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Modelling vegetation health from the interaction of saline groundwater and flooding on the Chowilla floodplain, South Australia

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Abstract. The native riparian vegetation communities on the Chowilla floodplain in the lower River Murray in South Australia are suffering severe declines in health, particularly the *Eucalyptus camaldulensis* Dehnh. (red gum) and *Eucalyptus largiflorens* F.Muell. (black box) communities. The primary cause of the decline is salinisation of the floodplain soils caused by increased rates of groundwater discharge and hence increased movement of salt up into the plant root zone. The salinity is driven by a lack of flooding and rising saline groundwater tables. Rises in the naturally saline groundwater levels are due to the effects of river regulation from Lock 6 and high inflows from regional groundwater levels increased by Lake Victoria to the east. River regulation has also led to reduced frequency and duration of the floods that leach salt from the plant root zone and supply fresh water for transpiration. The frequency of medium-sized floods occurring on Chowilla has been reduced by a factor of three since locking and water extractions were commenced in the 1920s to provide reliable water for urban and agricultural use. The soil salinisation on the floodplain was modelled by using a spatial and temporal model of salt accumulation from groundwater depth, groundwater salinity, soil type and flooding frequency. The derived soil water availability index (WINDS) is used to infer vegetation health and was calibrated against current extent of vegetation health as assessed from fieldwork and satellite image analysis. The modelling work has shown that there is a severe risk to the floodplain vegetation from current flow regimes. This paper estimates that 65% (5658 ha) of the 8600 ha of floodplain trees are affected by soil salinisation matching a field survey of vegetation health in 2003 (Department of Environment and Heritage 2005*a*), compared with 40% in 1993 (Taylor *et al*. 1996). Model results show that the best management option for Chowilla is lowering the groundwater down to 2 m below current levels, which predicts an improvement in the health of the floodplain tree species from 35 to 42%.

Introduction

Throughout the world, regulation of rivers by weirs and storages in order to provide reliable urban, industrial and irrigation water supplies has had profound hydrological and ecological side-effects on the rivers themselves and their adjacent floodplains. This is particularly the case in arid and semi-arid regions where the unique dynamics, structure and composition of floodplain vegetation are a direct result of the episodic flooding these areas experience naturally (Jolly and Walker 1996).

The native riparian vegetation communities on the Chowilla floodplain in the lower River Murray in South Australia are suffering severe declines in health. The primary cause of the decline is salinisation of the floodplain soils caused by movement of salt up into the plant root zone driven by evapotranspiration. Flooding has decreased and groundwater is closer to the surface since river regulation began in the 1920s. Rises in the naturally saline groundwater levels are due to the effects of river regulation from Lock 6, 1 of 12 flow-control structures on the lower River Murray. River regulation has also led to reduced frequency and duration of the floods that leach salt from the plant root zone. The frequency of large floods on Chowilla has been reduced by a factor of three since locking and water extractions and the last 5 years have been the worst on record. Taylor *et al*. (1996) estimated that in 1993 ~40% of the floodplain was affected by soil salinisation and this has increased to 65% in 2003 (Department of Environment and Heritage 2005*a*). The major tree species being affected are *Eucalyptus camaldulensis* (red gum) and *E. largiflorens* (black box). Large die-backs of black box trees have been anecdotally observed in the past and a current red gum dieback is affecting 80% of the trees (Murray Darling Basin Commission 2003).

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A proposal is being developed for a Salt Interception Scheme (SIS) at Chowilla that needs to be justified on the basis of salt-load decline and improvements to vegetation health. The development of the SIS is addressing the needs of reducing salt loads to the River Murray, along with the environmental benefits of lowering the watertable underneath the floodplain. A Chowilla Environmental Flows Management Plan is also being developed, along with a management plan for the Ramsar listed wetland, a wetland of international importance that includes Chowilla (Ramsar Convention 1987). Hence, there is a need for modelling tools to assist in the prediction of the impact of current and future river management on floodplain salinisation.

A spatial model for the floodplain has been developed to model the soil salinity over time from the interaction of groundwater salinity, groundwater depth, flooding frequency and soil hydraulic properties. The model is able to predict the soil salinity and, therefore, infer vegetation health from critical water availability for the different floodplain tree species. A number of management scenarios, including weir raising, groundwater lowering and enhanced flooding, were tested for their long-term impact on vegetation health.

The model has been validated against current vegetation health as assessed from fieldwork and satellite image analysis. Previous studies on the vegetation at Chowilla and its health have been used to build an overall picture of the whole floodplain. As a requirement for the modelling work a number of spatial layers required generation, including vegetation communities, vegetation health, soil hydraulic properties, groundwater salinity and groundwater depth. Many of these layers were available from previous spatial-modelling projects but required updating, given the declining vegetation on the floodplain, the spatial accuracy of these layers and the specific requirements of the modelling approach taken in this study.

Site description

The Chowilla floodplain is ~50 km east of Renmark, and is located on the borders of South Australia, New South Wales and Victoria (Fig. 1). The region has a semi-arid climate, receiving an annual rainfall of about 260 mm year^{-1} and a potential evaporation of about 2000 mm year^{-1}. Annual rainfall is highly variable and is distributed reasonably uniformly throughout the year with only slight winter dominance. The study site is defined by the extent of the 1956 flood, and has an area of ~17 400 ha. It is the largest remaining area of natural riverine forest in South Australia, and in addition to being a Ramsar site, is listed as one of the six major ecological assets along the River Murray under the Living Murray Initiative of the Murray Darling Basin Commission (Murray Darling Basin Ministerial Council 2002). The floodplain is also the second-largest contributor of salt to the river. The floodplain is typical of those in the lower reaches of the River Murray in that it is underlain

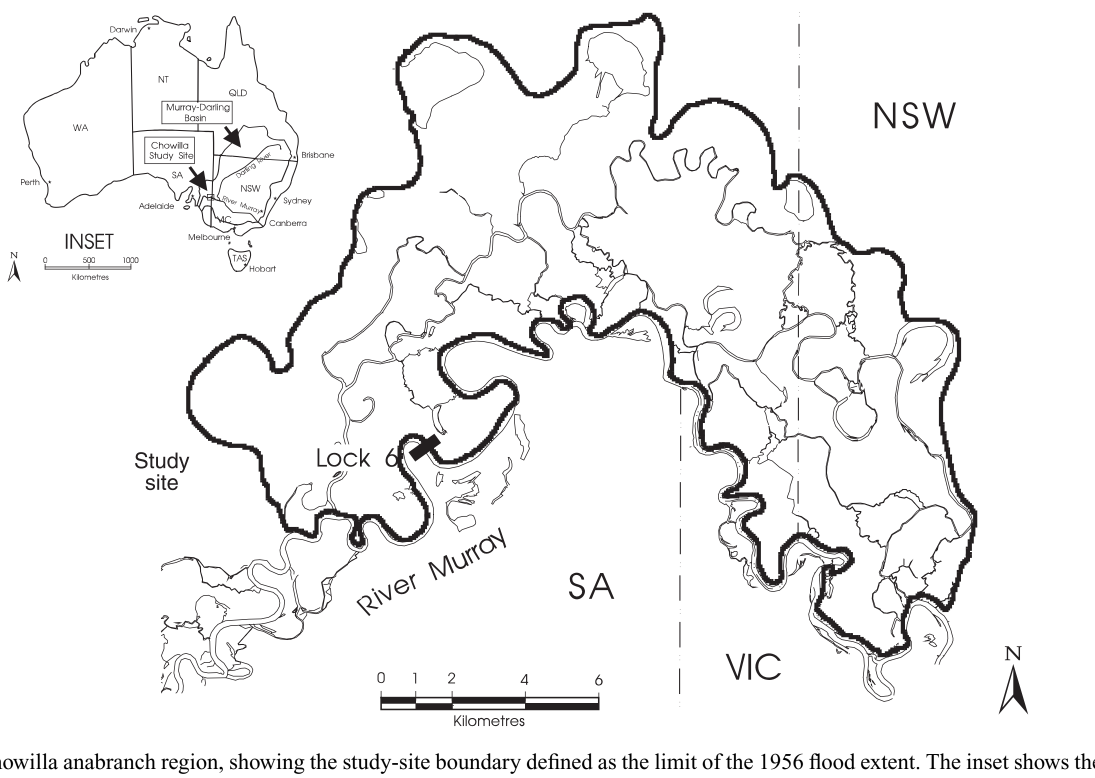

Fig. 1. The Chowilla anabranch region, showing the study-site boundary defined as the limit of the 1956 flood extent. The inset shows the position of the floodplain at the base of the Murray–Darling Basin.

by saline groundwater at depths of 2–4 m. This is in contrast with floodplains upstream, such as the Barmah Forest, that are generally underlain by deeper fresh groundwater (Jolly *et al*. 1994).

