ELSEVIER

Agricultural Water Management 39 (1999) 245–264

Agricultural water management

Dynamics of *Eucalyptus largiflorens* growth and water use in response to modified watertable and flooding regimes on a saline floodplain

P.G. Slavich[b,*], G.R. Walker[a], I.D. Jolly[a], T.J. Hatton[a], W.R. Dawes[a]

[a]*CSIRO, Division of Land and Water, Private Bag No. 2, Glen Osmond, Adelaide 5064, Australia*
[b]*NSW Agriculture, Wollongbar Agricultural Institute, Bruxner Highway, Wollongbar 2477, Australia*

Abstract

Reduced flooding and raised watertables have caused increased soil salinity and die-back of native forests on the floodplains of the lower River Murray of south Australia. Proposed management options include increasing flood frequency by regulating flows from upstream storages, and groundwater pumping to lower the watertable. This paper uses a soil-vegetation-atmosphere-transfer model (WAVES) to evaluate the impact of these proposals on soil salinisation processes and vegetation growth (black box, *Eucalyptus largiflorens*) for soils with different hydraulic properties. The changes in canopy leaf mass and plant available soil water were simulated for the period 1970–1994 using historical daily climate and river level records. The river level records were used to reconstruct the flooding and watertable history of sites where tree water use studies were conducted to calibrate the model. Then the watertable depth and/or flooding frequency was modified and the changes in the canopy leaf mass and soil water availability relative to the historical simulation were evaluated. The simulations suggest that, with the present watertable and flooding regime, very large floods (e.g. 205 days as in 1974–1976) are needed to sustain tree cover on the higher parts of the floodplain where die-back is most severe. They also indicate that soil hydraulic properties have a large influence on the magnitude and time scale of the growth response of salt stressed vegetation to floods and salt accumulation. Infrequently flooded vegetation exhibiting die-back was predicted to increase its canopy leaf area for up to 12 years following the large floods of 1974 and 1976, at sites where the soil was relatively permeable and groundwater highly saline (EC $= 55$ dS m^{-1}). The changes in canopy leaf area in response to the floods was predicted to be relatively small on sites with heavier clay soils. The growth response of the vegetation to a long term lowering of watertable depth by 1 m was greater than that induced by the small potential increase in flooding frequency which is feasible given the current water storage limitations. The simulations predict that changes in the average annual soil water availability which

* Corresponding author. Tel.: +61-02-66261200; fax: +61-02-66281744; e-mail: peter.slavich@agric.nsw.gov.au

PII: S0378-3774(98)00081-X

arise from flood events and soil salinisation, drive a long term cycle in the annual average transpiration rate per unit leaf area suggesting the soil-plant-climate system is adjusting towards a hydrological equilibrium but is not in equilibrium. The proposed management options may control die-back in parts of the floodplain with more slowly salinising heavy clay soils and lower salinity groundwater but are unlikely to prevent die-back on relatively permeable soils with high salinity groundwater. However, they may assist vegetation survival between the long duration flood events which appear to be essential to sustain tree cover on the higher floodplain. The management options need to be evaluated further at the floodplain scale using the understanding from site specific conditions to test simple approaches which can be linked to a geographic information system (GIS) of the floodplain.

Keywords: Salinity; Model; Floodplain; Eucalyptus

1. Introduction

Die-back of native woodlands due to increasing salinity on floodplains within the Murray-Darling Basin in Australia is widespread. Regulation of flows in the Murray River has raised the level of the watertable under adjacent floodplains whilst upstream dams and diversions have reduced the incidence of medium sized floods (Margules et al., 1990). Shallower watertables and reduced flooding has increased soil salinisation causing vegetation die-back (Jolly et al., 1993). Management proposals to reduce salinity induced die-back include regulating river flow to increase the flooding frequency and/or groundwater pumping to lower shallow watertables. The proposed management strategies may also have impacts on salt loads to the river and off-site effects associated with groundwater disposal.

The Chowilla floodplain (140°52′E, 33°59′S) (Fig. 1) is typical of those on the lower River Murray. It supports 200 km^2 of native woodland and is listed under the UNESCO Ramsar Convention as a wetland of international importance as a habitat for migratory birds (National Environmental Consultancy, 1988). The main vegetation communities on the flood plain are red gum (*Eucalyptus camaldulensis*) which is found close to the ephemeral and permanent creeks; black box (*Eucalyptus largiflorens*) at sites with higher elevation away from the creeks but with access to shallow groundwater; and of lesser importance lignum (*Muehlenbeckia cunninghamii*) and Cooba (*Acacia stenophylla*). A noticeable increase in die-back of black box, characterised by loss of much of the canopy foliage and the development of epicormic growth, occurred in the mid 1980s. This increased community concern and initiated studies to assist the development of management guidelines. The Chowilla floodplain has a semi-arid temperature climate with average annual rainfall of 250 mm. With this climate healthy black box stands develop a leaf area index of approximately 0.5–1.0 depending on the tree density.

The hydrological processes affecting die-back of black box on the Chowilla floodplain have been described by Walker et al. (1995) and Jolly (1996). Regional groundwater is generally highly saline (Electrical Conductivity (EC) > 40 dS m^{-1}) and flows towards the River Murray, discharging through the vegetation and directly to the river. The closest weir on the river (lock 6) was completed in 1930 and has raised the base flow river height which has caused the once ephemeral anabranch creeks to be permanently flooded.

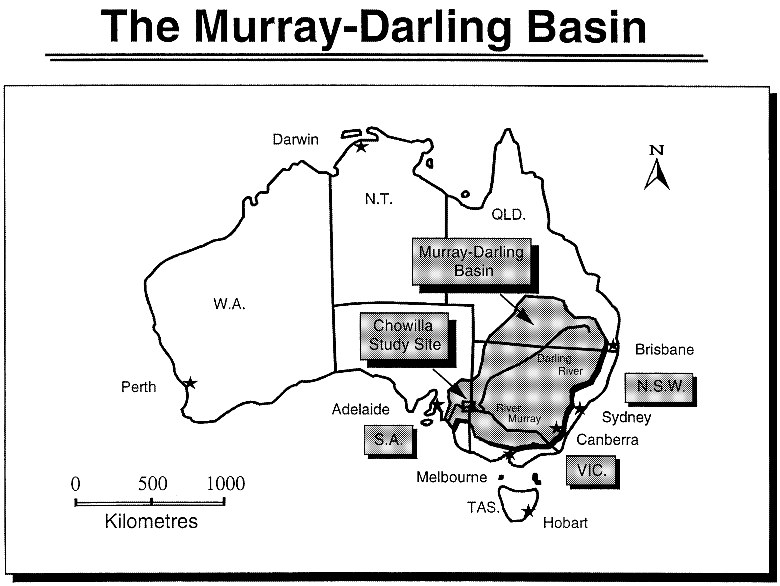


Fig. 1. Location of Chowilla floodplain within the Murray–Darling basin.

Consequently, the groundwater pressures under the floodplain have increased, raising the watertable depth by 2–3 m to 1–5 m below ground level. River flows in this section of the river vary from 30 000 ml/day for non-flood conditions to over 100 000 ml/day for large floods. Dams in the head waters and upstream diversions of water for irrigation have reduced the frequency of medium sized floods (80 000–100 000 ml/day) by a factor of 3 (Ohlmeyer, 1991).

