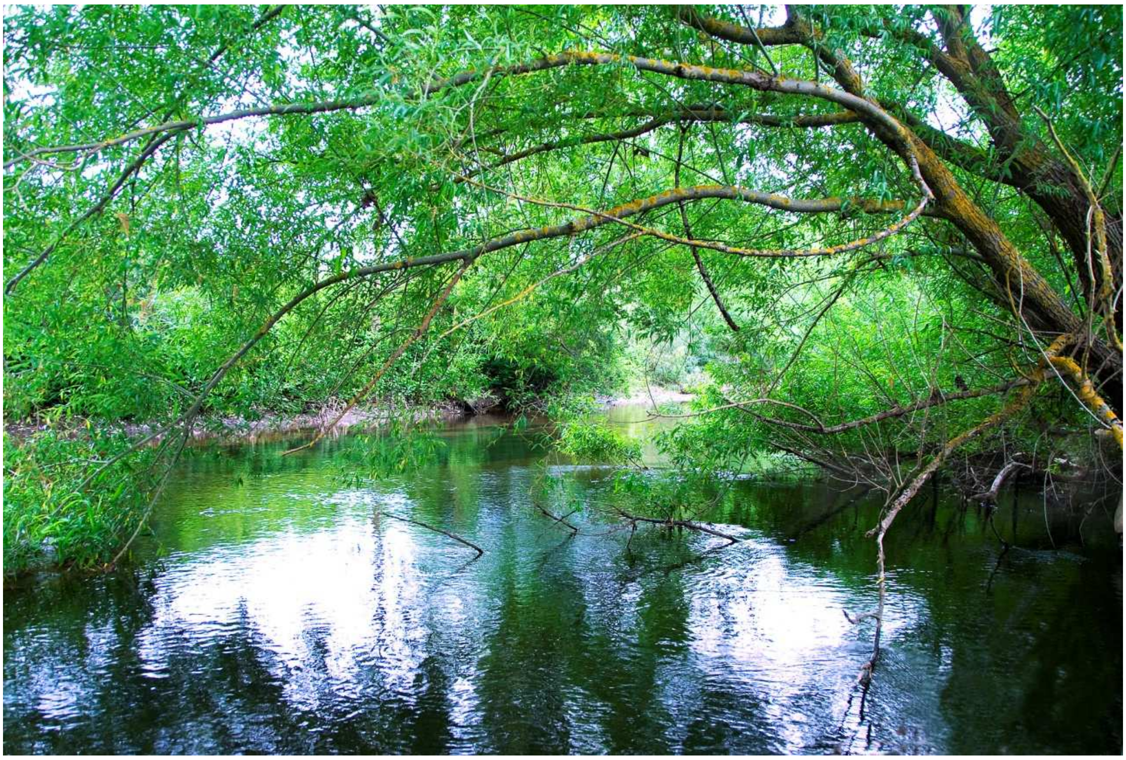
Quantifying water savings from willow removal in southeastern Australia

Tanya Marree Doody



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DECLARATION

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ABSTRACT

Abstract

Two global issues are brought together in this thesis to address a facet of both water resource and weed management in Australia. Water resource security is of global concern as human need for water increases and uncertainty in future water availability associated with climate change continues to evolve, particularly in arid and semi-arid regions. Furthermore, invasive species modify landscapes around the globe in response to anthropogenic ecosystem alterations, with significant impacts within aquatic systems. Water savings projects are under investigation in Australia in response to resource over-allocation and impacts of a prolonged drought from 1997 to 2009 ('The Millennium Drought'). An overarching aim of such investigations is to return water to the environment to meet future consumptive and environmental water requirements. In southeast Australia, invasive willows (Salicaceae: *Salix* spp.) have been identified as naturalized weeds which invade stream beds. In natural systems, stream beds are generally unoccupied and willow establishment increases total riparian leaf area and therefore total evaporative losses. Anecdotal evidence suggested water could be returned to creeks and streams if willows were removed, creating water saving. Strategies exist within State and Commonwealth agencies in Australia to monitor willow invasion, reduce environmental impacts and establish programs to reduce further spread. However, current methods to identify and monitor willow distribution are costly and time consuming.

