

Quantifying water savings from willow removal in creeks in south central NSW

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Abstract

Willow infestation in creek systems in eastern Australia has become a major environmental problem. In south central New South Wales, various willow species, including weeping willow (*Salix babylonica*), have spread along creek systems and, in many locations, now occupy the stream banks, floodplains and stream bed. The government owned corporation, Water for Rivers, commissioned a two stage project to quantify the net impact on evapotranspiration of removing willow trees from creeks used to transport irrigation water. In stage one of the project, evapotranspiration from the stream bed and banks with and without willows was modelled over a 12 year period (1986 to 1997) using the Penman-Monteith equation. However, lack of literature on willow stomatal behaviour meant willow water use was only simulated within broad confidence limits. Rainfall interception, and soil and surface water evaporation were also modelled. Predicted mean annual evapotranspiration, per hectare of willow projected crown area was 1250 to 1900 mm year⁻¹ (12.5 to 19 ML ha⁻¹ year⁻¹) across a range of assumed stomatal responses to vapour pressure deficit (VPD). The simulated net water saving from willow removal was in the range -5 to +9 ML ha⁻¹ year⁻¹ of willow projected crown area, depending on stomatal behaviour and the proportion of willow crown area shading water compared to dry creek bank.

In stage two of the project, evapotranspiration from willows and nearby natural riparian vegetation was monitored over the August 2005 to May 2006 growing season. Sap velocities in eleven willow (*Salix babylonica*) and six river red gum (*Eucalyptus camaldulensis*) trees were scaled to canopy-level estimates of daily transpiration based on measurements of stand conducting wood area. Results indicated a large difference in transpiration between willows in the stream bed and those only 5-10 meters away on the drier banks. Maximum daily transpiration of 15.2 mm was recorded in willows in the permanently inundated stream bed compared to only 2.3 mm for slightly more elevated willows on banks, and 1.6 mm for the riparian red gum vegetation on the bank. These results indicate that the amount of water taken up by willows from the stream system varies considerably depending on their location. The field data will be used to revise the modelling predictions from stage one, to improve the estimate of potential net water savings achievable by willow removal.

Introduction

Willows were introduced into Australia during the 1800's for a range of purposes including stream bank stabilisation, production of materials to make baskets and cricket bats, and shelter. However, willow infestations are now extensive along creeks in south central New South Wales and elsewhere, with substantial adverse impacts on stream and wetland hydrology and biodiversity. Invading willows, forming dense stands of trees or shrubs with extensive, thick root mats, can cause destruction of indigenous vegetation communities, elimination of faunal habitats, alteration of stream hydrology, decreased water quality and increased water use from the stream (Thorp, 2001).

In southern New South Wales, the Yanco Creek system (Figure 1) has become extensively willow infested, primarily with *S. babylonica* which were originally planted for shade and bank stabilisation. These willows have spread from the stream edge to the natural floodplain of the creek and into the stream-bed. The Yanco Creek System Natural Resource Management Plan identifies willow infestation as a major environmental issue. Actions 3.5 (A) and 3.5 (B) of the

plan call for the preparation and approval of an operational plan for the removal of willows from the creek, including bank stabilisation and a revegetation program.

The Yanco Creek system (Figure 1) forms part of the effluent regime of the Murrumbidgee River. It is a complex water system, supplying water to at least eight towns and numerous private irrigators in the region. The Yanco Creek System Natural Resource Management Plan seeks to identify current water losses from the system and institute rehabilitation works in order to save 36 GL year⁻¹ which can potentially be returned to the river. Without these savings, irrigators might be forced to reduce their water allocations.



Figure 1. Map of the Yanco Creek System

Water for Rivers, a private company established by the Federal and NSW and Victorian State Governments to invest in water saving projects, believes there is potential to undertake a large-scale willow eradication program along the Yanco, Colombo and Billabong Creeks. At the current value of water licenses, net water savings resulting from willow removal might equate to sufficient funds to undertake such a program (Phil Deamer, Water for Rivers, pers. comm.). Water savings might arise directly from reduced evapotranspiration, and indirectly from improved hydraulic efficiency of the creek. The research reported here only considers the direct water saving arising from reduced evapotranspiration.

To assess the potential water savings from willow removal, Water for Rivers commissioned a two stage project to quantify the net impact on evapotranspiration of removing willow trees from creeks used to transport irrigation water. Stage One of the project consisted of a literature review and desk-top modelling of willow water use, while stage two involved a field study of willow and natural riparian red gum water use.

Materials and Methods

Stage one: desk top analysis

The Penman Monteith model was used to simulate evapotranspiration, with and without willows, per unit of willow crown projected area in the climate of Deniliquin, NSW. To run the simulations, data on leaf area index (LAI; maximum and seasonal variation), maximum stomatal conductance (which can also be expressed as minimum stomatal resistance) and the relationship between stomatal conductance (or resistance) and atmospheric water vapour pressure deficit (vpd) were sought from the literature.

Very little data useful for modelling the water use of *S. babylonica* in southern Australia was available. Only three studies referred to this species and only one reported water use measurements, the results of which were considered doubtful. There were no reliable estimates available for water use or leaf area index for *S. babylonica* in any environment. Maximum LAI for dense willow stands of *S. viminalis* is reportedly 7 (Iritz *et al* 2001, Lindroth *et al* 1994). To our knowledge, there have been no measurements of the maximum stomatal conductance of willows or the relationship between stomatal conductance and atmospheric water vapour pressure deficit. The highest daily transpiration rate of 10 mm was recorded in southern UK (Hall *et al* 1998) where maximum evaporative demand is less than in south central NSW. This compares with daily maximum transpiration rates of 7 mm that have been observed in well-watered eucalypts and 8 mm in *Pinus radiata* in southern NSW (Benyon *et al.* 1996). As a result of the lack of data on willow stomatal behaviour, it was necessary to model willow water use for a wide range of stomatal behaviour.