An understanding of the relative sensitivity of vegetation growth and water use to changes in soil salinity induced by changes in flooding and watertable depth is required to evaluate management options for the Chowilla floodplain. Water use studies using natural isotopes (^{2}H,^{18}O) and sap flow measurements indicate that the eucalypts on the flood plain transpire mainly soil water derived from groundwater during dry periods between floods and rain events (Thorburn et al., 1993; Jolly and Walker, 1996). The effects of groundwater discharge by vegetation on the soil salinisation rate has been modelled assuming simple steady state conditions (Jolly et al., 1993; Thorburn et al., 1995). This paper uses the understanding gained from the water use and isotope studies and steady state modelling to guide the application of a soil-vegetation-atmosphere transfer (SVAT) model to evaluate management options.

SVAT models which describe the daily vegetation growth in relation to changes in climatic and soil conditions may be used to increase the understanding of the sensitivity of the vegetation to a change in hydrological conditions. Such models have great flexibility and enable a range of specific management options to be compared without the limiting assumptions of steady state models. However, SVAT models are more complex and have a larger number of parameters, some of which may be difficult to measure or calibrate. Many parameters in such models are best considered constants (and hence, never adjusted) which formulate explicit generic assumptions. Even complex models are still based on a limited range of assumptions of the how the major processes interact and hence, must be understood as simplifications of real systems. The predictions of such models need to be carefully evaluated in terms of both the model assumptions and the sensitivity of the prediction to model parameters.

This paper uses a dynamic SVAT model to evaluate the interaction between the growth of *E. largiflorens* and soil salinisation when the watertable depth and the flooding regime are changed to represent potential impacts of proposed management options. The management scenarios, i.e. lowering the water table and/or enhanced flooding, were evaluated for two contrasting soil types on the flood plain.

2. Methods

2.1. SVAT model description

WAVES (Water Atmosphere Vegetation Energy and Solutes) is a one-dimensional daily time step model describing water and carbon transfer through the soil-plant-atmosphere system. WAVES uses an efficient numerical solution to solve Richard's equation for one dimensional unsaturated water flow and the convective dispersive equation for non-reactive solute movement (Dawes and Hatton, 1993; Dawes and Short, 1993). Convergence and stability of the numerical solution can be guaranteed when the Broadbridge and White (1988) model (BW) is used to describe soil hydraulic properties, greatly facilitating application of the model across long time scales and wide ranges in soil water content. Transpiration is estimated using the 'big leaf' Penman–Monteith equation with the canopy conductance to water vapour exchange estimated from a similar 'big leaf' carbon assimilation model. The carbon assimilation model assumes that soil water availability, determined by daily soil matric and osmotic potential, modifies canopy gas phase conductance and hence, carbon assimilation rate, and the proportion of assimilated carbon allocated for canopy growth. A detailed description of the model is given by Slavich et al. (1998).

2.2. Input data and parameter calibration

WAVES is derived by daily climatic data (maximum and minimum temperature, vapour pressure deficit, daily radiation, rainfall, depth radiation, rainfall, depth of flood) which determine the upper boundary conditions, and daily watertable depth which sets the lower boundary condition. Parameters must be set to describe the soil hydraulic properties and vegetation characterstics. Parameters represented in the model were either set as generic constants based on literature, measured or calibrated that is set by running the model and matching modelled and observed data.

The soil (Table 1) and vegetation (Table 2) parameters of WAVES were calibrated from monitoring of transpiration rates and soil data collected during a flood at five sites on the Chowilla floodplain. The methods used to calibrate the model are summarised

Table 1
Soil hydraulic parameters of site. Parameters of Broadbridge and White (1988) moisture characteristic, *K*s saturated hydraulic conductivity, θ_s saturated water content, θ_r residual water content, λ macroscopic capillary length scale, *C* reflects pore size distribution

Depth (m)	Ks (m/day)	θ_s	θ_r	λ (m)	C
Site 1					
0–0.6	0.006	0.36	0.1	0.5	1.05
0.6–4.0	0.006	0.36	0.1	0.3	1.04
Site 6					
0–0.3	0.002	0.45	0.1	0.6	1.1
0.3–0.75	0.002	0.45	0.1	1	1.1
0.75–1.8	0.001	0.45	0.1	0.5	1.1
1.8–4.0	0.001	0.45	0.1	1	1.1

below. Soil pits were dug at each site to characterise the thickness of the main textural horizons. Four main textural classes were identified i.e. <15% (T1), 15–30% (T2), 30–45% (T3) and >45% (T4) clay. Soil profiles were sampled at the start of the simulation period, before the flood, in January just after the flood, and in April after a dry period. The hydraulic properties of each texture class were characterised using the Broadbridge and White (1988) soil hydraulic model. The BW soil parameters λ (determined by flow

Table 2
Vegetation parameters used in black box simulation

Serial No.	Description	Value	Units
1	Canopy albedo (α_c)	0.1 (S)	–
2	Soil albedo (α_s)	0.15 (S)	–
3	Rainfall interception coefficient	0.001 (S)	m/LAI/day
4	Light extinction coefficient (k)	0.4 (S)	$(LAI)^{-1}$
5	Maximum carbon assimilation rate (A_{max})	0.01 (S)	kg C/m^2/day
6	CO_2 ratio (a_1)	0.6 (S)	
7	Minimum potential for plant available soil water (ψ_{min})	−350 (M) m	
8	Ratio of maximum mesophyll to stomatal conductance (W)	0.2 (S)	–
9	Maximum proportion of assimilate allocated to leaves ($n_{1\ max}$)	0.31 (C)	
10	Minimum proportion of assimilate allocated to leaves ($n_{1\ min}$)	0.1 (S)	
11	Temperature when growth rate is 1/2 optimum (T_h)	10 (S)	°C
12	Temperature when growth rate is opltimum (T_{op})	25 (S)	°C
13	Saturation light intensity (Q_{psat})	1200 (S)	μ moles/m^2/s
14	Maximum rooting depth (Z_{max})	4 (S)	m
15	Specific leaf area (S_{la})	12 (M)	m^2/kg C
16	Leaf respiration coefficient (R_{OL})	0.001 (S)	kg/kg/°C/day
17	Stem respiration coefficient (R_{OS})	–	kg/kg/°C/day
18	Root respiration coefficient (R_{OR})	0.001 (S)	kg/kg/°C/day
19	Leaf mortality rate (M_{OL})	0.003 (M)	% leaf C/day
20	Osmotic matric potential weighting factor (W_{osm})	1 (S)	–
21	Aerodynamic resistance (r_a)	20 (S)	s/m

(S) is set as a constant representative value, (M) set from observation or measurements, (C) manually calibrated weighted average pore size) and C (pore size distribution parameter) for each horizon were initially estimated from an evaluation of the texture profiles at each site. Relatively large values were set for the clayey textured classes and smaller values for the sandier textured classes. Similar soil parameter values were used for similar textured materials at the different sites.