In this dissertation, field investigations were undertaken to quantify water use of willows and to determine the potential water savings associated with removal of willows from creeks and streams within the Murray-Darling Basin. Methods are described which can potentially be applied across riparian zones worldwide, to aid water accounting and water resource management. Three years of sap flow and water balance measurements, undertaken to determine willow evapotranspiration, indicate that removal of *Salix babylonica* located within stream beds with permanent access to water ('in-stream' willows) in semi-arid areas will potentially return 5.5 ML ha^{-1} $year^{-1}$ of willow crown projected area to the stream when removed. A similar yearlong study undertaken in a cooler temperate region established potential water savings of 3.9 ML ha^{-1} $year^{-1}$ if *Salix fragilis* stands were removed from stream beds. Evapotranspiration of willow and endemic woody species were compared, establishing that removal of willows from water limited environments is unlikely to return a water saving. Two Penman-Monteith models (a model for *S. babylonica* and *S. fragilis*) were calibrated using field measurements of leaf area index and stomatal conductance. Each model was validated using field measured evapotranspiration and then run to calculate monthly pan coefficients (the ratio of evapotranspiration to pan evaporation) for each species across broad climatic ranges in Australia. Derived monthly pan coefficients and monthly pan evaporation predict evapotranspiration of willows across various climatic zones to assist accounting and management of water resources at broader scales. Furthermore, development of a simple open water evaporation model coupled with

evapotranspiration pan factors provides a means to estimate potential water savings from willow removal across broader climatic zones. The pan coefficient method presented has broader application across riparian systems worldwide providing a method to scale woody vegetation evapotranspiration across climatic zones using validated evapotranspiration models.

To further enhance and improve willow management practices, an economical remote sensing technique was developed to discriminate canopy area of willows located within stream beds from native vegetation and willows situated on banks which are generally water limited environments. A method is described using very high resolution WorldView-2 imagery (2x2 m) to identify and calculate total canopy area of both in-stream and water-limited willow infestations within a target region. Delineating willow canopy area provides a method to scale willow evapotranspiration and water savings predictions associated with removal of in-stream willows to catchment scale, to account for catchment evaporative losses, thus providing essential information to catchment managers.

As intensive and science-based resource management policies are required to address predicted future water scarcity in Australia, the knowledge delivered from this research addresses some important knowledge gaps. For example, current and future water availability is predicted within catchments using hydrological models, while vegetation evapotranspiration is predicted from remote sensing. Direct measurement of riparian evapotranspiration strengthens water availability estimates and addresses some 'unspecified losses' associated with Murray-Darling Basin water balance estimates. Estimates of potential water savings related to removal of willows also assists with catchment water accounting. Tools derived within this dissertation provide methods to scale willow and native riparian evaporative losses and water savings estimates from local to regional scales, further improving efforts to account for and manage water resources in Australia and worldwide.

This thesis provides evidence that water savings can potentially be achieved by removing willows located within stream beds which have permanent access to water and inhabit an otherwise unoccupied niche, increasing both total canopy leaf area and riparian evaporative losses. Methods are also provided to scale willow water use information from local to regional catchment scales.

Dedication

This thesis is dedicated to my amazing family. Firstly, to my husband Tom, for his unwavering support and patience throughout. There have been so many days when I thought I wouldn't make it through this PhD but thanks to the love and support of you Tom, I have. Secondly, to my daughter Madison (now 16) and my son Liam (now 14) for your love and patience and for allowing me the quiet periods I required when I required them! I hope, if nothing else during this time, you have learnt to chase your dreams no matter how high the mountain might seem or how impossible the situation might be. You will succeed, just hold onto to the passion in your heart and keep visualising the end result.