Various attributes of evapotranspiration were simulated using daytime solar radiation, daily average air temperature, average relative humidity between 6 am and 6 pm, sunshine hours and 24-hour wind run. A 12 year sequence (1986 to 1997) of actual daily weather data from Deniliquin, a nearby town (Figure 1), was used to run the model. Daily water use was predicted based on these weather conditions and assumed resistances to evaporation imposed by the atmosphere (aerodynamic resistance) and the tree canopy (canopy resistance).

Canopy resistance (r_s) of trees depends on their leaf area (expressed as leaf area index, LAI). It shows a marked diurnal variation and therefore requires complex models to estimate. Trees also moderate the environmental effect on evapotranspiration through opening and closing of stomata. Canopy resistance is, therefore, also a function of factors that affect stomatal conductance such as radiation, air saturation deficit and soil moisture stress. Raupach (1991) expressed the relationship of r_s to these variables in an empirical equation:

$$r_s = \frac{r_{s(\min)}}{f_R(R_s)f_D(D)f_W(W)f_L(L)} \quad [1]$$

where

$r_{s(\min)}$ is the minimum value of the canopy resistance under optimal growth conditions
and

R_s is solar radiation

D is saturation vapour deficit

W is soil water deficit

L is leaf area index

f_R , f_D , f_W , and f_L are dimensionless functions which vary between 0 and 1

Reduced transpiration is caused by lower incoming solar radiation, higher saturation deficit, higher soil water deficit and lower LAI. Threshold values for reducing transpiration can typically be: solar radiation of 350 W m^{-2} (Leuning *et al.* 1991); saturation deficit of $0.020\text{-}0.035 \text{ kg kg}^{-1}$

(Hookey *et al.* 1987, Raupach 1995) and LAI of 3.0-3.5 (Dunnin and Aston 1984, Persson 1995).

A range of values for minimum canopy resistance ($r_s(min)$) from 12 to 36 s m⁻¹ and threshold saturation vapour deficit from 0.01 to 0.05 kg kg⁻¹ were used in a sensitivity analysis to examine the variation in willow water use. This gave 16 model runs. Available data on the variation in willow LAI with season were not applicable to the Yanco Creek. Leaf flush in *S. babylonica* in southern Australia reportedly begins in September. There is no precise information on when leaf shed occurs. From observations of willow stands along Billabong Creek, it does not occur until late May. For the simulations of water use it was therefore assumed a significant increase in LAI begins on September 15th, reaching the peak of 7 by December, declining to 0.1 on June 1.

Simulated evapotranspiration following willow removal

It was assumed removal of willows would result in a substantial increase in the amount of net radiation reaching the water and soil surfaces that were previously shaded by the willows. To determine the net change in evapotranspiration after willow removal, evaporation was simulated from the stream surface and stream banks assuming no shading by willows. Open water evaporation was simulated as defined by Penman (1956), and the Penman Monteith equation was used to estimate evaporation from open water using values for $r_s(min)$ ranging from 0 to 6 s m⁻¹, and for threshold saturation vapour deficit ranging from 0.01 to 0.05 kg kg⁻¹. It was assumed that evaporation from exposed, bare soil on the banks would equal 60% of rainfall. To estimate the net water saving from willow removal, we undertook sensitivity analysis to determine the effect of variation in the proportion of willow projected crown area shading open water and non-saturated bare soil. Simulations were run using four different ratios of water surface area to bare soil surface area shaded, ranging from 1:0 (willows only shading open water and wet soil), to 1:1 (willows shading an equal area of open water and dry soil). It is possible willows in some creeks shade more dry soil than water, but this was not simulated.

Stage two: field study

Stage two of the study consisted of a field experiment measuring water use by willows and natural riparian *E. camaldulensis* in order to verify the predictions of the desk top study. Two measurement plots 30 m long and 10 m wide were established on the 2nd of August 2005, along the edge of a section of Billabong Creek to the east of Jerilderie (Figure 1). One plot, occupied mainly by willows, extended from the approximate willow crown edge on the western creek bank, east towards the centre of the creek for 10 m. Due to rising and falling water levels, this plot was at times partially or completely inundated during spring, but for much of summer and autumn was largely dry. A second plot, representing a non-infested length of creek, was solely occupied by river red gums. As the red gums were slightly higher up the bank, this plot was never completely inundated, and for most of the time was entirely above the creek water level. An additional plot of willow trees in the permanently saturated part of the creek was measured in February 2006 to enable conducting wood area of willows in this wetter environment to be determined.

Evapotranspiration measurements (tree water use, canopy interception of rainfall and evaporation from bare soil) were collected from each plot, from which estimates of approximately monthly total evapotranspiration were derived using:

$$ET = I + T + E_{bank} + E_{wat}$$

Where: ET = total evapotranspiration
I = rainfall interception loss

T = tree water use
E_{bank} = soil evaporation from non-saturated soil along the creek bank
E_{wat} = modelled evaporation from the shaded open water surface and saturated soil

All values can be expressed either in mm or ML ha⁻¹ of willow or red gum projected crown area. E_{bank} and E_{wat} were weighted according to the approximate proportion of the plot occupied by free water and unsaturated soil, which varied over time as creek levels rose and fell.

Climate

A weather station (Monitor Sensors, model J950805C, Caboolture, Queensland Australia) was established in an open area at the site to collect measurements of temperature, wind speed, wind direction, relative humidity, solar radiation (hourly means) and rainfall (hourly totals). In addition a standard rain gauge was installed and rainfall measured each time the site was visited (approximately monthly).