The floodplain has seen a large reduction in flooding frequency since the construction of the locks and weirs in the 1920s. Medium and large floods have been reduced by up to a factor of three from natural conditions (Ohlmeyer 1991). This has led to large-scale dieback of floodplain and creek-edge vegetation. Gippel and Blackham (2002) described the environmental impacts of the changing flow regime in this region.

The distribution of the riparian vegetation is closely linked to the flooding frequency governed by surface elevation (Margules and Partners 1990). Black box is the dominant species on the floodplain, covering ~37% of the area (Noyce and Nicolson 1993). In the lower lying areas of the black box, the trees are associated with lignum (*Muelenbeckia cunnunghamii*), in higher areas with ephemeral grasses (many species), and in those areas infrequently flooded they are associated with perennial saltbushes (*Atriplex nummularia*, *A. Rhagodioides* and *A. Vesicaria*) (Hollingsworth 1990). In the low-lying areas along the river channels, river red gum dominates. Above the level of the black box, native pines and chenopod shrublands exist, extending to the mallee regions beyond the floodplain. River Cooba (*Acacia stenophylla*) occurs throughout the floodplain in isolated areas and is found in association with red gum and black box. Smith (1989) noted that although the flooding regime may be the most important factor determining vegetation patterns on a local scale, on the broader scale it is soil salinity that appears to have the dominant effect. Currently, ~35% of the floodplain trees are considered in good health (Department of Environment and Heritage 2005*a*). Many areas of non-tree vegetation are in poor condition, with increasing occurrence of saltbush species. Many wetlands too are slowly changing from ephemeral wetland environments to floodplain halophytic communities.

The floodplain is covered by a layer of alluvial clay known as the Coonambidgal Clay (Hollingsworth 1990). The clay can be up to 5 m thick close to existing or prior creek beds. The clay is absent on the high areas of the floodplain and the beds of the creeks. Jolly *et al*. (1994) noted that the presence and thickness of the clay is an important controlling factor on the hydrology and vegetation of the floodplain. The Coonambidgal Clay overlies an unconsolidated alluvial sand deposit known as the Monoman Sands.

Groundwater flow into the aquifer underlying the floodplain (Monoman Formation) comes mainly from the regional saline Parilla Sands aquifer (electrical conductivity (EC) of ~60 dS m^{-1}), with some upward leakage from the fresher confined Murray Group Limestone aquifer (EC ~40 dS m^{-1}) (Barnett and South Australian Department of Mines and Energy 1991). The average groundwater inflow is about 5 ML day^{-1}, resulting in a salt load to the Murray of about 120 t day^{-1} (45 000 t year^{-1}) (Sharley and Huggan 1995). The groundwater is found at shallow depths (<5 m) under most of the floodplain. The Chowilla floodplain acts as a groundwater sink for the naturally saline regional aquifers of the western Murray Basin. The salinity of the groundwater is fresh in some areas of the floodplain where the surface clay layer is absent. These areas act as recharge zones freshening the groundwater. The groundwater is also fresher in areas that are close to the river where the pressure of the high river levels forces recharge of the adjoining aquifer (the flushed zone). In other areas the salinity, measured as EC, ranges from 35 to 85 dS m^{-1} (Noyce and Nicolson 1993). Flooding causes only limited freshening of the groundwater within the alluvial Monoman Formation aquifer (Jolly *et al*. 1992*a*).

Review of modelling floodplain salinity impacts on vegetation health

Salt accumulates in the floodplain soils as a result of capillary rise of water transporting the natural salts to the surface. This involves shallow groundwater being drawn up and either evaporated at the surface, or used by the trees. The salt is left behind in the upper soil layers where it slowly accumulates. Studies have indicated that there is very little leaching of this salt under the current flooding regime (Jolly *et al*. 1994; Akeroyd *et al*. 1998). Before regulation, this upper part of the soil profile was leached free of salt by floods that came approximately every 4 years. However, since regulation, the frequency of floods of sufficient size to carry out this freshening has been greatly reduced. Medium-sized floods (60 000–100 000 ML day^{-1}) have been decreased by a factor of between two and three, following river regulation (Ohlmeyer 1991). Second, locking has led to rises in groundwater, which have accelerated the rates of groundwater discharge and hence salt accumulation. For example, a soil profile with a depth to groundwater of 4 m would take 20 years to reach a level of salinity that is detrimental to black box health, compared with a soil profile that has a depth to groundwater of 3 m and would take 5–7 years to reach such critical levels.

A number of factors affect the extent of soil salinisation, including the salinity of the groundwater, groundwater depth, flooding frequency and soil texture. All these factors vary across the floodplain. The spatial nature of groundwater depth and flooding frequency are of particular interest as these affect the balance in water movement through the soil profile and are affected by flow management and river regulation. Groundwater is generally saline except for the flushed zone near Lock 6 and isolated recharge zones.

Owing to the low rainfall and high potential evaporation of the semi-arid climate and the predominantly saline groundwater, black box and red gum on the floodplain rely on periodic flooding for fresh water and leaching of salt stored in the profile. Taylor *et al.* (1996) remarked that as a consequence of this, black box is adapted to be relatively tolerant to drought conditions, high salinity and prolonged waterlogging. A number of studies (e.g. Hollingsworth 1990; Jolly *et al.* 1993*a*, 1993*b*; Thorburn 1993; Mensforth *et al.* 1994) showed that soil salinity is a major factor affecting the health of floodplain trees. The combination of a semi-arid climate with surface clay soils of low permeability means that, generally, there is little leaching of salt between floods. Consequently, the dieback of black box and red gum is attributed primarily to water stress caused by a combination of 'osmotic drought' (resulting from high soil salinities) and a reduction in water supply (owing to less frequent flooding).

Black box and red gum use groundwater for survival in dry times, provided that salt levels are not excessive. Where the salt levels of the groundwater are excessive the trees must draw their water from the upper soil levels and they become sensitive to salt accumulation (Jolly *et al.* 1993*a*, 1993*b*). Jolly *et al.* (1992*b*) found that at sites where groundwater salinity was less than 40 dS m^{-1} the black box was generally healthy. The salinity level is lower for red gum, as they are less salt tolerant than black box. Above this value health was found to be variable. The depth to groundwater was also found to affect tree health. They suggested that a critical depth to groundwater existed and this was dependent on flooding frequency. This was shown to be consistent with soil-salinisation processes, in that a critical depth to groundwater exists, at which there is no vertical movement of salt through the soil profile. As flooding frequency increased, the critical depth to groundwater decreased. For areas that only flood at a peak flow rate of 100 000 ML day^{-1} or more, this critical depth is about 4 m for black box (Jolly *et al.* 1992*b*) and for areas that flood more frequently, it is between 2 and 3 m. Most black box exists on the higher parts of the floodplain where depth to groundwater is rarely less than 2 m. The black box in areas flooded by flows of less than 82 000 ML day^{-1} (1 in 10 years), in general, appear to be healthy. Taylor *et al.* (1996) observed that the black box on the dunes (sandy soils) appear healthy, although not tall, in contrast to those on the clay which appear taller but not as healthy. The threshold levels for red gum are less well known but are likely to be similar. The lower tolerance to salinity and the need for more frequent flooding are the main differences between red gum and black box.