As well as creating this thesis I have maintained a full time position with CSIRO which overlapped an additional post graduate degree. I could never have been achieved any of this without the three of you. At various times you have all helped with the little and big things required in keeping a house running and a family together over 9 years of continuous study. I love all three of you dearly and cannot express my gratitude to your support which has allowed me to achieve a goal that is so meaningful to me. I dedicate my time from here to helping the three of you achieve your dreams and goals.

Every day I count my blessings to have such an amazing and loving family and this simple poem sums up the feeling in heart so beautifully.

I love my family so much

To be a part of a family like mine
is so divine
where love is shown
hurt is shared
our love for each other is never impaired

we talk
we laugh
we cry
but we are a family
and we do it all together
for as a family
we do it all as one

you hurt one
you hurt all
and as a family unit
we will all stand tall
for we are family
a family full of strength
a family full of love
a family no one can touch
that's why I love my family so much.

(Author unknown)

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CHAPTER 1

Background and Context

Introduction and Context

Importance of water accounting to the Murray-Darling Basin

Water scarcity is an increasing phenomenon worldwide, brought to the attention of the general population by the uncertain future impacts of global warming and climate change on water resources. Australia has been referred to as the "driest inhabited continent" (Smith, 1998) with landscapes strongly water limited by evaporative demand exceeding rainfall across the majority of the continent. Over 70% of Australia is designated as an arid or semi-arid zone (James *et al*., 1995), so projected shifts in climate resulting in less rainfall and higher temperatures pose a significant threat to water resources in Australia. Fears have recently been amplified as the most severe drought on record, 'The Millennium Drought' (Timbal *et al*., 2010; Leblanc *et al*., 2012), between 1997 to 2009, greatly reduced water availability in the nation's food bowl – the Murray-Darling Basin (Leblanc *et al*., 2012; Figure 1). Approximately 60% of Australia's water is used for agricultural irrigation within the Basin (CSIRO, 2008). In preparation for predicted future water shortages, the Australian Government requires science-based resource management policies to protect water resources and environmental assets. Currently an integrated approach to water reform is underway, to improve the accounting and management of water resources within the Murray-Darling Basin. Accounting for hydrological fluxes within designated catchment areas is critical to our understanding of overall water availability in the Basin, in an effort to balance environmental and consumptive water use requirements. To date this balance has not been achieved, culminating in severe degradation of environmental assets within the Basin and significant agricultural economic losses (Wei *et al*., 2011).

Water extraction for irrigation purposes began in Australia in the late nineteenth century, particularly in the Murray-Darling Basin, and has continued throughout the twentieth century with ever-increasing pressure on water resources, as development has continued with little resource management. Growth in irrigation diversions in the latter half of the twentieth century has subsequently caused serious environmental degradation and intensified competition between water users, culminating in water reform with the development of the National Water Initiative in 2004 (CoAG, 2004). The focus has since shifted from developing water resources to maximising productivity while ensuring environmental, economic and social sustainability (Leblanc *et al*., 2012).