Interception

Canopy interception of rainfall was estimated based on measurements of throughfall. Throughfall is the component of rainfall which falls or drips through plant canopies to the ground. In each plot, throughfall was measured using five randomly located collection troughs. These were 90-degree, V-shaped pieces of aluminium, each 1.20 m long by 0.14 m wide, draining into a collection drum. The volume of water collected in each drum was measured each visit and converted to a depth in mm. Interception loss was calculated as rainfall minus throughfall. To be accurate, estimates of interception based on measurement of throughfall should also include measurements of stem flow, as a small amount of rainfall will usually reach the soil by flowing down the tree stems. However, due to the large size of some of the red gum stems and the very twisted and leaning form of many the willow stems (some were horizontal), we did not attempt to measure stem flow. Our estimates of interception are therefore probably slightly too high. As rainfall in this environment is low (<400 mm year⁻¹), the effect of not accounting for stem flow is likely to have made a difference of <20 mm year⁻¹ to our estimates of total evapotranspiration.

Evaporation

Soil evaporation was measured in each plot using three mini lysimeters. Each lysimeter contained a soil column collected *in situ* to 0.27 m deep. Net rainfall for each lysimeter was measured with a standard rain gauge situated beside the lysimeter. Drainage through the lysimeter was collected and measured. Evaporation from the soil column for each measurement period (approximately 1 month) was estimated on the basis of rainfall in, drainage out and the change in weight over the period. Total evaporation was then calculated as the average of the evaporation calculated from each lysimeter.

Water table evaporation lysimeters, which simulated evaporation from soil with water tables at 0.15 m and 0.30 m depth, were also installed beneath the tree canopies. One 0.15 m and 0.30 m water table was simulated in each plot where a soil column collected *in situ* was mounted on a saturated sand table to represent the presence of a water table. Each month, the water reservoir was refilled to the same level and evaporation from the lysimeter was estimated based on incoming rainfall and the change in water volume from the reservoir.

It was not possible to measure evaporation of water from under the willows in the inundated part of the creek bed. Instead this was estimated conservatively from measurements of evaporation rates from wet soil under dense pine plantation canopies (LAI ~8) near Mt Gambier, South Australia, and scaled up slightly to allow for higher solar radiation at Jerilderie. An alternative in future might be to measure evaporation rates using evaporation pans located beneath the trees

and in the open, with a scaling factor to account for higher evaporation from a pan compared to a larger water body.

Open water evaporation

Evaporation directly from unshaded open water was estimated based on pan evaporation at Deniliquin and multiplied by 0.9 to account for lower evaporation from a large water body compared to an exposed evaporation pan.

Transpiration

Transpiration was initially measured continuously in six trees per plot using sapflow sensors (model SF300, Greenspan Technology, Warwick, QLD). Each sapflow sensor system has four sensor heads, which each measure sap flow velocity at a point within the tree stem by injecting a 2 s pulse of heat into the sapwood every 30 minutes. To select the sample trees from each plot, the stem diameter 1.3 m along the stem from the base of each tree was measured and stem basal area over bark calculated. Plot total basal area was also calculated and trees in each plot were classified into three size classes, with each class containing a third of the total plot basal area. Two trees per size class were randomly selected for sapflow measurement, to total six trees per plot.

Estimates of wound size around the drill holes were based on previously measured values (Benyon 1999) and were assumed to be 3.0 mm for eucalypts and willows. Wood and water volume fractions of sapwood were determined using 5 mm diameter cores. Heat pulse velocities were converted to sap velocities after Swanson and Whitfield (1981) and Edwards and Warwick (1984). To account for radial variation, the sapwood area was divided into four concentric rings of equal area, and one sensor was located at a random depth and azimuth within each ring, after Benyon (1999). Zero flows were identified using the method described by Benyon (1999). Tree mean sap velocity was calculated as the average of the four sample points within the tree. A check of the technique was conducted by removing a moderate-sized willow branch, placing it in a bucket of water and recutting the branch underwater to restore xylem sap flow. Over a 24 hour period, total water loss from the bucket, which also included a small amount of evaporation, was 0.93 L, compared with 0.83 L estimated using the heat pulse technique, indicating the heat pulse technique is appropriate for this willow species.

Sapwood thickness was determined using the sap flow sensors after Hatton *et al.* (1995) and Benyon (1999), at the start, mid way through and at the end of the project. Tree sapwood area at the sapflow measurement height was determined based on measured stem diameter, bark thickness and sapwood thickness. For trees in which sap velocity and sapwood thickness were not measured, sapwood area was estimated based on a regression with tree basal area over bark. Plot sapwood area was calculated by summing the estimated sapwood areas of all trees in the plot. Plot daily transpiration was estimated as the product of the 24 hour mean sap velocity (6 am to 6 am) of the sample trees and plot sapwood area.

All the sapflow sensors installed in the willow stems and three of the six in the red gums were removed on 19 September 2005 due to high river levels which threatened to submerge and damage the equipment. They were reinstalled on 19 October 2005 when the water had receded.

By December it became apparent the willows on the edge of the stream above the creek line were becoming water stressed, as indicated by their poor physical health and vigour and slightly lower tree water use than the natural riparian vegetation and visibly low leaf area index compared with willows in the permanently wet part of the creek. The study was expanded on 13 December when one set of sapflow equipment (four sensors) was moved from one of the willows on the bank to a tree that stood in the streambed and was permanently surrounded by

creek water. In addition, sapflow sensors were installed in a new plot in the permanently inundated creek bed in a dominant willow tree. On 8 February sapflow sensors were installed in a further three willows in the permanently wet part of the creek. Measurements in the six red gums, five of the original six willows, and the additional five 'wet' willows continued until May 18 when most of the willow leaves had yellowed prior to leaf fall.

Crown Projected Area

Crown projected area of the original willow plot and the red gum plot was estimated by measuring the distance from the plot edges to the edge of the willow crowns at 2 m intervals. The second willow plot was located within a large area of continuous, dense willow cover, so crown projected area was assumed equal to plot area.