Environmental threshold model

Previous attempts to apply a model to tree health on a floodplain scale have considered the use of the critical threshold values of the main factors that affect black box health (Hodgson 1993; Noyce and Nicolson 1993; Taylor *et al.* 1996). Further modelling with the class/threshold concept, (Overton *et al.* 1995) found that the spatial matching of known health to modelled health by using the common agreed threshold values for groundwater salinity, groundwater depth and flooding frequency was 69%, using total area matching in the GIS. Although the GIS class model is useful for vegetation mapping, it is less useful for predicting the effects of changes in management. This is because classes are relatively broad and do not give any indication of the degree of health.

Steady-state moving-salt front model

Modelling vegetation health in shallow watertable environments requires an understanding of the interaction between the physical and biological factors that determine the rate of root-zone salinisation. The root-zone salinisation rate is determined by the net groundwater discharge rate (vertical discharge minus recharge) and the groundwater salinity. Groundwater discharge can occur by evaporation at the soil surface or by vegetation water use. The rate of groundwater discharge from bare soil depends only on the hydraulic properties of the unsaturated zone, whereas that from vegetated areas is affected by both soil hydraulic properties and vegetation characteristics, such as leaf area, the maximum rooting depth, the profile distribution of soil water uptake and the physiological tolerance to salinity. The relative importance of biological and physical factors can be understood through the use of unsaturated flow and vegetation water-use models.

The groundwater discharge rate, and hence soil salinisation rate, can be modelled with varying degrees of 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. With these assumptions the potential groundwater discharge from the soil surface can be modelled by using only soil hydraulic properties (Warrick 1988). Warrick (1988) showed that the maximum upward water flux from a given watertable depth could be represented with 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) that is driven by transpiration of groundwater (Jolly *et al.* 1993*b*). This approach can be used to predict the effect of the salt front position on the groundwater uptake rate and to estimate the time scale for complete salinisation of soils on the Chowilla floodplain.

Jolly *et al.* (1993*b*) showed that although the salt front within the profile of a given soil may vary throughout the year in response to flooding, rainfall, water extraction by vegetation and groundwater fluctuations, over the long-term a dynamic salt 'balance' generally exists in which there is no net accumulation or leaching of salt. This balance will be different on different soils, with more leaching on light-textured sandy soils and less on heavy clayey soils.

A full description of the derivation of the balance equation is given in Jolly *et al*. (1993*b*). 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.

An index of soil salinisation and therefore, black box health, was derived by Jolly *et al*. (1993*b*) and can be summarised as

$$\mathrm{S} = W^{-n}/z. \tag{1}$$

The soil salinisation index (S) is derived from the three major factors that affect the health, flooding frequency (represented as the fraction of time inundated (W)), groundwater depth (z) and soil texture (represented by a soil texture variable (n)) (Eqn 1). This index can be used in areas of saline groundwater (with an EC greater than 40 dS m^{-1}). The advantages of using Equation 1 to give an index on soil salinisation over the threshold classes, is that it provides a value that can change with changing conditions. It therefore gets over the limitations of the class model and allows the predictions of soil salinisation with varying management options.

Temporal and spatial modeling–dynamic WAVES model

The assessment of management options for the floodplain requires a model that can predict changes in vegetation health resulting from small changes in the flooding regime and the groundwater depth. The balance models described above are steady-state models of the long-term salt balance. The models are not dynamic and there is no current way of predicting groundwater depth changes over time. A feature of the groundwater hydrology of the Chowilla floodplain is that the watertable can fluctuate several meters with changes in river level.

WAVES is a one-dimensional daily time step, soil–vegetation–atmosphere model that simulates the movement of water and salt in soils as well as plant water use and growth, responding to climatic changes, flooding frequencies and fluctuating water tables (Dawes *et al*. 1998). WAVES has been employed to evaluate groundwater discharge under transient conditions associated with fluctuating watertables and seasonal changes in climate, transpiration and soil moisture. The WAVES model may also be used to evaluate the conditions for which the assumptions of the simpler steady-state MSF model are satisfied. WAVES was first applied at Chowilla by Slavich *et al*. (1999*b*) and was shown to be useful for predicting Chowilla floodplain vegetation health. However, it requires a large range of parameters and cannot be easily implemented within a spatial framework.

Quasi-steady-state moving salt-front model

Slavich *et al*. (1999*a*) further developed the concept of the moving salt-front (MSF) model by combining limiting vegetation characteristics, soil hydraulic properties and flood history to develop a salinity index which is indicative of vegetation health. The parameters for this quasi-steady-state MSF can be feasibly represented within a GIS of the floodplain. Some of the soil hydraulic parameters of the WAVES model are incorporated into the MSF model so that long-term simulations with a fluctuating watertable can be compared with similar simulations conducted using WAVES.

The flood history was modelled by defining flood recharge and discharge periods and assigning a weighting factor to these periods on the basis of their duration and time since the present. This weighting factor was combined with a salinisation index that relates the height of a salt front above the watertable. The combined index related well to the weighted temporal average leaf area index modelled by using WAVES, giving confidence for using the quasi-steady-state model for management scenarios within the GIS.

Materials and methods

WINDS—GIS quasi-steady-state moving salt-front model

The methodology adopted previously to extend the MSF model to include a weighting component for the effects of previous floods was incorporated into the GIS by Overton *et al*. (1997). This provided a spatial model of vegetation health that considered the impact of flooding history. The parameters used within the GIS model are similar to the ones used for the steady-state MSF model. The model outputs are highly susceptible to changes in the initial salinity of the soil water at the beginning of the period and on the soil hydraulic parameters. These have to be estimated as the starting conditions are unknown. In 1956, the largest flood since the 1890s, occurred and lasted approximately 18 months. Therefore, 1957 is used as the starting point in the model and initial soil salinities are set on the assumption that most of the soil salinity would have been leached out by this flood.

WINDS (weighted index of salinisation) is calculated by the following steps within a GIS. Step 1 is to calculate the groundwater discharge rate (q):

$$q = A(Z_{\mathrm{w}})^{p}, \tag{2}$$

where A and P are soil parameters and Z_{w} is the groundwater depth. Previous studies (Jolly *et al*. 1993*b*) have used Z_{w} minus Z_{f} (the depth of salt front) in Eqn 2 but it proved an unnecessary detail for this model.

Step 2 is to calculate the soil salinity for each 5-year time period ($C_{\mathrm{s_i}}$)

$$C_{\mathrm{s_i}} = C_{\mathrm{s_{i-1}}} + C_{\mathrm{g}}/Z_{\mathrm{wmax}}(q \times t_{\mathrm{d}}/q_{\mathrm{d}} - K_{\mathrm{s}} \times t_{\mathrm{s}}/q_{\mathrm{s}}), \tag{3}$$

where C_{g} is the groundwater salinity, Z_{wmax} is the maximum water table depth, t_{d} is the number of days not flooded (dry), t_{s} is the number of days flooded (saturated), K_{s} is the saturated hydraulic conductivity and q_{d} and q_{s} are the soil water content during discharge and flooding periods, respectively.