Simulations were run for the period 29 September 1993–12 March 1994 which included a flood which lasted 78 days on the lowest site and 13 days on the higher site. The initial root distribution was assumed to be distributed proportionally to the water availability profile, i.e. most root carbon was assigned to soil layers with the highest soil water availability. This assumption reflects that used by the model for root growth and water uptake i.e. that roots grow and extract most water from soil layers with the most available water (highest total water potential). The initial soil water potential and hence water availability was estimated from the measured water content, chloride and watertable depth. The saturated and residual water contents of each textural class were set using sampled observations water content. The bulk density was set to 1500 kg m^{-3} which was similar to measured values. The saturated hydraulic conductivity (K_s) of T1 and T4 texture classes was measured using undistributed cores (7.5 cm diameter). This provided an initial estimate of 0.05 m/day for T1 and 0.04 m/day for T4. The value of λ, C and K_s were then adjusted until the modelled and measured water content and chloride profiles were similar to those measured in both January and April. Adjustments to K_s had a marked effect on the modelled chloride distribution. The K_s was adjusted downward to the values shown in Table 1 so that the degree of salt movement in the measured and modelled profiles was similar in the 1–3 m depth interval. The amount of water stored in the profile was most sensitive to adjustments of λ, whereas adjustments to C mainly affected the curvature of the modelled water content profile. Hence different criteria were considered when setting each soil hydraulic parameter. The calibration approach also required a compromise between the degree a parameter could be adjusted for a particular soil textural layer at an individual site and the degree the parameter varied across different sites for the same textural layer.

Vegetation parameters values (Table 2) were set either as constants using representative values for C3 woody plants, estimated from measurements or calibrated. The minimum plant available soil water potential was set from seasonal observations of pre-dawn leaf water potentials (Eldridge et al., 1993). The leaf mortality rate was set from leaf survival studies on black box (Roberts, pers. comm.). The aerodynamic resistance corresponds to wind speed of 2–3 m s^{-1} at a height of 2 m above a canopy height of 6–12 m. The light extinction coefficient was set to represent erect leaves and canopy. The maximum canopy carbon assimilation was set to a value considered representative of dry sclerophyll vegetation (Larcher, 1980). The only vegetation parameter whose value was calibrated by running the model was the maximum proportion of assimilate allocated to the canopy. This was adjusted so that the modelled LAI remained close to values estimated in field assessments (P. Taylor, pers. comm.).

The model gave a reasonable description of the seasonal changes transpiration, soil water content and profile chloride distribution at sites with different health, groundwater salinity and flood frequency. An indication of the models performance for the above responses at a unhealthy site (Site 1) is shown in Fig. 2(a–c). The model simulated the

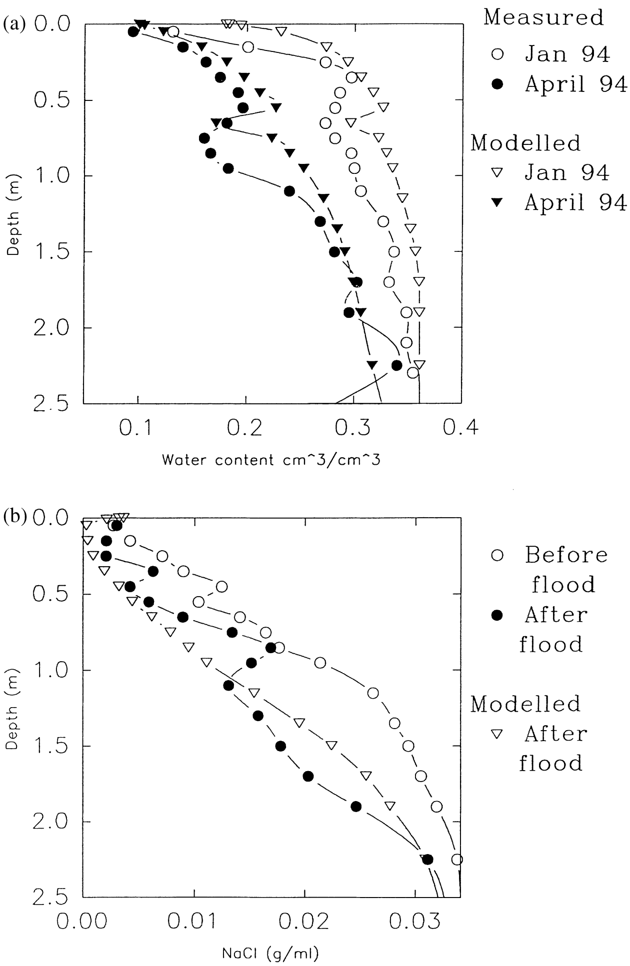


Fig. 2. Comparison of simulated and measured changes used to calibrate the soil parameters used by the model at Site 1 (a) soil water content (b) soil water sodium chloride concentration (c) and transpiration rates.

general depth and rate of drying reasonably well (Fig. 2(a)). However, water contents at particular depths were often slightly over predicted. Similarity between the salinity profiles measured after the flood and the modelled profiles (Fig. 2(b)) is expected as this was used to set K_s. However, the model predicted greater leaching in the 0–1 m layer than was observed. This suggests that the leaching process in the 0–1 m layer is, relatively, inefficient and that not all the solute is readily mobile as is assumed by the model. Inefficient leaching would be expected near the soil surface in aggregated clay soils. The modelled and measured transpiration rates were also reasonably similar in both magnitude and seasonal variation (Fig. 2(c)). The transpiration rates were very low as would be expected from the low leaf area.

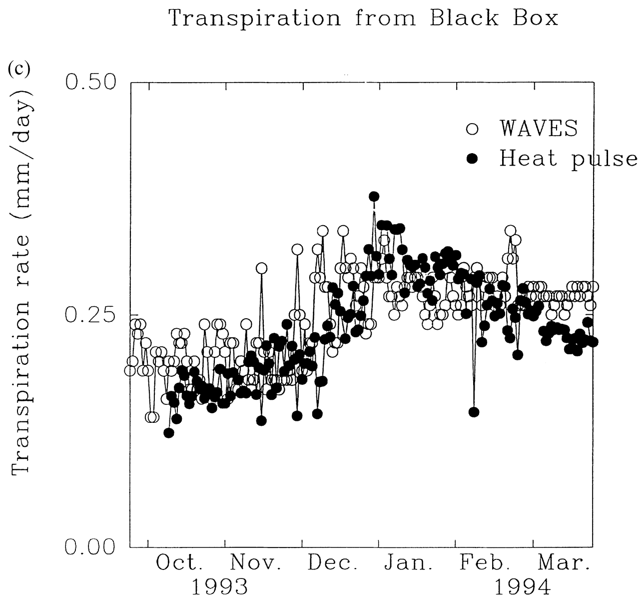


Fig. 2. (*Continued*)

2.3. Description of simulations

The calibrated model was used to evaluate the sensitivity of the vegetation growth response to changes in flooding regime and/or watertable depth over a 25 year period, 1970–1994. This was the longest period for which a complete climate record could be constructed from near-by weather stations. This period also included the large floods of 1974–1975.