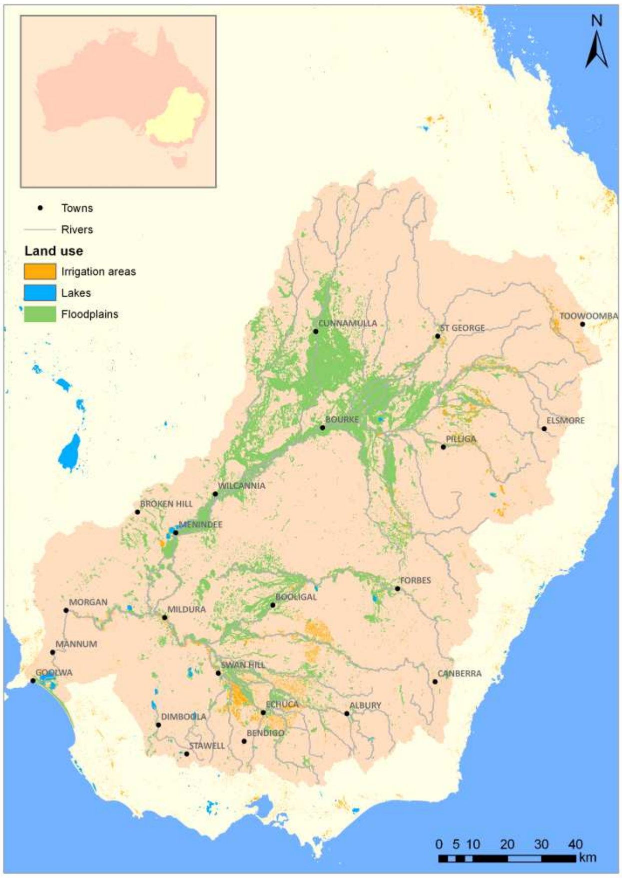

Figure 1. Map of the Murray-Darling Basin highlighting major rivers, floodplains and wetlands and irrigation areas.

During the Millennium Drought, an independently established and funded government company, 'Water for Rivers' was commissioned to achieve significant improvements in environmental flows in the Snowy River in New South Wales and the River Murray. The objective of the company was to find 282 gigalitres in annual water savings through infrastructure improvements and water savings projects. Increased riparian water use from invasive willow species (Salicaceae: *Salix* spp.) within the complex Basin river system was an option investigated as a potential source of water saving. Anecdotal evidence suggested willows were high water users. Accurate water accounting and recent development of water trading markets could potentially fund the cost of willow removal if real water savings are demonstrated. Investigation is therefore required to determine the impact that invasive willow species have on water availability from local to regional scales.

Considerable effort is underway to improve the accounting of hydrological fluxes within the Murray-Darling Basin. Modelling undertaken within the Basin integrates available stream flow and consumptive water use data and estimates of evapotranspiration losses to create water accounts within 18 catchment zones to report future water resource availability under various climate change scenarios (CSIRO, 2008). More recently, the Water Information Research and Development Alliance (WIRADA, http://www.csiro.au/partnerships/wirada) has been designated a principal role of forecasting water availability across Australia. However, the current national scale modelling approaches using a median climate change scenario to predict water availability in 2030, have large uncertainty surrounding them (Leblanc *et al*., 2012), requiring finer scale approaches to quantify water availability.

At the local scale, Catchment Management Authorities (CMAs) are required to protect and enhance the ecological assets in their regions, balanced with sustainable productive farming practices, and to facilitate irrigation efficiencies and water sharing plans. Tools to aid catchment managers to identify, monitor and manage invasive species and to understand associated risks to water resources within their catchments are therefore required.

Invasive species

Floodplain ecosystem health deteriorated severely in the Murray-Darling Basin during the Millennium Drought as a result of reductions in flooding frequency (Murray-Darling Commission and Brett Lane Associates, 2005; Armstrong *et al*., 2009; Cunningham *et al.*, 2010), compounded by other factors such salinity, grazing, pests and weeds (Mac Nally *et al*., 2011). Invasive species, particularity in the riparian zone, establish as a result of disturbance or hydrologic alteration (Poff *et al*., 1997; Busch and Smith, 1995). River systems are spatially and temporally dynamic environments influenced by high flow variability and sporadic, often unpredictable flooding, in which riparian communities are more susceptible to invasive species than adjacent upland communities (Gregory *et al*., 1991; DeFarrari and Naiman, 2000; Stohlgren *et al*., 1998, Hood and Naiman, 2000; Brown and Peet, 2003). Floods in smaller streams and tributaries within the Basin can displace existing vegetation and remove and redeposit sediment, creating cleared substrate patches in which competition for light, space and nutrients is decreased (Ede *et al*., 2010). These altered riparian ecosystems are vulnerable to invasion by weed species (Lonsdale, 1999; Parks *et al*., 1997) such as *Salix*. In some cases, weed invasions increase the total riparian canopy area, leading to additional riparian evaporative losses. In Australia, high invasiveness of willows is facilitated by long-distance propagule dispersal along riverine corridors (Hancock *et al*., 1996; Tickner *et al*., 2001; Richardson *et al*., 2007), allowing willows to establish on stream banks and within stream beds in an otherwise unoccupied habitat, to increase total riparian canopy area.