Step 3 is to calculate soil water availability for each 5-year time period ($X_{\mathrm{w_i}}$):

$$X_{\mathrm{w_i}} = 1 - (C_{\mathrm{s_i}}/C_{\mathrm{lmin}}), \tag{4}$$

where $C_{\mathrm{s_i}}$ is the soil salinity for that time period and C_{lmin} is the limit of the soil salinity the plants can withdraw water against.

Step 4 is to calculate cumulative X_{w} for last 15 years (WINDS index):

$$\mathrm{WINDS} = X_{\mathrm{w_i}} \times W_{\mathrm{i}}, \tag{5}$$

where X_{w_i} is the average soil water availability for each time period and W_i is the weighting factor for each time period (0.55 for the last 5 years, 0.30 for the previous five years and 0.15 for the first 5 years). Figure 2 demonstrates the moving salt-front theory and the calculation of a WINDS index over time.

The calculations are performed with the parameters discussed below and a WINDS index between 0 (dead) and 1 (good health) is produced. The index is actually a measure of the soil water availability but it is indicative of the tree health. Trees in an environment of highly saline soil water at their root tips will have less water available to be used by the tree for transpiration and will, therefore, have limited health potential. For the purposes of this model, and for floodplain management in general, vegetation health is considered as the canopy condition of the trees. It does not reflect on other factors of vegetation health such as recruitment. The WINDS value is therefore a value of the osmotic stress that the plant perceives in the soil profile. The other major impact on vegetation health in this environment is likely to be matric potential stress from drought conditions.

The WINDS model incorporates matric potential stress by using a threshold time period of 5-year drought as a critical period when vegetation health will decline. The WINDS index is reduced by 0.3 (to ensure that all good vegetation with a WINDS of 1 will move to the poor category of 0.7 or less) following a period of 5 years with no flood or freshwater recharge in those areas identified as using freshwater reserves from bank recharge or freshwater lenses. This is a highly simplified approach to drought stress and will be improved in future versions of the model.

Model parameters and spatial datasets

A number of previous investigations and reports on Chowilla have provided spatial and non-spatial datasets. The data included the flooding extent from nine flood events (Sharley and Huggan 1995), and the flood inundation model to predict the extent of inundation from flows at every 1000 ML day^{-1} step (Overton *et al*. 1999; Overton 2005). Groundwater salinity data are from field observations linked to the spatial extents of low-salinity areas. One low-salinity area is the 'flush zone' where fresh water from the river recharges the groundwater laterally through the river bed (Collingham 1990). Other low-salinity areas were observed by using airborne geophysical data from the soil surface. These areas delineated the 'flush zone', mapped as 5 dS m^{-1}EC, along creek edges freshened by lateral recharge of fresher creek water into the soil profile, mapped as 18 dS m^{-1} EC, and sandy high areas of the floodplain that act as recharge areas with high infiltration rates creating 'freshwater lenses' on the saline groundwater, mapped as 18 dS m^{-1} EC. All other parts of the floodplain have a groundwater salinity of 55 dS m^{-1} EC. Initial conditions for soil salinity were mapped as 5 dS m^{-1} EC in all of these recharge areas and 18 dS m^{-1} EC in other areas of the floodplain. Groundwater depth was provided by Yan *et al*. (2005) from a MODFLOW model.

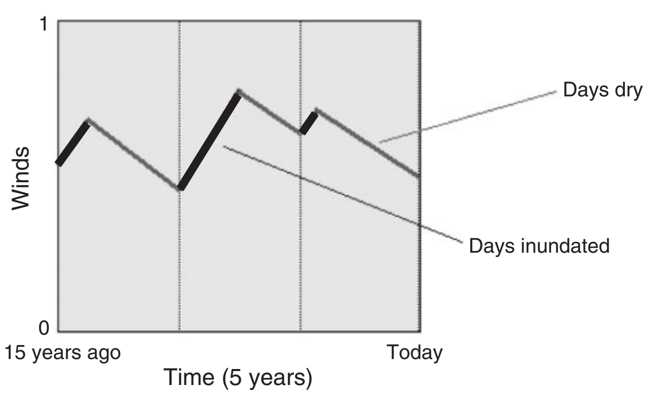

Fig. 2. A graph of WINDS over a 15-year period, showing the increasing soil water availability during floods, and decreasing availability during drought.

The floodplain vegetation was recently surveyed by Department of Environment and Heritage (2005*a*) for the South Australian side and Department of Sustainable Natural Resources (2003) for the New South Wales side. The vegetation mapping had to be merged and some refinement of the areas were edited to distinguish Red Gum and Black Box from mixed Red Gum/Black Box classes (Overton and Jolly 2004). The health of the tree species was recorded in 1993 (Taylor *et al*. 1996) (Fig. 3) and again in 2003 (Department of Environment and Heritage 2005*a*) (Fig. 4). A soil survey had been conducted to map landscape units and soil types (Hollingsworth 1990), and an elevation map was available from an airborne laser survey. A number of remotely sensed images were also available including Landsat TM imagery and aerial photography for assessment of current and historic conditions.

The spatial data generation process required a combination of GIS analysis and integration of existing data, the spatial generation of existing non-spatial data and the generation of new spatial data by cartographic procedures. The major datasets that were developed included vegetation community type, vegetation health, soil-limited groundwater recharge, groundwater depth and groundwater salinity. The methodology for generating these layers can be found in Overton and Jolly (2004). The community map was simplified to generate the limiting salinity-tolerance map used in the WINDS vegetation health modelling discussed later.

The WINDS modelling approach assumes that current tree health is indicative of the soil water available to the plant during the last 15 years, with greater emphasis on the last 5 years, and decreasing each 5-year period. This is likely to be true for black box trees that respond very slowly to flood events. WAVES modelling has shown an approximate 10-year response time to a major flood event (Overton and Jolly 2004). Red gum trees will respond much quicker to flood events than black box and also decline much quicker during droughts.

The WINDS model parameters included the number of days inundated from 1957 to 2003. The number of days inundated and dry during 5-year periods from 1957 to 2003 was calculated from recorded hydrographs (Fig. 5). The starting date of 1957 was chosen as this was the end of a very large flood, the 1956 flood is the largest on record and was estimated at over 350 000 ML day^{-1}. This allowed some prediction of the starting soil salinities. Rainfall amounts for each 5-year period were taken from a nearby rainfall gauge and the effective rainfall was expressed in terms of equivalent flooding days and further divided by a factor of 10 to estimate the effective rainfall infiltrating the soil profile and apposed to the rainfall evaporated, washed-off or used by surface vegetation.

Future river flows are difficult to predict as they are reliant on climatic variation. The methods chosen here were to repeat the last 5 years (which have been the worst on record and very relevant, given that they represent current conditions) and to repeat the last 15 years. A management scenario using increased flows from an enhanced flow regime was also modelled. The flow-enhancement scenario used was a 750 GL day^{-1} release strategy from water recovery proposed under the Living Murray MDBC Program (Murray Darling Basin Ministerial Council 2002). A hydrograph for the last 15 years, had the 750 GL day^{-1} enhancement strategy been in operation, is presented in Fig. 5 and was used as the future flow scenario for this management option.

