the plane of water extraction and hence the groundwater discharge rate was canopy area limited.

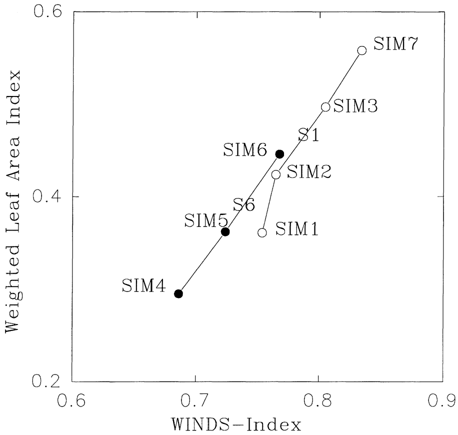

Fig. 7. Computed relationship between the salinity index and the weighted average leaf area index for simulations with varying watertable and flooding regimes (Fig. 2).

4. Discussion

To understand the implications of these results we need to consider the relative importance of the soil hydraulic parameters and canopy constraints in determining the groundwater discharge rate. We also need to consider conditions which will maintain a salt balance in the root-zone over the long term.

4.1. Hydraulic parameters and groundwater discharge

The relative effect of the hydraulic parameters C and λ on the dimensionless discharge rate $q^*(q^* = \mathrm{q}/K_s)$ at Chowilla can be assessed using Fig. A.1. The C parameter has a greater effect on q at low q^* and low dimensionless watertable depth Z^*_w ($Z^*_w = z/\lambda$), whereas λ has a greater effect at high q^* and Z^*_w. The Z^*_w for the soils and watertable depths considered at Chowilla range from 8 to 1. Hence, λ will be the dominant parameter affecting q^* when high river flows drive the watertable close to the zone of groundwater extraction and the C parameter will assume greater important as the watertable drops to its maximum depth after the flood has passed. The soils at both of the sites were comprised of layers with varying soil hydraulic parameters. We used hydraulic parameter values which represent the main soil layers between the depth of the watertable and the depth of water extraction.

4.2. Watertable depth, leaf area and MSF model assumptions

The assumptions of the moving salt front model were most adequately satisfied when the watertable was relatively deep (e.g. 1–4 m) and the soil was less permeable (i.e. SIM1 and SIM4). The moving front model over-predicted leaching and salt accumulation rates when the watertable was relatively shallow as in SIM7. The moving salt front model would have performed even more poorly if it attempted to account for leaching caused by rainfall. The poor performance for shallower watertables reflects a breakdown in the validity of model assumptions. In general these results agree with expectation, that is we would expect the simplifying assumptions to be most adequately satisfied under conditions which favour steady soil moisture conditions between the watertable and Z_e and the development of a defined solute front, such as would occur with less frequent flooding and a relatively deep watertable.

The low leaf area of the vegetation limits the potential groundwater discharge rate when the watertable is close to the depth of active water extraction by roots. The steady state model only predicted a similar trend in water availability when the transpiration capacity per unit leaf area (T_L) was used to limit the discharge rate. The WAVES simulations (Slavich et al., 1998, 1999) showed that transpiration capacity of the canopy varies with the availability of soil water and drifts about a mean value as the canopy leaf area slowly expands and contacts. However, the dominant effects of groundwater discharge could be captured using the moving front model with a constant mean T_L and LAI to limit discharge. This is because the discharge rate was canopy limited for only relatively short periods (Fig. 6(a)).

The WAVES simulations (Slavich et al., 1999) predicted that the canopy LAI expands very slowly after floods. This is because it is starting from a low level and that semi-arid climatic conditions causes soils to dry relatively quickly after floods. The salinity index attempts to sum together salt leaching and accumulation events and hence, the slow growth responses to successive floods.

4.3. Conditions for long-term salt balance

If a root-zone salt balance is to be maintained in the long term, the amount of salt leached during the inundated period (represented by downward movement of the salt front) must equal that accumulated during groundwater discharge period between floods (represented by upward movement of the salt front). Equating the salinity of the unsaturated zone after flooding to the initial salinity before the discharge period gives the condition required for long term salt balance. Hence, by integrating and equating Eqs. (6) and (7) we can derive

$$\frac{t_s}{t_d} = \frac{-\theta_s}{a_0\theta_d}\left(\frac{Z_w - Z_f}{\lambda}\right)^p \tag{14}$$

where t_s is the average number of days inundated per flood, and t_d is the average number of days of the discharge period between floods. We define the relative inundation time (RIT) as t_s/t_d. Note that t_d must be less than t_{dmax}.

Eq. (14), termed the critical salt balance criterion (CSBC), defines the critical watertable depth in relation to soil hydraulic parameters, the depth of groundwater uptake (or evaporation), the average inundation time and average time between flood events (Fig. 8). The critical watertable depth is very sensitive root-zone salt balance with the current flooding regime.

The CSBC concept could be extended to dryland and irrigated environments if the RIT is interpreted as a ratio of the discharge and recharge rates. Furthermore, the ratio $t_s/(t_s + t_d)$ may be interpreted as a probability of recharge which may be assessed from

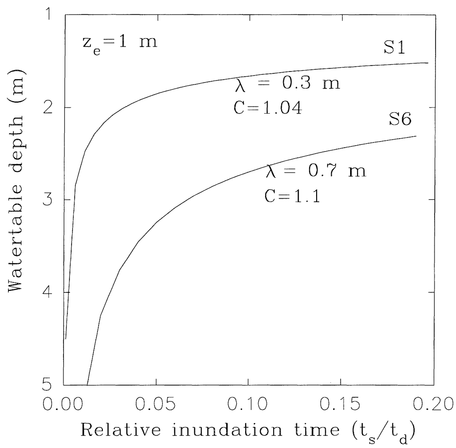

Fig. 8. The dependence of the critical watertable depth for salinity control on the relative inundation time (i.e. days inundated/days not inundated, t_s/t_d) for soils (Sites 1 and 6) with contrasting hydraulic properties.

climate analysis and irrigation water use. However, the concept is only applicable where there is potential for the groundwater to discharge either laterally or vertically to a drainage system.