Results and discussion

Stage one: desk top analysis

Simulated evapotranspiration from willows

The results of the 16 simulations of evapotranspiration from willows are listed in Table 1. Predicted mean annual evapotranspiration ranged from 1250 mm year⁻¹ if willows have low maximum stomatal conductance and high stomatal sensitivity to VPD (vapour pressure deficit), to 1900 mm year⁻¹ if willows have high maximum stomatal conductance and low stomatal sensitivity to VPD. This compares to expected evaporation from an unshaded water surface of 1700 to 1800 mm year⁻¹ and 240 mm year⁻¹ from non-saturated bare soil. Across the range of values of minimum stomatal resistance and stomatal sensitivity to VPD tested, minimum stomatal resistance had a greater influence on water use; there being almost a 500 mm year⁻¹ difference between the lowest and highest values tested for $r_{s(min)}$, compared with only about 200 mm year⁻¹ difference between the highest and lowest values for threshold saturation vapour deficit.

For comparison, near Deniliquin NSW, Polglase *et al.* (2002) observed annual evapotranspiration of ~1400 mm year⁻¹ in a 4-5 year old *Corymbia maculata* (spotted gum) plantation which had access to groundwater of low salinity at ~3 m depth. Maximum transpiration rates in summer were ~7 mm day⁻¹, whereas Hall *et al.* 1998, observed maximum daily transpiration rates of 10 mm day⁻¹ in willows in southern UK. Our simulations of willow water use gave estimates of mean daily evapotranspiration in January (the month with the highest evapotranspiration), ranging from 6.6 to 9.3 mm day⁻¹. The higher maximum daily transpiration from willows in the UK in a less evaporative environment suggests willows have higher stomatal conductance than spotted gum, and that annual water use of willows is likely to be closer to the middle or upper range of our model simulations, unless they have a high stomatal sensitivity to vpd.

Table 1. Simulated mean annual evapotranspiration, mm year⁻¹. Includes rainfall interception loss, transpiration and surface water and soil evaporation

Threshold sat. vap. deficit (kg kg ⁻¹)	Minimum stomatal resistance (s m ⁻¹)			
	36	24	18	12
0.010	1250	1440	1570	1740
0.013	1300	1490	1620	1780
0.026	1410	1600	1710	1860
0.052	1480	1660	1770	1900

Simulated evapotranspiration following willow removal

The simulations produced estimates of mean annual evaporation from unshaded water of 1720 to 1820 mm year⁻¹. Thus if minimum stomatal resistance of willows is moderate to high, willow annual water use is predicted to be lower than evaporation from an open water surface.

Evaporation from unsaturated bare soil was predicted to be 240 mm year⁻¹. Therefore a large difference in evapotranspiration between willows having unlimited access to water from the creek, and evaporation from bare soil on the creek banks was predicted. Removing willow crowns from above bare soil was predicted to save between 10.1 and 16.6 ML ha⁻¹ year⁻¹. Taking this into account, Figure 2 illustrates the simulated mean annual water savings under each scenario, showing the relationship between simulated willow annual water use and net annual water saving for ratios ranging from willows shading only water to willows shading an equal area of water and dry soil.

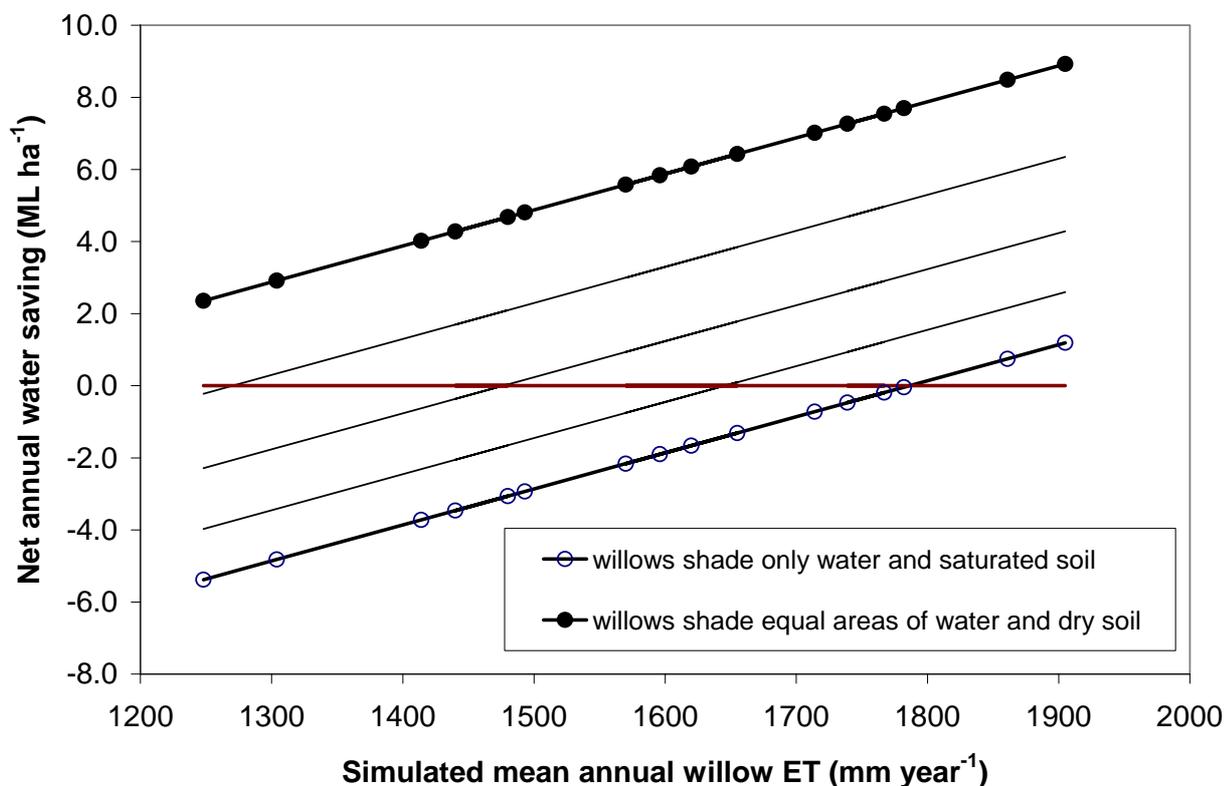


Figure 2. Simulated net annual water saving from willow removal for different ratios of shading of open water/wet soil to dry soil

The simulations indicated that if the willows are shading water and saturated soil but not dry soil, willow removal would only result in a net reduction in evapotranspiration if willow stomatal conductance is in the upper range of values tested. It was predicted that, even at the highest likely rate of willow evapotranspiration, willow removal would only deliver net water savings of 1 ML year⁻¹ for each ha of willow crown projected area removed.