The soil salinity limit for healthy red gum was set at 30 dS m^{-1} EC and for black box the threshold was set to 55 dS m^{-1} EC. These numbers represent a conservative limit of healthy trees that equates to the osmotic potential that these plants can handle, to successfully extract water from the soil. The salinity of the water available to the plants is determined by the ability of the plant to lower the root water potential below that of the adjacent soil, causing water to move down

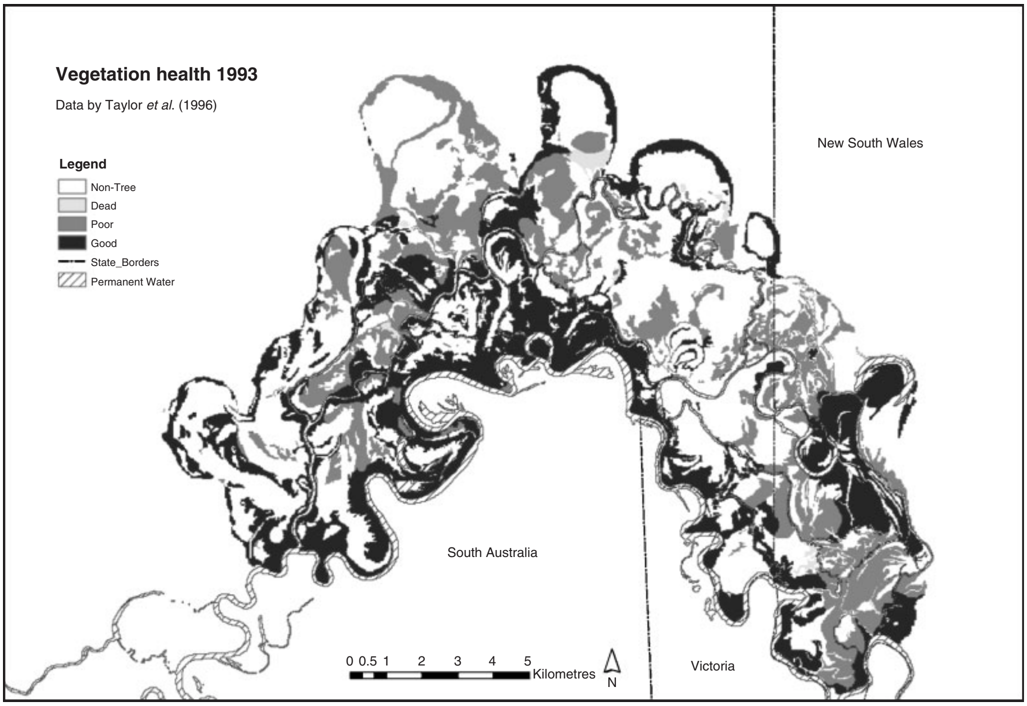

Fig. 3. The 1993 vegetation-health map for Chowilla, showing the tree health of the three major tree species classified as good or poor/dead (Taylor *et al*. 1996).

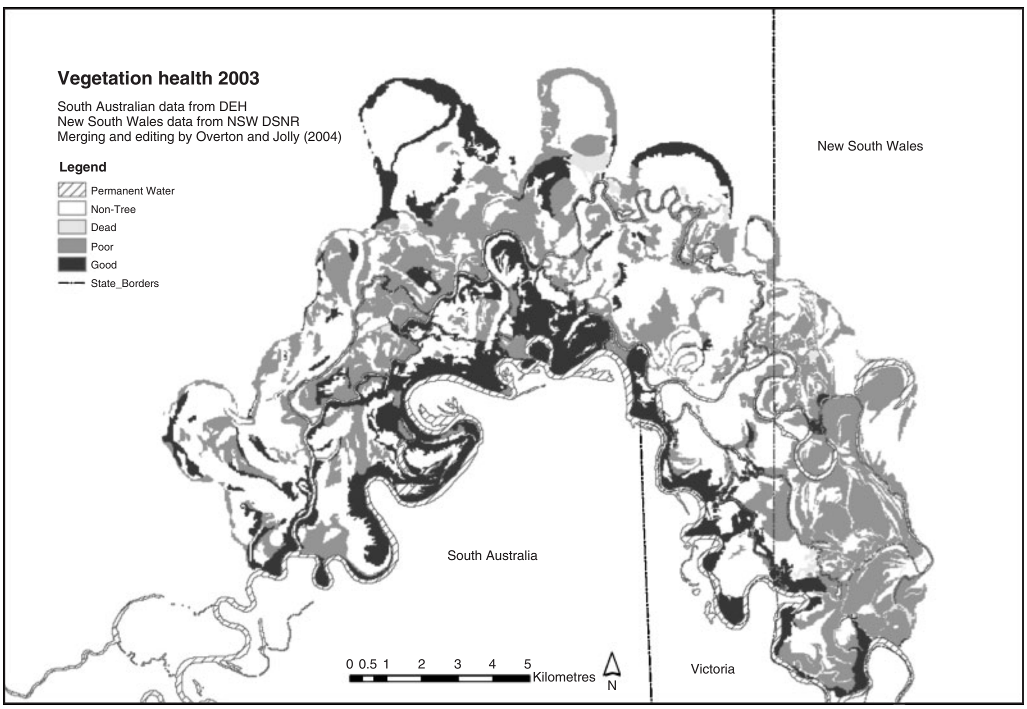

Fig. 4. 2003 Vegetation-health map for Chowilla, showing the tree health of the three major tree species classified as good, poor and dead (Department of Environment and Heritage 2005*a*; Department of Sustainable Natural Resources 2003; Overton and Jolly 2004).

the hydraulic gradient from the soil into the plant. The minimum predawn water potential measured for black box trees growing on the River Murray floodplain is $\psi_{\mathrm{lmin}} = -3.5$ MPa (Eldridge *et al*. 1993; Zubrinich *et al*. 2000). This corresponds to a threshold osmotic potential for extraction by black box (C_g) of -3.0 MPa, or a groundwater salinity approximating seawater salinity (~60 dS m^{-1} EC). Similarly,

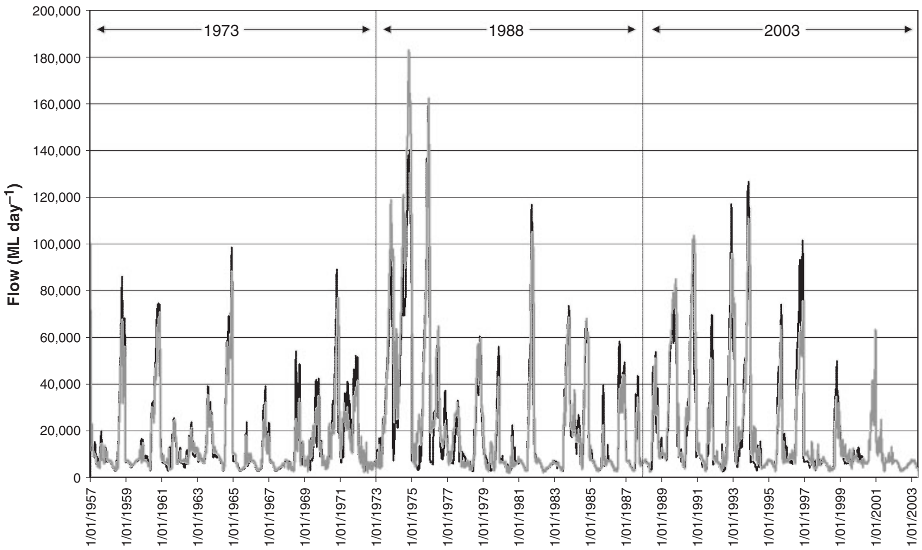

Fig. 5. Living Murray Initiative of the Murray Darling Basin Commission proposed flow strategy to increase flows by 750 GL day^{-1}. The hydrograph represents actual flows (grey) and enhanced flows (black). The graph clearly shows the dry period observed in the last 5 years. The top lines indicate the time period that was used for the 1973, 1988 and 2003 predictions.

the minimum predawn water potential measured for red gum growing on River Murray floodplains is $\psi_{lmin} = -2.2$ MPa (Mensforth *et al.* 1994). This corresponds to a threshold osmotic potential for extraction by red gum (C_g) of -2.0 MPa, or a groundwater salinity approximating half seawater salinity (~30 dS m^{-1}EC).