Simulations were run for two sites with poor health at a relatively high elevation on the floodplain and, therefore, likely to be the most sensitive to a decrease in the watertable or an increase in flooding. The sites (Sites 1 and 6) have similar watertable depths and flooding histories but different soil hydraulic properties (Table 2) and groundwater salinities. The elevation of both sites is 20.45 m Australian height datum (AHD) and are inundated by when river flows exceed 100 000 ml/day. Minor flooding starts when the water level at lock 6 exceeds 17.8 m AHD or 50 000 ml/day.

Site 1 has a relatively permeable loamy clay surface soil and is underlain by a clayey sand subsoil whereas Site 6 has a heavy clay profile throughout. The watertable salinity at Site 1 has an EC of 55 dS m^{-1} and at Site 6, which is closer to the river, is only EC 18 dS m^{-1}. The black box trees at Site 1 had severe die-back symptoms with most of the major branches without crown foliage and most foliage present as epicormic growth whilst those at Site 6 had sparse thinning crowns and were less densely populated than those at Site 1.

Prior to 1993–1994 the trees at each site had not been inundated by flood since 1974–1975, i.e. approximately 19 years. The only major flood at these sites prior to 1974 would have occurred in 1956, i.e. 18 years previously. Hence, it is likely that the soil salinity would have been moderate to high at the start of the simulation period in 1970. Since soil data was not available for 1970 we assumed the soil salinity and leaf area were similar to that in 1993–1994.

Daily watertable depth and flood depth are also input requirements of the model and were estimated using records of river levels (Fig. 3(a)) taken at lock 6. Higher groundwater pressure during floods causes the watertable to rise. Following the floods the watertable at these sites falls to a maximum depth of approximately 4 m as groundwater drains into the river. Observations of the watertable response to changes in river height made during the 1993–1994 flood were used to derive the watertable history from the river level data (Fig. 3(b)). The historical river flows indicate that since 1970 the sites were flooded only in 1974–1976 (205 days) and 1993–1994 (14 days). However, 12 other minor floods (greater than 50 000 ml/day) occurred in this period which did not inundate these sites but would have caused the watertable to rise and fall.

The sensitivity of the vegetation growth and salt accumulation to long term changes in watertable depth and flooding were evaluated separately and in combination. Firstly, the effect of increasing the depth to the watertable was evaluated by subtracting 1 m from the watertable depth at each site, without changing the flood frequency. This simulation (Scenario A) represents the possible impact of a groundwater pumping scheme.

Secondly, the flooding regime was modified by assuming that an upstream storage (Lake Victoria) was used to maximise the flood peak by reducing its discharge as the flood first entered the lake then increasing its discharge by 15 000 ml/day for 15 days so as to add to the flood peak flow and hence the area of the floodplain inundated. This flow was the maximum amount that river managers indicated was feasible to deliver and could only be achieved if there was sufficient reserve capacity in the lake prior to the floods. The effect of water releases at Lake Victoria and hence enhanced flood flow on the flood level at lock 6 was estimated empirically using linear regression equations developed from data on observed flows and lock 6 water levels over the 1970–1994 period. This release strategy (Scenario B) was applied to each of the 14 floods (i.e. flow of greater than 50 000 ml/day or 19.2 m AHD at lock 6) that occurred between 1970 and 1994. This increased the number of days flooded from 219 to 252 with additional floods inundating the sites in 1981 (11 days), 1990 (15 days), 1992 (14 days) and slightly reduced the inundation time in 1974–1976 and 1993–1994 (7 days) (Fig. 3(c)). The relative inundation time (RIT), defined here as the number of days inundated divided by the number of days not inundated during the total simulation period, for the historical flow regime was 0.0207. The highest RIT that the proposed water release strategy could effect at these sites was 0.024, i.e. only slightly higher than the historical flow value.

Thirdly, the above two scenarios, that is lowering the watertable and increasing the flooding frequency, were combined for Site 1.

The model was used to simulate changes in plant availability in the 0–4 m layer and changes in canopy leaf mass. The soil water availability index (X_w) in these simulations was calculated as the average soil water potential (matric (ψ)+osmotic (π) potential) of the root-zone normalised (0–1) against the minimum pre-dawn leaf water potential ($\psi_{1\ min}$) observed at stressed sites that is -350 m. Hence for 'nl' soil layers of thickness Δz the water availability index was estimated as

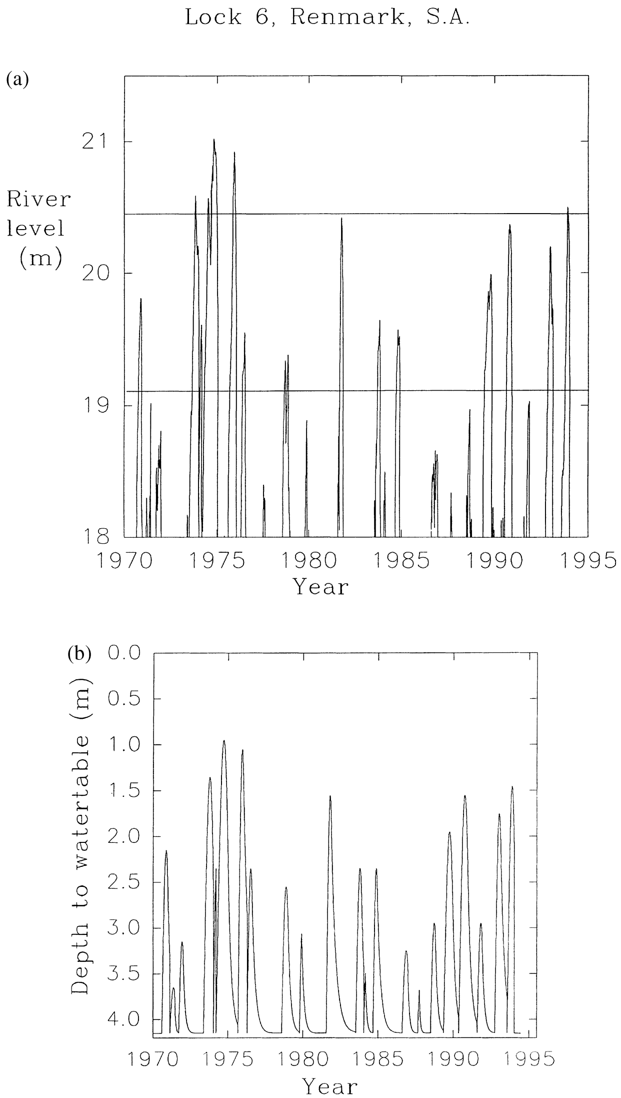


Fig. 3. Input data used for the simulations. (a) Water level in lower pool of lock 6 on the lower River Murray (b) watertable depth for simulation period, (c) example of change in river level caused by enhancing peak flood flows using water released from Lake Victoria. Note that sites are at elevation 20.45 AHD.

$$X_{\mathrm{w}} = \frac{\sum_{i=l}^{\mathrm{nl}} (1 - (\psi_i + \pi_i)/\psi_{1\mathrm{min}}) \Delta_{\mathrm{Zi}}}{\sum_{i=1}^{\mathrm{nl}} \Delta_{\mathrm{Zi}}} \tag{1}$$

A specific leaf area of 12 m^2 (kg C)$^{-1}$ was estimated from leaf samples and used to convert the mass of canopy carbon metre to a LAI. Throughout the paper either leaf mass or leaf area are used synonymously as a modelled indices of canopy health.