However, if the willows are shading equal areas of water/saturated soil and dry soil, even at the lowest rate of willow evapotranspiration, the net water saving delivered by willow removal was predicted to be 2 ML ha⁻¹ year⁻¹. For this scenario, the water saving for the mid range of predicted willow water use was 4-6 ML ha⁻¹ year⁻¹. For an intermediate scenario whereby willow water use is moderate and willows shade twice as much water/saturated soil as they do dry soil, the net water saving from willow removal would be 2-4 ML ha⁻¹ year⁻¹.

Stage two: field measurements

The results of the field study were unexpected and contrary to the assumptions of the desk-top modelling. Daily transpiration rates of willow trees and red gums located on the creek banks were substantially lower than expected (Fig. 3), indicating neither had unlimited access to creek water as we had assumed. This discovery led to the project expansion from mid December, to include daily transpiration measurements of willows permanently surrounded by water, situated in the creek bed. We extrapolated back to mid October based on regression relationships relating daily sap velocities in willows in the creek to sap velocities in willows on the creek bank. We did not extrapolate back to August because of the missing willow data during the flood period and because we had no data from willows in the creek bed in early spring.

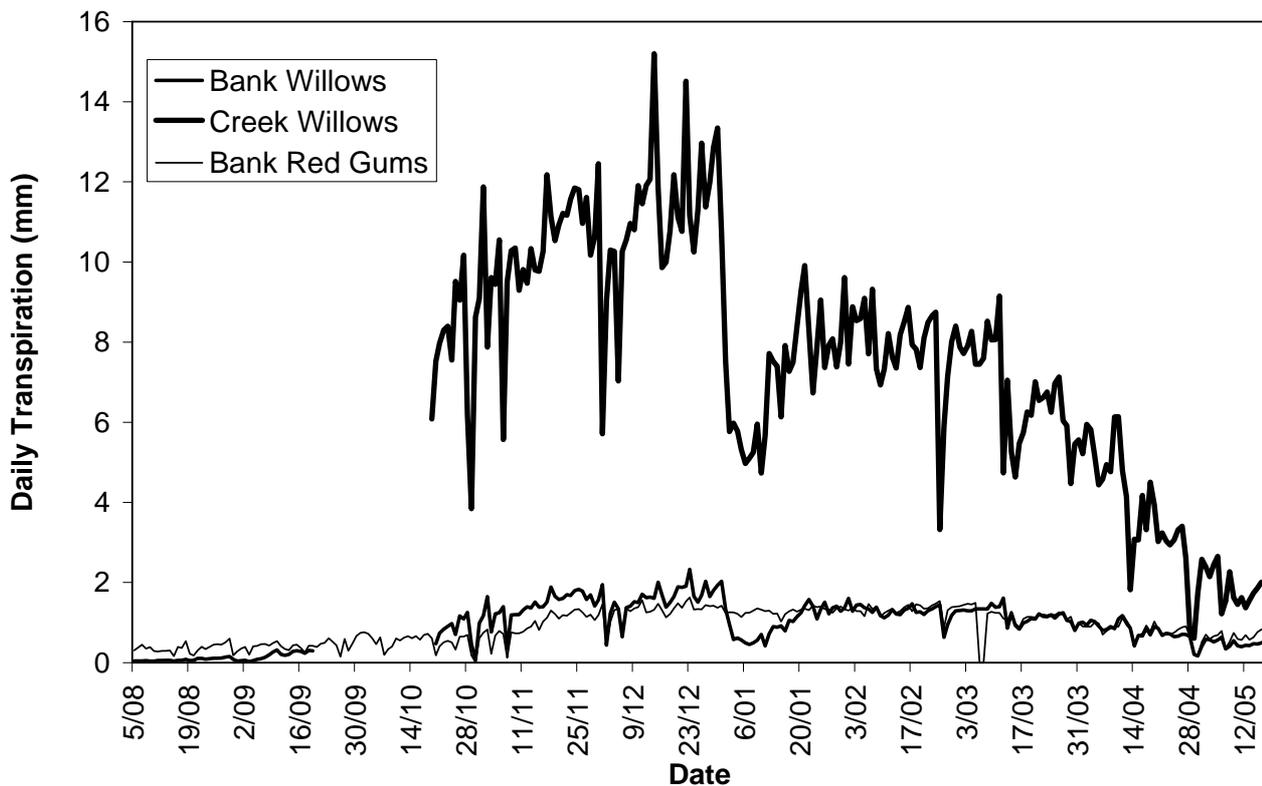


Figure 3. Daily transpiration of red gum trees and willows situated on the bank and in the creek

The willows in the creek bed had transpiration rates about six times higher, on average, than that of the bank willows, reaching a peak of 15.2 mm day^{-1} in December compared to a peak of 2.3 mm day^{-1} in the bank willows. The red gums reached a peak of 2.7 mm day^{-1} , also in December. The average water use of the 'wet' willows through the peak period in December was approximately 12 mm day^{-1} which was 25% higher than the maximum predicted by the model for this climate and was about 30% higher than published estimates of point potential ET for this region (Wang *et al.* 2001).