Results

From the starting conditions the WINDS model was run for each 5-year time step from 1957 to 2003. The first step in the WINDS calculation is to predict the average soil salinity in the profile. Figure 6 shows the soil salinity map for Chowilla and is a useful step in assessing the impacts of salt accumulation on the whole floodplain, including non-tree vegetation. Complete results for all simulations are given in Overton and Jolly (2004) and only the key results are presented here.

The results were then classified into the three health classes of dead, poor and good. The predicted tree health results for 1993 (Fig. 7) show that 54% of the floodplain vegetation is in poor health or dead, compared with the estimate of 40% in 1993 (Taylor *et al.* 1996) (Fig. 3). The predicted tree health for current conditions (Fig. 8) show that 65% of the floodplain vegetation is in poor health or dead, compared with the same percentage recorded by field assessment in 2003 (Department of Sustainable Natural Resources 2003; Department of Environment and Heritage 2005*a*).

The results for 2003 (the most accurate vegetation health mapping) show that there is a 74% spatial matching between the predicted health *v.* the recorded health (Table 2). The classes have a $\chi^2 = 1.18$ ($n = 1$, $P < 0.05$) and are therefore statistically significant. The area of incorrect prediction is equally distributed between areas recorded as good but predicted as bad and areas recorded as bad but predicted as good. As vegetation health was mapped at a 1 : 10 000 scale of homogenous areas, and not at the same scale as the 30 m by 30 m pixels of the WINDS model.

Once the WINDS model parameters had been validated for 1994 and 2003, a number of future predictions and management scenarios were run. The future predictions of the model cannot of course be tested. Generally, the health of the woody trees on the floodplain is predicted to decrease over time if there is no increase in the frequency of floods over the flow regime of the last 15 years.

A prediction for 30 years (up to 2033), with the last 15 years of flows repeated twice, show a decrease in the percentage of healthy trees form 35 to 32% (Table 3). It is unlikely that the future hydrograph will be exactly the same and there may be a wetter or dryer period approaching.

The first management scenario tested was the raising of Lock 6 weir pool during the late spring period each year. The low flow conditions meant that the effect of the weir raising of 50 cm above pool level did not achieve overbank flow in most of the years. Consequently, the improvement in vegetation health over the 30 years is negligible.

Another major management option is to increase the frequency of floods. The vegetation health improvements from the '750 GL day^{-1} enhanced-flow regime' were predicted, with 36% of the tree community expected to be healthy in 2033. An inspection of the hydrograph shows that the amount of extra water is small and even though floods are extended in magnitude, the number of floods makes only minor differences to the number of days inundated.

The final management scenario tested was the lowering of groundwater levels to decrease the salinisation process. A groundwater pumping scheme needs to be developed

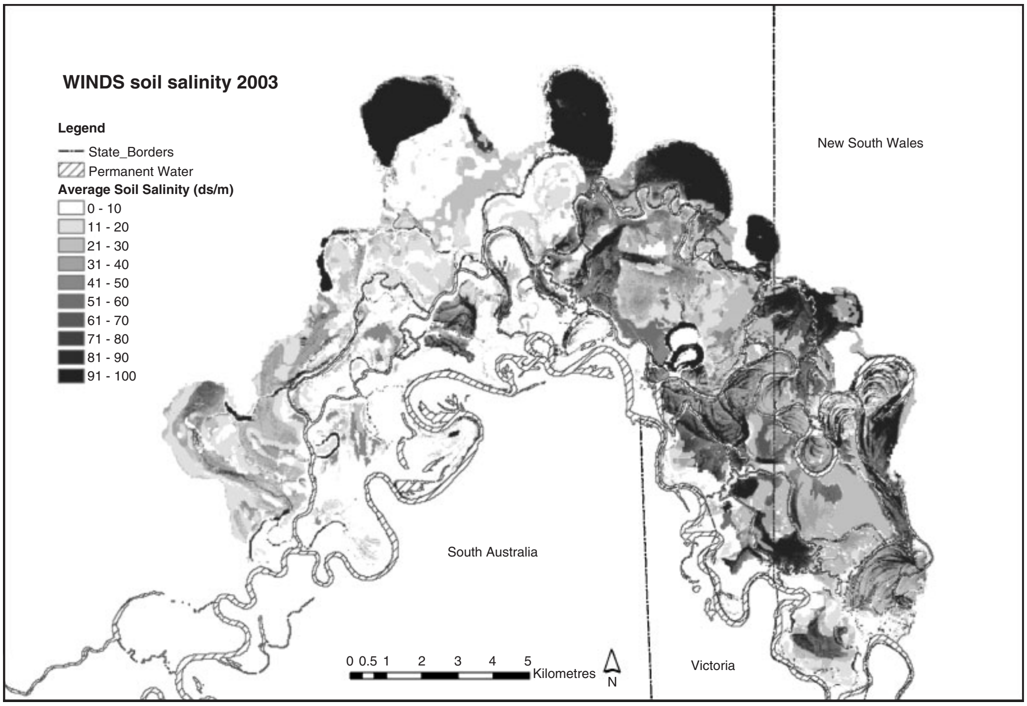

Fig. 6. WINDS soil salinity predicted for the Chowilla floodplain (2003). The WINDS value indicates the vegetation health and can be grouped into classes by comparison with the mapped health classes (Department of Environment and Heritage 2005*a*). Table 1 shows the mean and standard deviation of WINDS values for each mapped health class. A WINDS value of 0 or below indicates no soil water present and would mean dead trees. WINDS values >0 to 0.7 indicate poor trees, and good trees have a WINDS value >0.7 to 1. The critical class break of 0.7 was determined by producing the best overall matching of modelled and mapped health classes. Table 1 shows the dead health class as having a mean and standard error of -0.39 ± 0.02, for the poor class the WINDS mean and standard error is 0.30 ± 0.001 and for the healthy class, 0.54 ± 0.003.

Table 1. WINDS values per mapping health class (2003)

WINDS mapping	WINDS mean value	WINDS s.d.	Count (*n*)
Dead	−0.39	0.88	2020
Poor	0.30	0.62	60 468
Good	0.54	0.71	33 230

to lower groundwater across the floodplain and reduce the saline groundwater entering the anabranch creeks. The draw-down cones of the pumps will create an uneven surface for groundwater lowering; however, to simplify the modeling, a constant draw-down of 2 m was modelled for the entire floodplain. The results of this show the best improvement in vegetation health, from 35% healthy in 2003 to 42% healthy in 2033. The effect of lowering groundwater is to reduce the rate of soil salinisation; however, this will not remove the salt already in the soil profile. Therefore, areas that are flooded frequently respond well as they then leach salt after the balance between the upward movement and downward movement of water is changed. The major areas of improvement are the areas that had very shallow groundwater (within 2 m) but that under this scenario would have groundwater deeper than 2 m and hence have a much reduced rate of soil salinisation.

A summary of the current and future predictions for the tree health at Chowilla is presented in Table 3.

Discussion

The WINDS model has distinct advantages over previous models of the floodplain vegetation health in that it is able to provide vegetation-health predictions at any particular time and can be used to show the possible effects of manipulating groundwater and flow regimes. The model has been shown to predict the majority of spatial patterns of vegetation health by modelling soil salinisation and a simple drought factor.