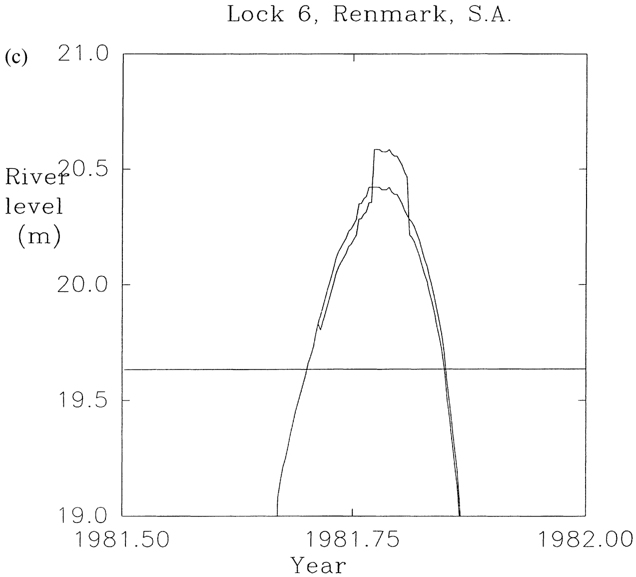


Fig. 3. (*Continued*)

3. Simulation results

3.1. Site 1

The modelled changes in canopy leaf mass and the average availability of water for historical (unmodified) river flows and flooding are shown in Fig. 4. The large increase in water availability during and after the long floods of 1974–1976 mainly reflects major leaching of salt from the root-zone. The vegetation responded to the reduced salinity by increasing its canopy leaf mass for 12 years after the flood. From 1987 salt accumulation from the watertable had reduced water availability to the extent that the canopy assimilation rate was not sufficient to support the carbon loss through respiration and leaf mortality, so that the canopy leaf mass decreased. This is interpreted as development of a die-back condition.

The small perturbations in water availability arise from watertable fluctuations caused by smaller flood flows which did not inundate the site and variation in seasonal rainfall. In the years when the watertable was close to the surface for many weeks there was a steep decrease in water availability caused by higher groundwater discharge rates and hence more rapid salinisation rates.

The modelled annual transpiration rates (Fig. 5) are consistent with rates measured at healthy and unhealthy sites (Thorburn et al., 1993; Streeter, 1995 pers. comm.). The transpiration was predicted to be highest in flood years even though leaf mass was predicted to be smaller in these years.

The impact of the management scenarios was evaluated from the changes in soil water availability and changes in canopy LAI relative to the historical simulations (Figs. 6(a)

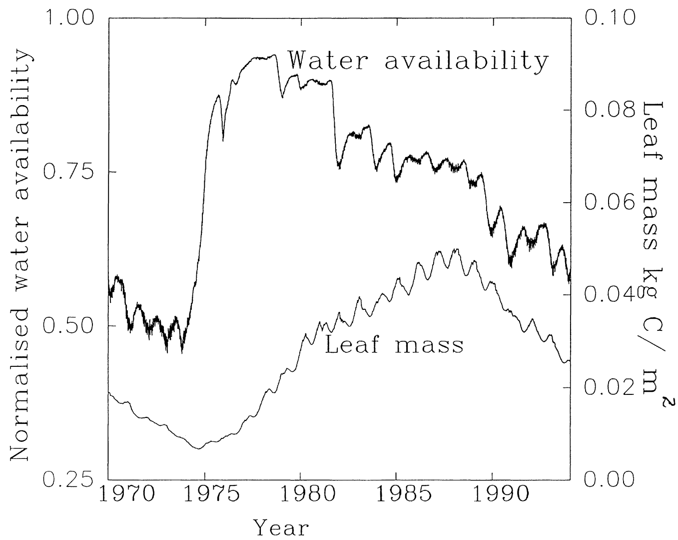


Fig. 4. Changes in canopy leaf mass and root-zone water availability modelled using historical watertable and flooding conditions at Site 1.

and 7(a)). The simulation indicted that a deeper watertable (Scenario A) would have resulted in greater leaching during the 1974–1976 flood and a higher maximum leaf mass than for the historical simulation. However, salt accumulation began to cause the canopy leaf mass to decrease at about the same time after the floods as the unmodified condition, and the canopy died back at a similar rate but from a higher leaf area. The change in growth and soil water availability for the increased flooding scenario was considerably

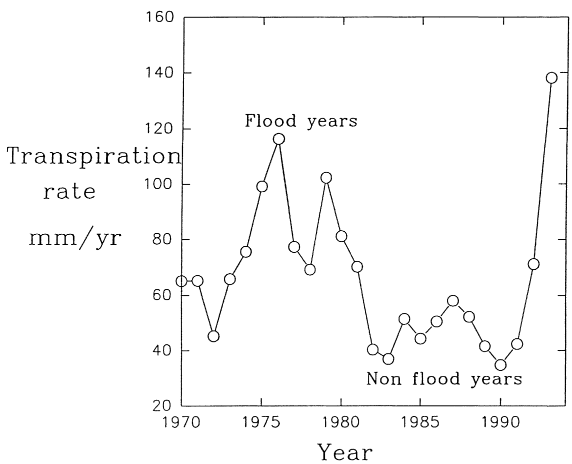


Fig. 5. Modelled changes in annual transpiration rates at Site 1.

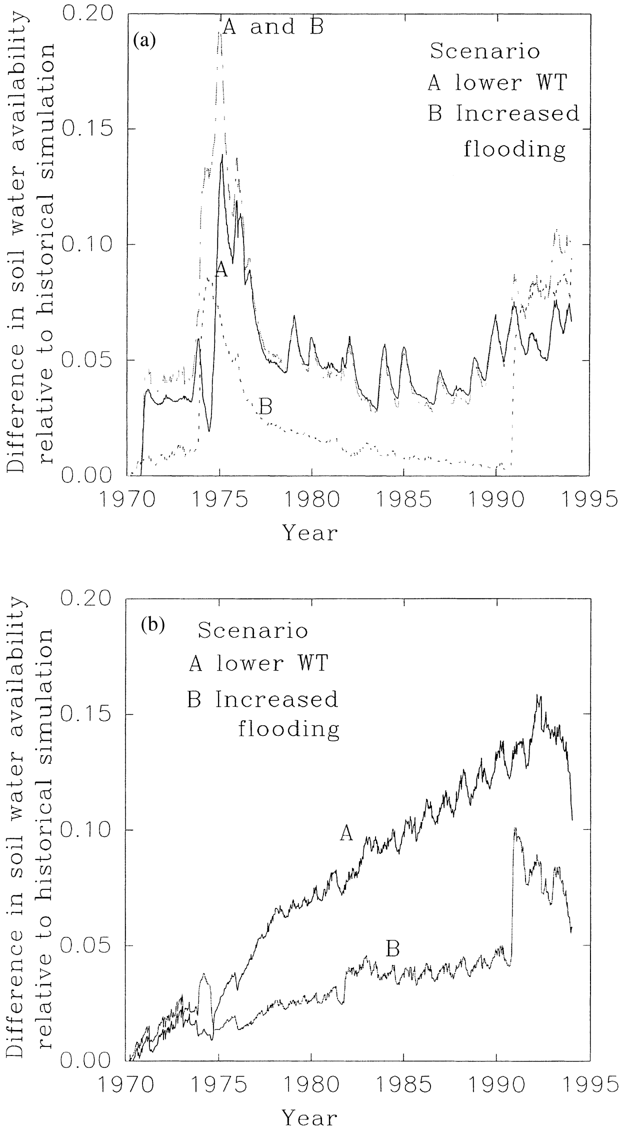


Fig. 6. Temporal changes in the difference between soil water availability of management scenarios and that of historical flooding and watertable condition at (a) Site 1 (b) Site 6.