All the willows shed a large proportion of their leaves following three extremely hot, dry days from December 30 to January 1. Maximum temperatures on these days reached 41, 44 and 45 °C and relative humidity fell to 8%, 7% and 13% respectively, corresponding to daily maximum VPD of 7.1, 8.5 and 8.3 kPa. This leaf shed caused a rapid reduction in daily transpiration in all willow trees between December 31 and January 3, with a partial recovery over the next month as new leaves grew (Fig. 3). Mean daily transpiration in the 'wet' willows fell from 11.9 mm

day⁻¹ (mean from December 12 to 31), to 5.5 mm day⁻¹ (mean from January 3 to January 12). In the bank willows the reduction was from 1.8 to 0.6 mm day⁻¹ for the same period, compared with means of 1.4 and 1.3 mm day⁻¹ in the red gums.

Overall, daily and cumulative water use (total evapotranspiration) by willows and red gums on the creek bank was about the same (Figs 4 and 5), while willows in the creek bed were estimated to have higher evapotranspiration than the amount of water that could be evaporated from open water. In Figs 4 and 5 we have used a linear interpolation to estimate transpiration of the wet willows between early August and mid October, assuming a linear increase from zero in early August to the estimated rate in mid October shown in Figure 3.

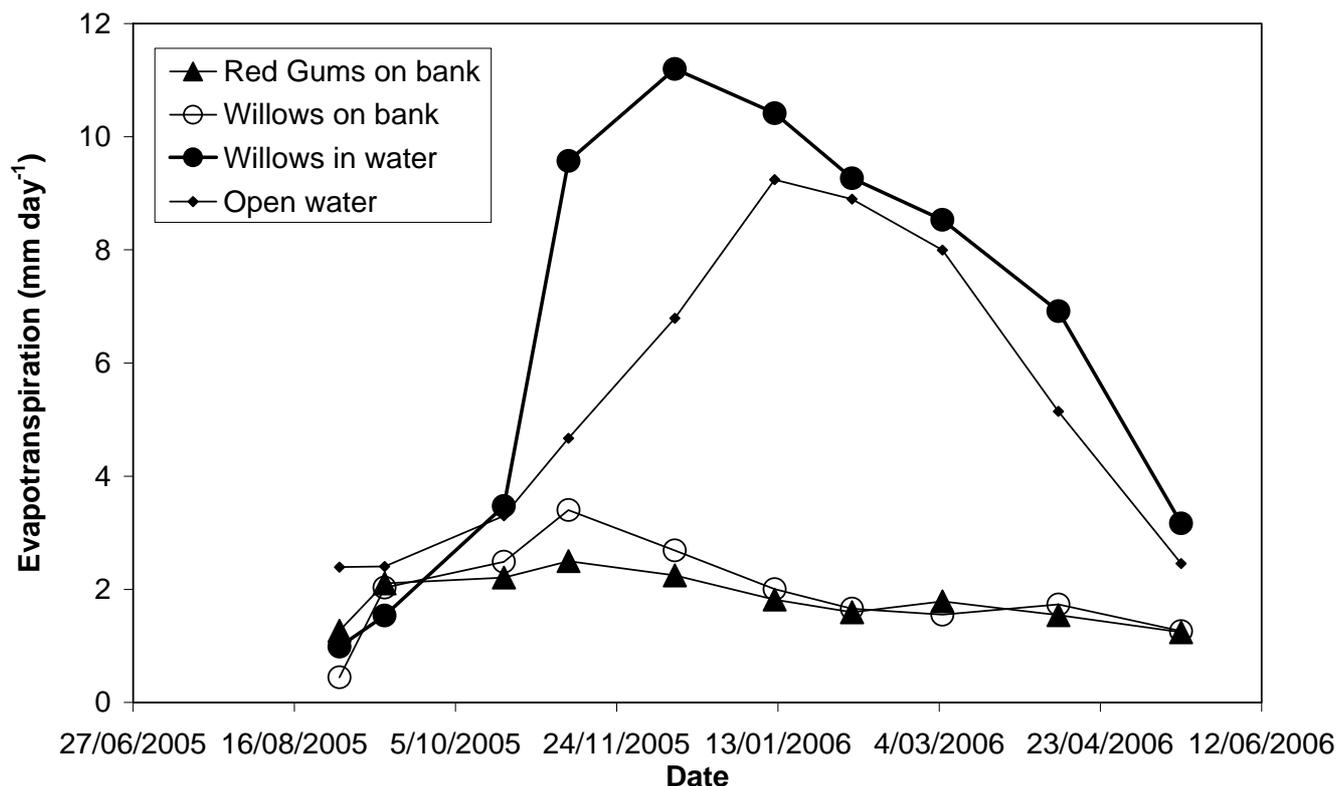


Figure 4. Daily water use during each measurement period based on crown projected area.

Total evapotranspiration is separated into its constituent components in Table 2. Field data were collected between 2 August 2005 and 18 May 2006 after which time evaporation, interception and transpiration were inferred until August 1 2006, to provide a 12 month period over which evapotranspiration could be calculated.

Table 2. Measured or estimated water balance components and calculated total evapotranspiration from red gums, willows and open water from August 2005 to July 2006

Water Use Site	Rainfall (mm)	Interception (mm)	Evaporation (mm)	Transpiration (mm)	Total ET (mm)
Red Gums	314	52	261	240	553
Willows - bank	314	26	257	280	563
Willows - creek	314	26	330	1633	1989
Open water	314	-	1642	-	1642