The major findings of the study, and their implications are the following:

- the simple moving salt-front balance model for soil salinisation incorporated in the WINDS modelling has produced a good correlation with observed vegetation health (74% spatial matching);
- there are areas of the floodplain that have highly salinised soil profiles but are also high in elevation, suggesting that the soil structure has changed. These areas require large floods to leach the salt and are therefore unlikely to be converted to good health unless irrigation methods are used;

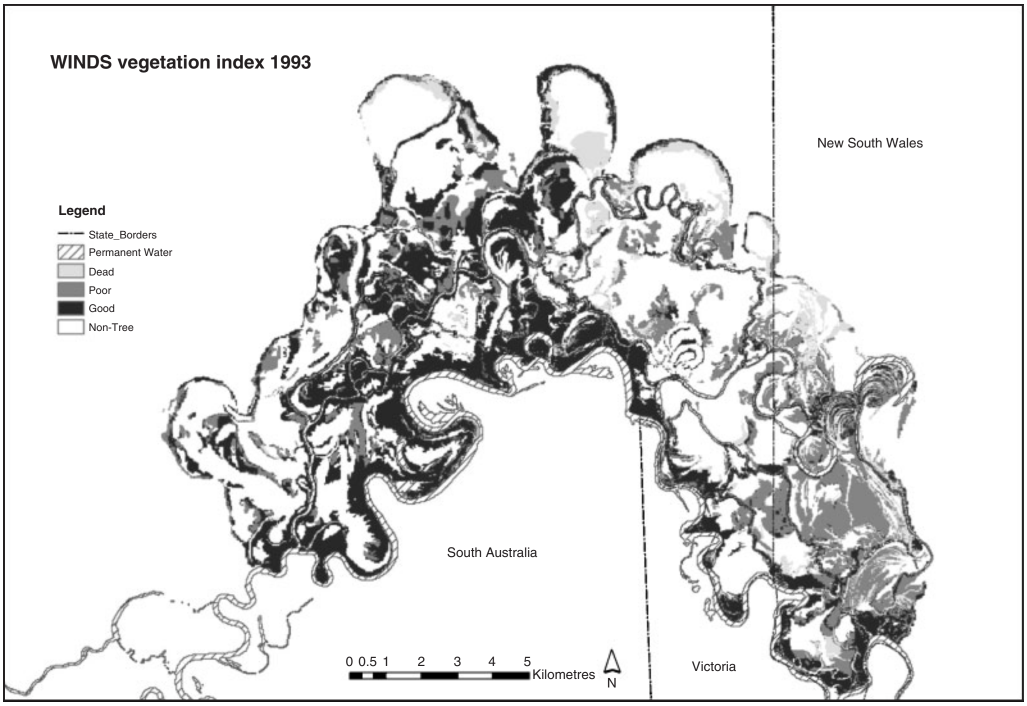

Fig. 7. Vegetation health prediction for tree species (1993). A WINDS index of less than 0 relates to dead trees, 0–0.7 to poor trees and 0.7–1 to healthy trees.

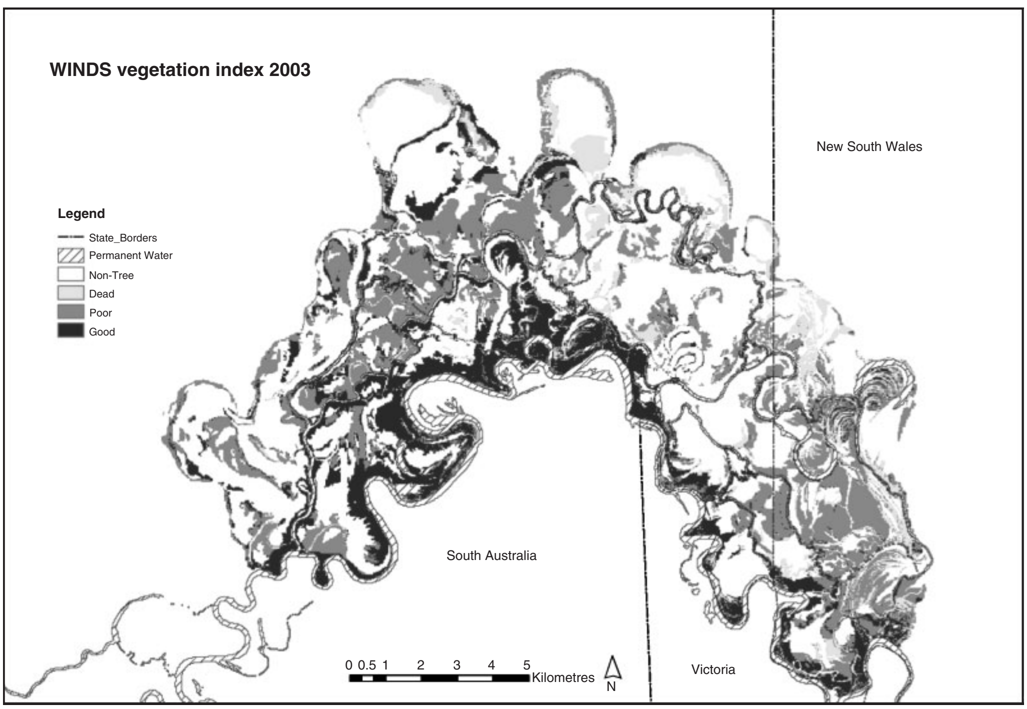

Fig. 8. Vegetation health prediction for tree species (2003). A WINDS index of less than 0 relates to dead trees, 0–0.7 to poor trees and 0.7–1 to healthy trees.

Table 2. Results for WINDS modelled and actual mapped health classes (DEH) in 2003

The spatial matching (%) values refer to the percentage of trees in each combination class; area is given in hectares

Mapping	WINDS Good	WINDS Poor/dead	Total
Good	1904 ha, 22%	1202 ha, 14%	3107 ha, 35%
Poor/dead	1145 ha, 13%	4525 ha, 52%	5669 ha, 65%
Total	3049 ha, 35%	5727 ha, 65%	8776 ha, 74%

- catastrophic events, such as the red gum dieback observed in the summer of 2003 (Murray Darling Basin Commission 2003), can be predicted once the critical thresholds for drought are known;
- there will be major declines in black box communities, along with red gum communities, in the next 5 years if we have similar flows in the river; and
- enhanced flow regimes and groundwater lowering will improve the vegetation health of the tree communities (a 20% improvement from groundwater lowering in 30 years); however, it will take a long time to restore full health to the floodplain under these management options.

Limitations and accuracy of the model

The mapping and modelling work has simplified the spatial variability of the floodplain into distinct classes and polygons that depict homogeneous environments and vegetation. The reality is that there can be large variability in soil types, groundwater depth, salinity and vegetation health at a large scale. Small distances can see large differences in depth of overlaying clay affecting soil hydraulic properties, groundwater salinity and depth. It is not uncommon to see a live tree in the middle of a patch of dead trees, and *vice versa*, with no visible cause. It is likely that the spatial variability of soils can be attributed to these health differences and our aim has been to model the patch as a whole, with an average health prediction.

WINDS uses a constant groundwater depth which does not change over time, even during flooding and drying cycles. In real flood events the groundwater does rise to become closer to the surface and could therefore affect vegetation in these areas, especially if they did not actually receive surface flooding. After flood events the groundwater levels drop to pre-flooding conditions. Given the short time frame of most flood events, and the complexity of modelling required to simulate a fluctuating water table, a stable groundwater surface has been used.

Groundwater discharge rates are driven by evaporation and average transpiration, without varying transpiration rates based on tree species and density. The vegetation growth and health are not modelled directly but inferred from the soil water availability. The model operates on a 30-m pixel size and provides the soil water availability for that area regardless of tree density. For a given soil water availability within this 900-m^2 area, 10 trees may be healthy whereas 50 trees, through competition for resources, could be poor. Moreover, the model assumes that no structural damage occurs to the trees during poor conditions and the age structure is not considered. The time lag of tree response to available water may not be modelled correctly.