less than that predicted for Scenario A. Die-back (as indexed by declining leaf mass) is still evident with Scenario B, however, the small flood events induced by the release strategy during 1990 and 1992 did partially compensate for the shallower watertable condition. There was no leaching or growth response to the short flood induced in 1981. When Scenarios A and B were combined the increase in water availability and leaf area was only slightly greater than that induced by lowering the watertable alone.

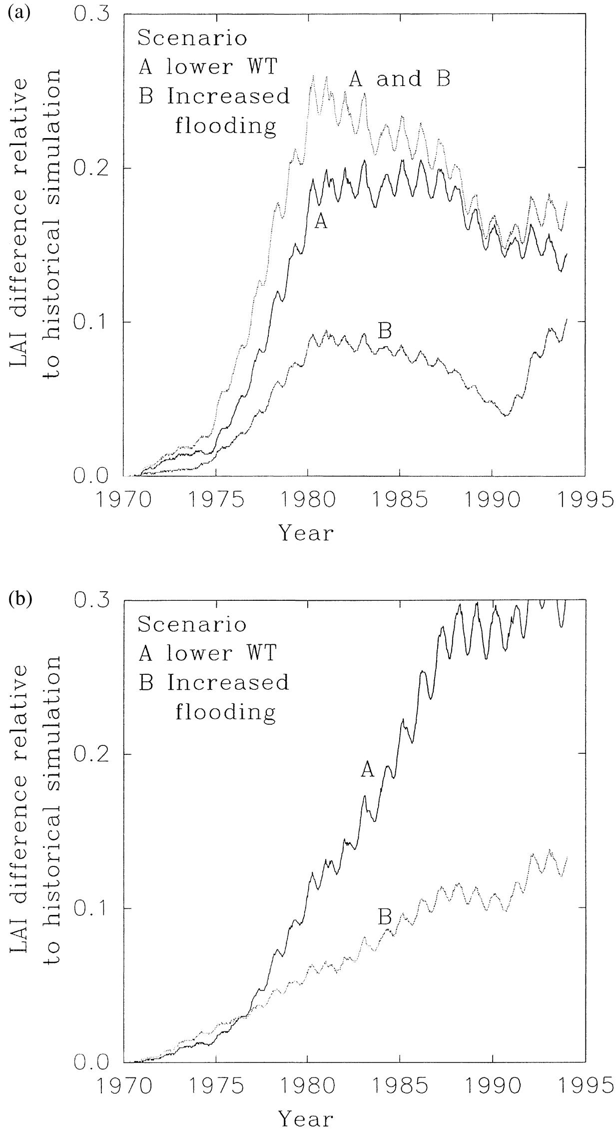
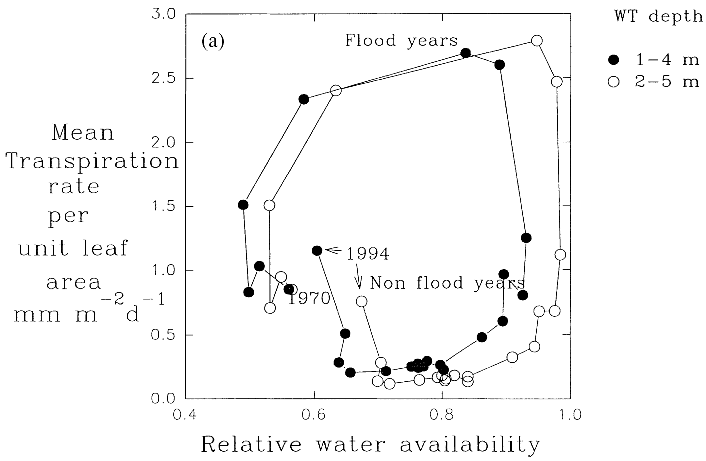


Fig. 7. Temporal changes in the difference between LAI of management scenarios and that of historical flooding and watertable condition at (a) Site 1 (b) Site 6.

The plant can regulate its transpiration rate by adjusting both its stomatal conductance and its leaf area. The long term effects of the changes in hydrological conditions on the combined effect of leaf area and stomatal regulation of transpiration can be illustrated by tracking the predicted annual average leaf transpiration rate (mm water transpired per m^2 leaf day^{-1}) and the annual average soil water availability from 1970 to 1994 (Fig. 8). The



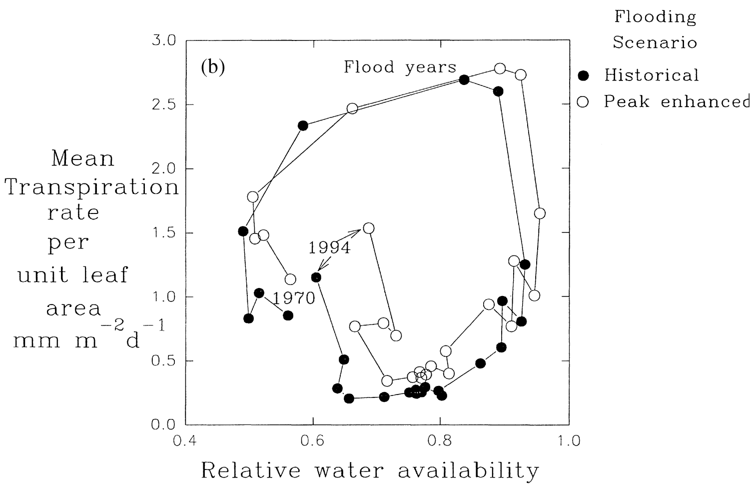


Fig. 8. Annual drift in the annual average transpiration rate per unit leaf area with changes in soil water availability induced by (a) watertable and (b) flooding conditions at Site 1.

simulations suggest there is a long term leaf transpiration-water availability cycle within which the canopy functions. Leaf transpiration rates were predicted to be highest during the flood years, increase in response to leaching, decrease rapidly in the years immediately following 1976 as the soil dried, then decrease slowly as the soil became more saline. Whilst lowering the watertable was predicted to give a greater increase leaf area in the 1980s, it decreased the average leaf transpiration rate at an equivalent soil water availability. In contrast, the model predicts that more frequent flooding would cause a corresponding increase in the average leaf transpiration rates. Thus the different management options are predicted to have different effects on how the vegetation regulates its water use in relation to the available soil water.