The existing GIS of the Chowilla floodplain includes data describing elevation (0.1 m contours), maximum watertable depth between floods (0.1 m intervals), indicative groundwater salinity (i.e. high EC > 40 dsm^{-1} or low EC < 40 dsm^{-1}) and indicative soil type (i.e. loan or clay). To apply the WINDS-Index to the GIS representative soil hydraulic properties need to be assigned to the soil classes. The elevation data can be used to estimate t_s and t_d histories. Future work will focus on applying the concepts outlined in this paper to GIS.

5. Conclusions

Long term trends in root-zone soil salinity as predicted by the fully dynamic soil-vegetation-atmosphere WAVES can be predicted using simplified representations of both leaching and salt accumulation processes as well as the time scales over which they are assumed to operate. These simplifications can be used to derive a salinity index which reflects the effect of flood history long term average soil salinity to which the leaf area of the vegetation slowly adjusts. The assumptions of the simplified theory breakdown when the watertable is always very shallow The salinity index has a role as a management tool within a GIS so that floodplain scale effects of flooding or watertable control strategies can be evaluated.

The concept of a critical watertable depth to maintain a salt balance can be extended to account for flood history using these simplifications. Soil hydraulic characteristics introduce a strong non-linearity in the relationship between watertable depth and (a) the groundwater discharge rate (b) the maximum duration between floods for vegetation survival and (c) the proportion of time a site must be inundated to maintain salt balance. Hence there are several hydrological conditions which need to be satisfied for long-term vegetation survival.

Acknowledgements

This work was conducted at the Centre of Groundwater Studies Adelaide whilst the first author was on study leave from NSW Agriculture. The work was supported by an Australian Postgraduate Research Award from Flinders University and the Land and Water Resources Research and Development Corporation.

Appendix A

Approximate relationships between the coefficients of Eq. (2) and the hydraulic parameters of the Broadbridge and White (1988) moisture characteristic and unsaturated hydraulic conductivity model (BW) were developed as follows. The unsaturated hydraulic conductivity and moisture characteristic functions for the BW model are, respectively;

$$K = K_s \frac{\Theta^2(C-1)}{C-\Theta} \tag{A.1}$$

and

$$\Psi = -\lambda\left[\frac{\Theta-1}{\Theta} - \frac{1}{C}\ln\left(\frac{C-\Theta}{\Theta(C-1)}\right)\right]$$

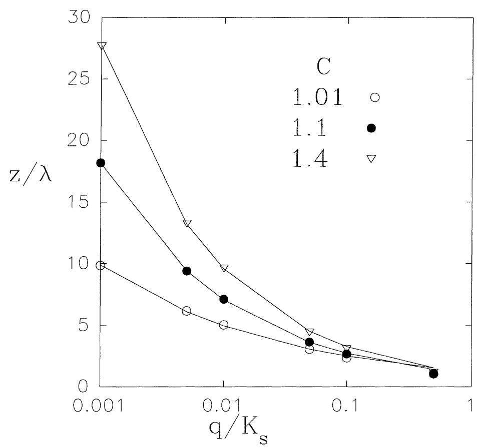

Fig. A1. Captions function curves relating dimensionless watertable depth (Z/λ) to dimensionless maximum groundwater discharge rate (q/K_s) for three values of the Broadbridge and White, 1988 soil hydraulic model parameter C.

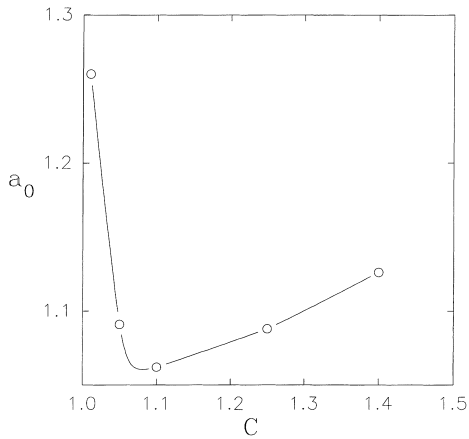

Fig. A2. The dependence of the coefficient (a_0) of the power function relating the watertable depth and the groundwater discharge rate on the *C* parameter of the Broadbridge White soil hydraulic model.

where K is the unsaturated hydraulic conductivity; Ψ is the soil matric potential; $\Theta=(\theta-\theta_r)/(\theta_s-\theta)$; θ is the soil water content; θ_s is the saturated soil water content; θ_r is a minimum residual soil water content; λ a matric potential scaling parameter; C is a soil structural parameter; and K_s is the saturated hydraulic conductivity. The BW model does not have an explicit expression for $K(\Psi)$.

The steady state upward flow Eq. (1) was integrated numerically using piecewise quadratic approximations following Simpson's rule (Kreysig, 1988) using Eqs. (3) and (4) to determine $K(\Psi)$. Integrations were calculated for a range of combinations of dimensionless discharge rates ($q^* = q/K_s$, 0.5–0.001), dimensionless watertable depth ($Z^*_w=Z_{wt}/\lambda$, 1–30) and C (1.01–1.4). Power functions were fitted to the computed dimensionless discharge curves (Fig. 1), then the power function coefficients of Eq. (2) were then regressed against soil hydraulic parameters (Fig. A1) to give the Eqs. (3) and (4). The coefficient a_0 varies slightly with C as shown in Fig. A2.

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