Phreatophytes are plants that frequently access the saturated zone for their water supply (Robinson, 1958). *Salix* species are known obligate phreatophytes (Stromburg *et al*., 2010), and thus are restricted to environments with consistently high water availability afforded by shallow depths to watertable Froend and Drake, 2006). In fact, *Salix* presence in the landscape has been recognised as an indicator of shallow groundwater (Busche *et al*., 1992). Likewise, in Australia, *Salix* species are closely associated with perennial channels which provide reliable sources of water, indicative of their perceived ability to extract large amounts of water from the environment (Thorp, 2001). A detailed literature review of *Salix* evapotranspiration is provided in Chapter 2.

Over recent decades, there has been increasing concern globally over the environmental impacts of 'environmental weeds' (invasive plant species). Environmental weeds are defined as introduced species which have naturalized and invaded natural ecosystems (Adair and Groves, 1998). Environmental weeds are the "most important drivers of change in ecosystems" (Millennium Ecosystem Assessment, 2005), however, surprisingly little is known about their overall impact on ecological processes (Millennium Ecosystem Assessment, 2005).

In Australia, national concern over the potential threat willows pose to stream and wetland ecology with respect to high water use, alterations to stream geomorphology and flow and dense deciduous canopies, has resulted in the majority of willow species being declared as 'Weeds of National Significance' (ARMCANZ, 2001). A national strategy co-coordinating effort to manage and control willows throughout Australia (Farrell, 2003) is underway in an attempt to prevent further alteration of waterways. Extensive willow removal programs have been undertaken since the 1990s to restore stream health with an assumption that willow removal will return water to streams. These programs are expensive however, with no research to quantify willow water extraction and few studies that quantify impacts on aquatic ecosystem function. Lester *et al*., (1994), Schulze and Walker (1997), Yeates and Barmuta (1999), and Jayawardana *et al*., (2006) report macroinvertebrate food sources and species richness and density for *Salix* infested streams in comparison to native species. Yeates and Barmuta (1999) conclude that macroinvertebrates might prefer willow leaves as a food source, Schulze and Walker (1997) found few differences between invertebrate colonists of willows and native River Red Gums, with Jayawardana *et al*., (2006) presenting a similar conclusion when comparing willow root habitat to native *Phragmites* habitat. Lester *et al*., (1994) however, found depressed invertebrate density in small New Zealand streams in sections occupied by willows. Similarly, Greenwood *et al*., (2004) report lower abundance and diversity of canopy arthropods in willow stands, likely related to lower wood plant diversity. It was found by Holland-Clift *et al*., (2011) that native transects had more birds, bird species and foraging guilds than willow invaded or cleared transects. These studies indicate potential negative impacts of willows on aquatic ecology.

In order to manage, monitor and account for water losses associated with invasive willows, research is required to quantify the water use of *Salix* species, determine if water savings can be achieved from removal of willows and to provide tools to map willow distribution and scale the findings across larger spatial scales and climates.

Water resource accounting and weed management in the Murray-Darling Basin

The Murray-Darling Basin covers approximately 1 million km^2 or 14% of Australia's total land area with 23 river valleys (Figure 1). The Basin consumes 60% of Australia's total agricultural water to generate 40% ($4.6 Billion, ABS, 2008) of national agricultural production. The majority of rice production and 90% of cotton grown in Australia occurs in the Basin. The Basin contains valuable environmental assets including 30,000 wetlands, recognized as important to water bird and fish for feeding and breeding (MDBA, 2010). Sixteen wetlands are listed under the Ramsar international convention (Ramsar, 1971) and approximately 200 wetlands are listed in the Directory of Important Wetlands in Australia (ANCA, 1996). The extensive wetland system performs essential hydrological and biogeochemical functions (Colloff and Baldwin, 2010) which support and maintain the productivity and health of river systems.