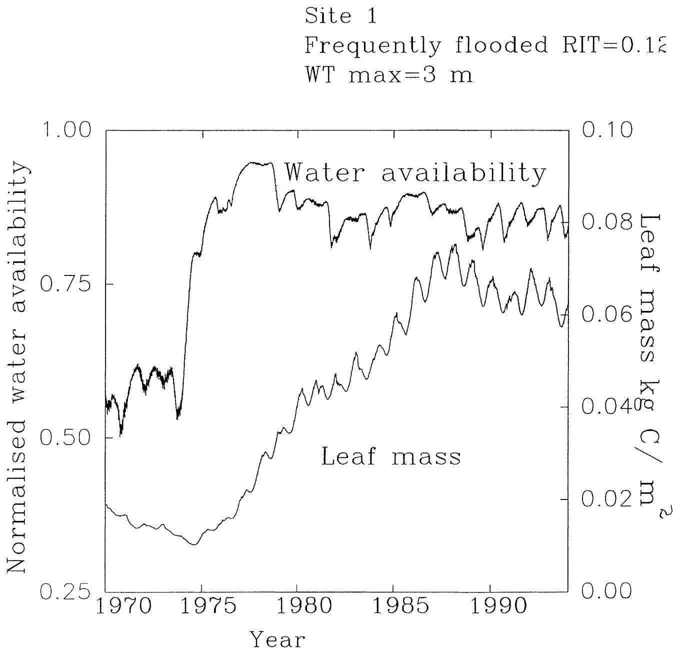


Fig. 9. Changes in canopy leaf mass and root-zone water availability modelled assuming high flooding frequency and maximum watertable depth of 3 m at Site 1.

A further simulation was conducted to consider the effect of a significant increase in the flooding regime. It was assumed that the site was located at an elevation 1 m lower than its actual level. Sites at this elevation would have been inundated for 1131 days during the 1970–1994 period and do not exhibit die-back. This is equivalent to a RIT of 0.117. It was also assumed that the maximum watertable depth between floods was 3 m rather than 4 m. The simulation results (Fig. 9) show that he water availability remained relatively high following the 1974–1976 flood and that the canopy leaf mass did not become affected by die-back.

3.2. Site 6

The changes in water availability and leaf mass (Fig. 10) for the historical flow and watertable condition were predicted to be much smaller than those at Site 1. There was also a much steadier decline in water availability arising from both the lower soil permeability and lower groundwater salinity. The simulation indicates that the soil is very slowly salinising and the leaf mass is stressed but relatively stable compared to Site 1. Lowering the watertable by 1 m and peak flow enhancement decreased the salinisation rate causing a steady increase in soil water availability relative to the historical condition (Fig. 6(b)) and allowed the canopy to steadily expand to a higher leaf mass (Fig. 7(b)). Lowering the watertable has a larger influence than increase the flooding, which is

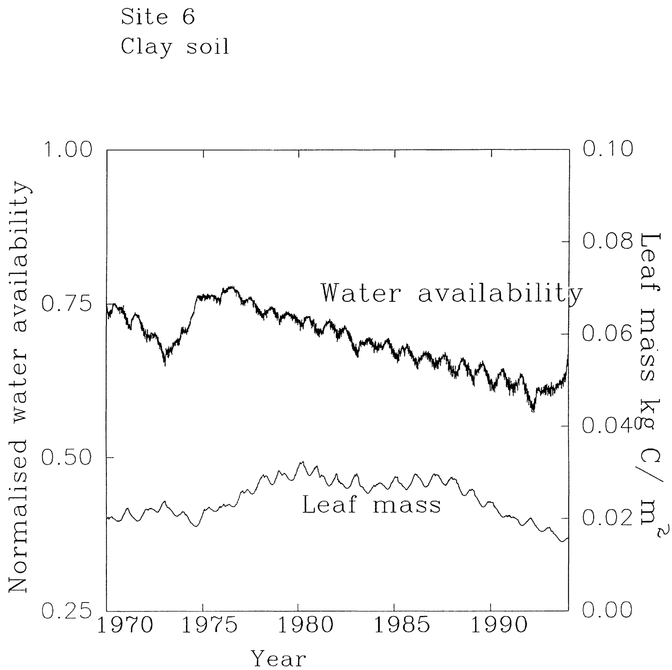


Fig. 10. Changes in canopy leaf mass and root-zone water availability modelled using historical watertable and flooding conditions at site 6.

similar to the response difference at Site 1. The canopy was predicted to operated within a more constrained average annual leaf transpiration-soil water availability domain than at Site 1 (Fig. 11).

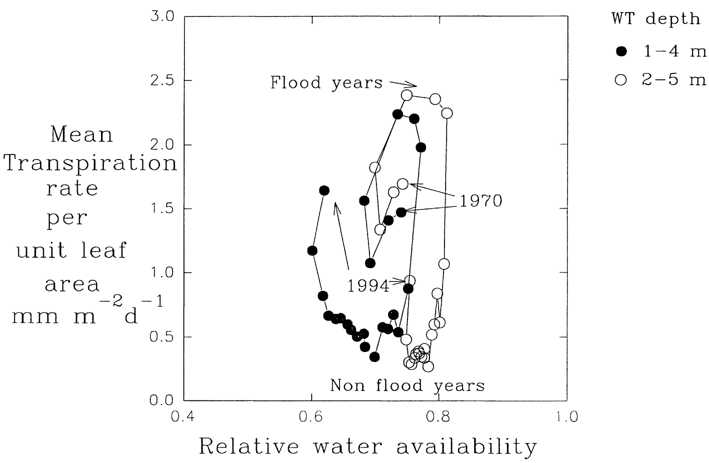


Fig. 11. Long term cycling of the annual average transpiration rate per unit leaf area with changes in soil water availability induced by change in watertable depth at site 6.

4. Discussion

The modelled responses described above only consider the effects of physiological stress caused by changes in soil water availability on canopy leaf area and hence growth and transpiration rates. Whilst water availability is likely to be the major factor controlling canopy growth, other ecological factors such as insect attack, grazing, understorey competition, regeneration or changes in nutrient status could also modify the vegetation community structure and leaf area. Hence, the simulation should be interpreted as representing potential vegetation responses to changes in hydrological conditions. In this sense it is the magnitude of the growth deviation from the historical condition simulated by the change in hydrological conditions that is of most interest.

The sensitivity of the growth model to parameter variability has been presented in detail by Slavich et al. (1998) and is beyond a full discussion in this paper. The point to note here is that only the maximum proportion of assimilate allocated to leaves ($n_{1\ \mathrm{max}}$) was used to calibrate the model. This parameter is not measurable at the canopy scale over any significant period of time and hence must be calibrated. All other parameters were fixed to measured or set to constant representative values. The sensitivity analysis outlined in Slavich et al. (1998) showed that varying $n_{1\ \mathrm{max}}$ by 0.1 could change the long term equilibrium LAI, that is the LAI at which canopy increase and loss are balanced, by one unit. This is a relative large change in LAI compared to the range of values observed across the floodplain.