In this study, the major factor influencing soil water availability is assumed to be the osmotic potential from the soil salinity, whereas the matric potential from the water content in the soil profile can be the cause of decline in some areas, despite salinity values within the threshold limit. In areas of low salinity, such as the edges of creeks and localised recharge areas, groundwater is often the most important water source. The current WINDS model has only a very simple drought factor that reduces the WINDS value following a 5-year drought. This area of the model will be improved by using a water budget approach.

The average wet and dry days over a 5-year period is a simplification of the dynamic upward and downward movement of the salt front on a more frequent basis. The variability in soil type is not truly represented at the scale of the mapping. Individual trees that show health different from the surrounding area are likely to be in small pockets of present or absent clay and the spatial

Table 3. Results for current and future predictions

Future predictions are based on the last 15-year flows repeated twice

	Dead		Poor		Good	
	Area (ha)	% Trees	Area (ha)	% Trees	Area (ha)	% Trees
1993	775	9	3187	37	4652	54
2003	1638	19	4020	46	2958	35
Do-nothing (2033)	1674	20	4086	48	2756	32
Weir raising (2033)	1671	20	4088	48	2757	32
Flow enhancement 750 GL day^{-1} (2033)	1635	19	3853	45	3127	36
2-m groundwater lowering (2033)	1188	14	3822	44	3605	42

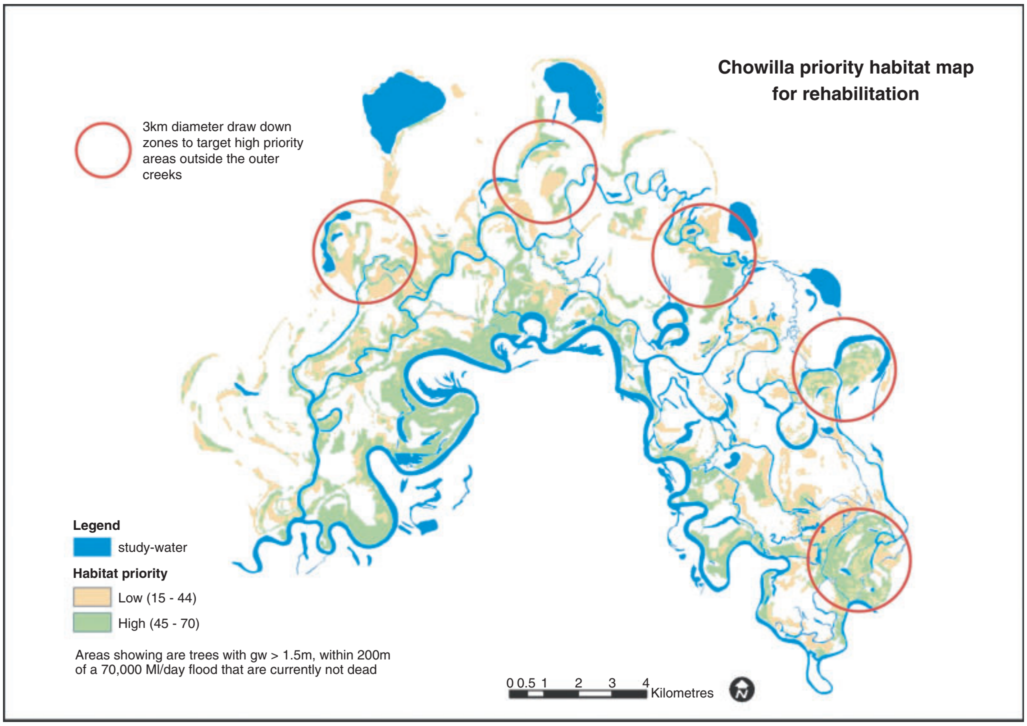

Fig. 9. An example of the use of the Department of Environment and Heritage (2005*b*) biodiversity rating in combination with the environmental risk modelling to prioritise areas for rehabilitation.

accuracy of the elevation map does not model the local variations that can cause single trees to die/survive in good/poor areas.

In summary, the results of the WINDS modelling are indicative of the potential health trends arising from salinity stress. WINDS only considers moisture stress in a simple way and does not account for potential changes in other factors, such as seedling recruitment, insect attack or natural senescence.

Management options

The management of the floodplain needs to consider the soil-salinisation rates and salt loads to the river from the shallow groundwater and the lack of water availability from reduced flooding frequencies. Lowering groundwater reduces the rate of soil salinisation and benefits will be achieved even in areas where the water table is drawn down a metre or two. The reduction in the soil-salinisation rate does not improve vegetation but only slows its rate of decline. Areas where the rate of soil salinisation can be reduced may be considered as 'flow ready' and their health may improve with flooding. Management options that increase only flooding frequency will still improve vegetation health, even though groundwater levels have not been lowered, because the ratio of leaching to discharge has still been increased. Increasing flooding without groundwater lowering is risky as it is reliant on the frequency of floods. These areas will quickly decline if a drought period occurs.

Further analysis of the model results can lead to the identification of target areas for management options. The areas of poor vegetation health on the floodplain can be managed on the basis of groundwater pumping or flow enhancement, or both. These areas can be depicted spatially and compared with priority areas identified on the basis of conservation value and social considerations. An example of using the model in this way is shown in Fig. 9, where the predicted map of vegetation health is combined with the biodiversity conservation value map of the Chowilla floodplain (Department of Environment and Heritage 2005*b*) to show how the WINDS modelling can be used to identify areas that can respond to groundwater lowering and environmental flows within economical limits. This economical limitation of groundwater lowering by 2 m and environmental flow strategies for flows under 70 000 ML day^{-1} is purely an example for presentation purposes. These are no real limits determined from any study and the first stage for prioritising areas should be to identify the best areas from a biodiversity value viewpoint and then to determine what is required to save these areas. A management combination of both lowering groundwater and increasing flooding frequency is likely to be required to conserve the majority of the Chowilla floodplain.

Conclusions

The results from the WINDS model for current and past years have shown that it is useful for modelling floodplain vegetation health. It is therefore considered a useful tool for predicting impacts from future scenarios and to inform policy for floodplain protection and salinity mitigation. Three management scenarios have been modelled, raising the Lock 6 weir pool, lowering groundwater by 2 m and a 750 GL day^{-1} enhanced flow regime, and results compared with future 'do-nothing' scenarios. The weir raising has little effect in the low-flow conditions of the past 15 years. The effect of lowering the water table reduces the rate of soil salinisation but does not remove salt from the profile. Flow enhancement reduces salt but leaves the vegetation susceptible to degradation should a drought occur as it has not addressed the rate of salinisation. The best benefit comes from a combination of the last two options. Major improvements in vegetation will take many years to achieve under these management options and flow requirements are likely to be greater than natural for some time. If a drought period occurs, such as in the last 5 years, the decline in vegetation will be dramatic.

The results of this study need to be considered in the light of the modelling limitations. The major limitation being that the results are indicative of the potential health trends from trees responding slowly to changes in soil-salinity stress. Although this is believed to be the major cause of health decline, other factors such as moisture stress, competition, regeneration, senescence, insect attack or extreme climate conditions are not considered fully (Jurskis 2005). Further work on the WINDS model could include better incorporation of the matric potential of the soil by modelling the soil water content and the further implications of drought periods on the vegetation. Including non-tree vegetation-health assessment (based on the soil salinity predictions from the WINDS model) and other factors such as recovery from stress, regeneration and senescence would also be beneficial. Population dynamics will be important in long-term future predictions. The current model can predict a suitable water availability for maintaining healthy trees but cannot comment on the sustainability of a population.

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