A stylised summary of the approximate water budget for the Murray-Darling Basin is shown in Figure 2 (Leblanc *et al*., 2012). The Murray-Darling Basin encompasses variable climates and rainfall patterns which are represented by an overall average precipitation in Figure 2. Available surface water resources are represented as 30 mm year or 6% of rainfall in the Basin after dryland evaporative losses. Of the available surface water, 42% is harvested in farm dams and from watercourses (Leblanc *et al*., 2012) to support irrigated agriculture. An additional 29% is lost to 'unspecified sources' which the authors suggest is a combination of evaporative losses related to floodplain and wetland replenishment (Leblanc *et al*., 2012).

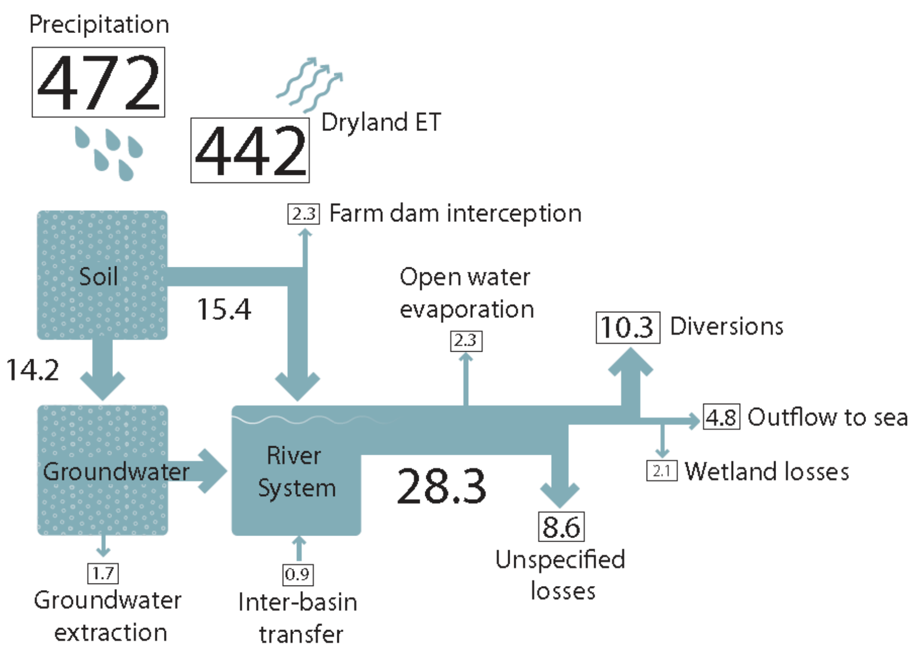

Figure 2. Approximate water budget for the Murray-Darling Basin in mm^{-1} $year^{-1}$. SOURCE: Leblanc *et al*., 2012.

Although riparian vegetation water losses are likely to be a small proportion of total evaporative losses within the Basin, such losses are important locally, representing large volumes of water which support environmental and consumptive water use. Field-based research to quantify evaporative losses associated with invasive willow and native riparian species may help to enhance estimates of unspecified evaporative losses for water management purposes. Elucidating if water can potentially be salvaged through removal of willows can then inform both catchment and water resource management bodies where water savings might be realised, while at the same time managing an environmental weed. Provision of tools to scale estimates of evaporative losses from local to regional estimates further enhances the investment in field-based research. A recent study (CSIRO, 2008) estimated vegetation evapotranspiration from satellite remote sensing but did not incorporate field measurements. Lack of field validation of evapotranspiration estimates creates some uncertainty in national estimates of vegetation evaporative losses.