According to hydrological equilibrium theory a constant average leaf transpiration rate is expected in systems where the leaf area is in equilibrium with the long term water availability. The prediction of a long term cycle in the average annual transpiration rate per unit leaf area is consistent with the transient non-linearity in the transpiration/leaf area relationship induced by water stress reported by Hatton and Wu (1995). In this case the predicted cycle reflects a perturbation of the equilibrium by the large episodic floods of 1974–1976. We also modelled considerable seasonal variation in this ratio that would make this long-term cycle difficult to detect experimentally.

The modelling results suggest that the growth response of the vegetation to a given watertable and flooding regime is strongly affected by soil hydraulic properties as these influence the rate of change is soil salinity. This interaction causes large differences in the magnitude and time scale of the growth response to similar floods and watertable conditions. Because Site 1 is relatively permeable and infrequently flooded, higher rates of salt accumulation during inter-flood periods as well as higher leaching rates during floods cause a greater range of salinity stress on the vegetation than occurs at Site 6. Hence, the vegetation growth response at Site 1 is likely to be particularly sensitive to changes in flood and groundwater management. The results suggest vegetation monitoring programs are likely to detect changes in canopy size related to vegetation health earlier at sites similar to Site 1 and should aim to detect changes which occur over the decades.

The simulations representing impacts of management options suggest that lowering the watertable by 1 m would have a greater beneficial effect on canopy growth than that caused by feasible increases in flooding frequency. This is because, with the flow volumes available, the peak flow enhancement strategy would cause only small changes in the total number of days flooded at the higher elevation sites. However, at Site 1 the leaf mass in all the scenarios was dying back under salinity stress at the end of each simulation. At Site 6 where the watertable was less saline the management scenarios appear to enable the vegetation to maintain a higher leaf area. Hence, the proposed management strategies are likely to have different effects depending on soil type and groundwater salinity. In some areas they may assist vegetation survive longer periods between major flood events but are unlikely to prevent die-back on their own. These induced changes in vegetation leaf area were still small relative to the effects induced by the prolonged period of flooding in permeable site.

To fully evaluate the management options, the site and soil specific understanding developed in this study needs to be extended across the whole floodplain. A GIS of the floodplain has been developed (Overton et al., 1994) which contains elevation, watertable depth, watertable salinity, soil type and vegetation cover. Future work will evaluate a simple quasi-steady state salt balance model which can be linked to the GIS, against the fully dynamic WAVES model.

5. Conclusions

Modelling indicates that soil hydraulic properties have a large influence on the magnitude and time scale of the growth response of salt stressed vegetation to floods and salt accumulation rates. Growth responses of stressed vegetation to large floods, as occurred in 1974–1976, were predicted to persist for up to 12 years on relatively permeable sites with highly saline groundwater. The growth response of the vegetation to a long term increase in watertable depth of 1 m was greater than that induced by a feasible increase in flooding frequency.

The simulations predict that changes in the average annual soil water availability which arise from flood events and soil salinisation, drive a long term cycle in the annual average transpiration rate per unit leaf area suggesting the soil-plant-climate system is adjusting towards a hydrological equilibrium but is not in equilibrium.

The proposed management options may control die-back on parts of the floodplain with more slowly salinising heavy clay soils. On relatively permeable soils with high salinity groundwater the groundwater pumping proposal may assist the vegetation to survive longer periods between the large flood events which are necessary to periodically leach accumulated salts from the root-zone. The dominant influence on vegetation health on these more permeable soils is likely to be the frequency of the large flood events.

The WAVES model has provided valuable insight into salinisation and vegetation growth processes over time scales and hydrological conditions which are impossible or difficult to evaluate experimentally. Dynamic soil-plant-atmosphere models enable the relative sensitivity of the vegetation to management options, represented by perturbing the hydrological conditions, to be evaluated.

References

Broadbridge, P., White, I., 1988. Constant rate rainfall infiltration: A versatile nonlinear model 1. Analytical solution. Water Resou. Res. 24, 145–154.

Dawes, W.R., Hatton, T.J., 1993. Topog-IRM. 1. Model description. Technical Memorandum 93/5. CSIRO Division of Water Resources.
Dawes, W.R., Short, D.L., 1993. The efficient numerical solution of differential equations for coupled water and solute dynamics: The WAVES model. Technical memorandum 93/18. CSIRO Division of Water Resources.
Eldridge, S.R., Thorburn, P.J., McEwan, K.J., Hatton, T.J., 1993. Health and structure of *Eucalyptus* communities on Chowilla and Monoman Islands of the River Murray floodplain, South Australia. CSIRO Division of Water Resources. Divisional Report 93/3.
Hatton, T.J., Wu, H., 1995. Scaling theory to extrapolate individual tree water use to stand water use. Hydrological Processes 9, 527–540.
Jolly, I.D., Walker, G.R., Thorburn, P.J., 1993. Salt accumulation in semi-arid floodplain soils with implications for forest health. J. Hydrol. 150, 589–614.
Jolly, I.D., 1996. Effects of river management on the hydrology and hydroecology of semi-arid floodplains. In: Anderson, M., Walling, D.E., Bates, P. (Eds.), Floodplain Processes. Wiley, London, UK.
Jolly, I.D., Walker, G.R., 1996. Is the field water use of *Eucalyptus largiflorens* F. Muell. affected by short-term flooding?. Aust. J. Ecol. 21, 173–183.
Larcher, W., 1980. Physiological Plant Ecology. Springer, Berlin.
Margules, Partners, Smith, P.J., Victorian Department of Conversion, Forests and Lands. (1990). River Murray riparian vegetation study. Murray Darling Basin Commission, Canberra, p. 187.
National Environmental Consultancy, 1988. Chowilla salinity mitigation scheme-draft environmental impact statement. Report prepared by National Environmental Consultancy for the Engineering and Water Supply Department of South Australia, Adelaide, SA, p. 166.
Ohlmeyer, R.G., 1991. Investigation of the feasibility of manipulating water levels in the River Murray. South Australian Engineering and Water Supply Department of South Australia, Adelaide. Library Ref. 91/11, p. 47.
Overton, I.C., Taylor, P.J., Hodgson, G., Correll, R.L., Hatton, T.J., Walker, G.R., 1994. The evaluation of a geographical information system for assessing the health of vegetation on a River Murray floodplain. In: Proc. Water Down Under 94, vol. 1. Institute of Engineers, Australian National Conference Publication No. 94/10, pp. 605–608.
Slavich, P.G., Hatton, T.J., Dawes, W., 1998. The canopy growth and transpiration model of WAVES: Technical description and evaluation. CSIRO. Technical Report No 3/98.
Streeter, T., 1995, unpublished data.
Thorburn, P.J., Hatton, T.J., Walker, G.R., 1993. Combining measurements of transpiration and stable isotopes of water to determine groundwater discharge from forests. J. Hydrol. 150, 563–587.
Thorburn et al., 1995.
Walker, G.R., Jolly, I.D., Jarwal, S.D., 1995. Salt and water movement in the Chowilla Floodplain. Water Resources Series: No. 15. CSIRO Division of Water Resources. Canberra.