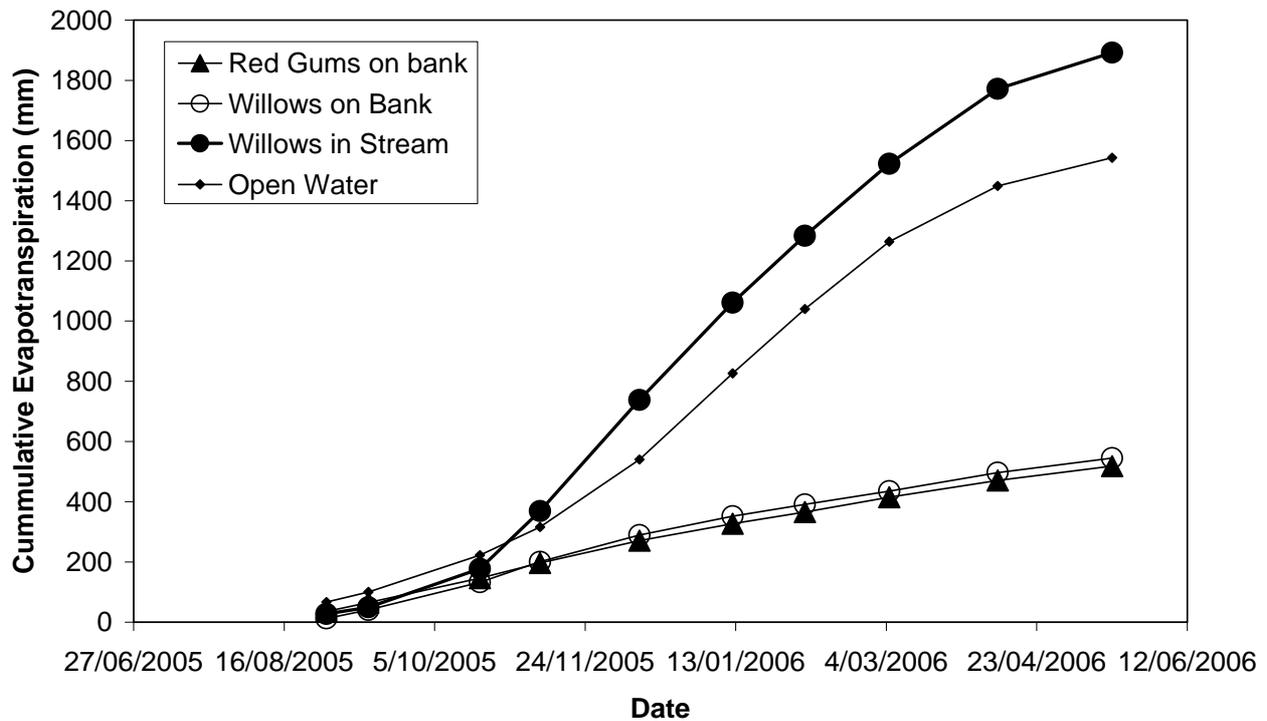


Figure 5. Cumulative total water use, 3 August 2005 to 18 May 2006, based on crown projected area.

Evaporation from bare soil was similar under the red gums and willows on the bank, totalling 83% and 82% of rainfall respectively, which was higher than the 60% assumed in the initial modelling. Our estimate of evaporation under the wet willows is slightly higher than that measured from the dry creek bank. As previously noted, evaporation under the wet willows was not measured, but estimated based on monthly maximum rates of evaporation from wet soil observed under tree plantations with dense canopies. Actual evaporation from the water surface under the wet willows would be difficult to measure directly. Maximum leaf area index of the wet willows was noticeably higher than that of the willows on the drier bank. This would have reduced radiation reaching the water surface, reducing the potential rate of evaporation. Conversely, lower resistance to evaporation from the water surface, compared to often dry soil on the banks, would have increased the rate of evaporation. We believe evaporation rates from wet soil in plantations with high LAI would be reasonably similar to or slightly less than evaporation from open water. Future studies might include comparative observations of water loss from evaporation pans in the open and in shade under bank willows and in shade under wet willows to obtain estimates of comparative evaporation rates.

Interception of rainfall was much lower than other evaporative losses, with 17% of rainfall intercepted by red gum foliage and 8% by the willow foliage. Leaf area index (LAI) of the 'wet' willows was not measured directly, but based on the stand sapwood area was probably substantially higher than for the willows on the banks. Therefore, interception of only 8% is probably an under-estimate for the 'wet' willows as higher LAI would be expected to result in higher interception loss.

Evapotranspiration from open water was calculated based on pan evaporation measured at Deniliquin and totalled 1642 mm for the 12 month period. Total ET of the red gums and bank willows of 553 and 563 mm respectively was similar. However, total ET of the 'wet' creek willows was considerably higher at 1989 mm due to their very high rates of transpiration. Total ET of the 'wet' willows would have been even higher if not for the substantial leaf shed, and consequent temporary halving of daily transpiration in early January. Despite this, total ET from

the 'wet' willows was 347 mm year^{-1} higher than the total maximum amount of evaporation expected from an unshaded water surface in this environment.

These results indicate a potential net saving of 3.5 ML ha^{-1} of willow crown projected area year^{-1} is possible by removing willows from the permanently wet part of the creek, based on the difference in total evapotranspiration between willows in the creek and open water. However, due to the small number of 'wet' willow sample trees, and the short period of measurement in three of these trees (only 3 months), the 95% statistical confidence interval for our estimate of evapotranspiration for 'wet' willows at the site is $\pm 5.6 \text{ ML ha}^{-1} \text{ year}^{-1}$. Hence, the difference between 'wet' willows and open water is not statistically significant at the 95% confidence level. Additional measurements over another growing season in a larger number of 'wet' willows will be needed to substantially narrow the statistical confidence interval and confirm whether the potential water saving is real.

From the literature, limited evidence exists indicating that, under well watered conditions, willows can use water at high rates (Hall *et al.* 1998). However, this field study has shown that the willows on the creek bank did not have unlimited access to the creek water as we had assumed. These trees appeared to be water stressed in summer, with low water use rates and obvious poor health and tree vigour.

Throughout the measurement period, daily transpiration rates of willows and red gums situated on the creek bank remained low relative to potential evapotranspiration, even though they were only a few meters from the water's edge in summer and, during spring floods were surrounded by water. Low transpiration rates of these trees during summer is possibly the result of shallow roots, and many years of summer water stress and reduced rates of growth compared to the willows located in the streambed, leading to a lower total leaf area. While soil properties were not measured, the soil on the creek banks appeared to be dense clay, which probably had low hydraulic conductivity. This would have restricted root growth through the soil and would have resulted in low rates of water conduction through the soil to the tree roots, limiting the rate of water uptake by trees on the creek bank. As the creek water receded rapidly in October and November, the willows on the creek bank probably became water stressed, leading to the low rates of water use observed. The willows situated permanently in water however, appeared to have unlimited access to water throughout spring, summer and autumn, resulting in very high transpiration rates. The sudden loss of approximately half the willow foliage in early January following three extremely hot, dry days, even in the willows surrounded by water, indicates the willow stomata may have closed to such a degree in response to very high vpd on those days, that lethal leaf temperatures were reached. Examination of long-term climate data for the region would reveal whether such hot dry periods are a common or rare occurrence.

Visual inspection of the creek indicated the willows are only occupying the lower creek banks and creek bed and only compete directly with the red gums on the edges of the willow infestation on the lower creek bank. Two lines of dead red gums, parallel to the direction of creek flow close to the centre of the permanently inundated part of the creek, suggest the flow regime of the creek has been substantially altered in recent years or decades. Whereas once creek levels would have been very low during summer, now, due to use of the creek to deliver irrigation water, there is moderate creek flow throughout the summer. This permanent inundation is probably responsible for death of red gums which inhabited what would have been the original creek bank in summer. Live red gums lining what is now the summer-time water's edge, would originally have been at the edge of the winter flood plain. All red gums in locations that are now permanently inundated are either dead, or almost dead, whereas willows in these areas are thriving. The willows appear to be well-adapted for surviving and growing in permanent inundation, but are unhealthy on the lower creek bank where they do not appear to have access to sufficient water in summer.

The willows appeared to be partly damming the creek, which probably reduces flow rates, and causes widening of the creek above the infestation, resulting in higher rates of surface water evaporation. Thus, in addition to the high rates of evapotranspiration directly from the willows, there are probably evaporative losses from an enlarged water surface area upstream.

The modelling carried out in stage one of the study, predicted a median net water saving from willow removal of approximately 2-4 ML ha⁻¹ for a scenario whereby willow water use is moderate and willows shade twice as much water/saturated soil as they do dry soil. The results of the field study suggests a 3-4 ML ha⁻¹ water saving is possible, although there is a low degree of statistical confidence associated with this estimate. However, savings could potentially be even higher if the hot dry weather over the New Year period hadn't caused the willows to lose a substantial proportion of their leaves. Although the willows regrew more leaves, the rate of transpiration remained reduced over the next 3 months despite weather conditions remaining warm to hot.

There is still considerable uncertainty about the potential water saving achievable by willow removal due to: (1) the wide statistical confidence interval for 'wet' willow transpiration at the site and (2) uncertainty about evaporation rates from the shaded water surface under the willow canopy compared to unshaded water without willows. The statistical confidence interval for willow transpiration could be narrowed considerably through further field measurements. Evaporation rates from shaded and unshaded water surfaces would be far more difficult to measure accurately and can probably only be estimated either a) through modelling (as in stage one of this study), b) as a fraction of pan evaporation, or c) as a minimum rate based on known rates of evaporation from wet soil under tree canopies (as in stage two of this study).

Measurements of willow and red gum leaf area and leaf conductance collected during the field study (data not yet available for reporting) will be used to re-run the stage one model to refine the prediction of water saving. The model predicted that mean annual evapotranspiration per hectare of willow projected crown area ranged from 1250 mm year⁻¹ if willows have low maximum stomatal conductance and high stomatal sensitivity to VPD, to 1900 mm year⁻¹ if willows have high maximum stomatal conductance and low stomatal sensitivity to VPD. The annual evapotranspiration obtained from the field trial was higher than the upper value predicted from the model by about 100 mm year⁻¹, indicating that some changes in the model input parameters are probably required. To estimate the net water saving from willow removal, the low water use rates of willows on the lower creek banks at the edge of the infestation needs to be taken into account. Field assessment of the proportion of willows in good health and poor health, during mid summer could be used to estimate the proportion of the total area occupied by 'wet' willows and stressed willows.

Predictions of the net water saving achievable by willow eradication could be improved by measurement of transpiration rates in a larger number of 'wet' willows at the site over a longer time period. This would provide a full season of measurements and would narrow the statistical confidence limits. There would also be value in undertaking such measurements in other environments to help refine parameters for modelling and to provide field verification of how broadly the results of this study can be applied to other river systems, climates, soils and willow species.

Conclusion

This initial study of willow water use in southern NSW indicates the potential for worthwhile water savings achievable by removing willows, estimated to be approximately 3-4 ML year⁻¹ ha⁻¹, although currently with a low degree of statistical confidence. However, the willows must be situated in the stream bed with permanent access to water if that saving is to be achieved. Removing willows might also improve flow rates, and reduce the width of the creek for a given

flow rate, resulting in lower evaporation rates from the stream surface up-stream of the willow infestations. The similarity of annual evapotranspiration from natural red gums and willows on the creek bank, indicate that removal of willows from the bank, followed by replanting with natural riparian eucalypt vegetation would provide bank stability without changing evapotranspiration.

Acknowledgements

We thank technical staff Michele Michael, Colleen Bernie, John Smith, Leroy Stewart, Vijay Koul and Mark Tunningley. Water for Rivers (WfR) provided substantial funding for the project, and in-kind support, particularly WfR's CEO Phil Deamer. We also thank Jeremy and David Barlow for providing access to the field site and Jeremy for his considerable in-kind assistance in monitoring creek levels in spring and removing equipment to prevent flood damage. Bruce Crittendon stored equipment and regularly charged batteries for us. Georgina Spencer of Department of Natural Resources provided the map for Fig. 1.

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