Key knowledge gaps within weed management and water management frameworks include (1) lack of knowledge on willow water use at both local and regional scales and (2) accurate evaporative loss information is required at local and regional scales to enhance uncertainties around current and future water availability modelling estimates with respect to riparian vegetation.

Scope

The research presented in this thesis addresses the need to improve our understanding of invasive riparian phreatophytic evaporative losses within the Murray-Darling Basin and provides tools to scale results across broader spatial scales and climatic zones. The aim of the research is specifically to:

(1) quantify *Salix* water use (evapotranspiration) and estimate the potential to return water to the environment from removal of willows, by undertaking intensive field measurements;

(2) undertake additional native riparian water use measurements to quantify the net impact on evapotranspiration from replacing willows with native tree species;

(3) develop a tool to scale local willow evapotranspiration and water savings estimates across seven climatic zones in Australia to regional scale estimates, using evaporative pan coefficients;

(4) assess the feasibility of using remote sensing to map willow distribution and develop a tool to delineate willow canopies from native vegetation, providing a method to link evapotranspiration and water savings estimated from pan coefficients to mapped regional scale areas of infestation. This allows accurate determination of evaporative losses and potential water savings associated with willow removal across climatic zones;

Collectively, this body of research provides essential information and tools to improve our understanding of the impact of willows on water resources in the Murray-Darling Basin. The outcomes inform accounting of evaporative losses associated with the presence of native and willow species along riparian corridors and provide new science-based knowledge to support management objectives and assist development of science based resource management policies. Tools are presented within this thesis which link evaporative losses to regional water accounting and aid in overall catchment willow management.

Thesis Structure

The body of research is presented as scientific manuscripts which are published in peer-reviewed international journals. Each manuscript provides an independent literature review relevant to the core area of research. The thesis is composed of six Chapters (Figure 3). The body of the thesis is presented as independent, published manuscripts in Chapters 2, 3, 4 and 5. This style of presentation results in some repetition, particularly in the Introduction and reference lists, with some overlap in methodology.

Chapter 1

Chapter 1 (Introduction) provides a brief overview of the factors driving the need for the reported research and provides a unifying research theme. Figure 3 highlights the conceptual framework and linkages between the published manuscripts which address knowledge gaps of willow water use and willow impact on water resources, and the tools developed to enhance water resource management and willow management from local to broader scales.

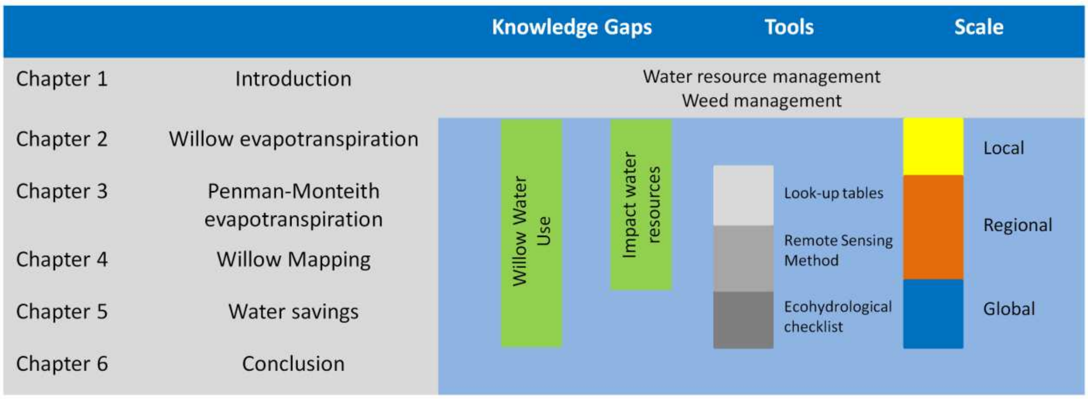

Figure 3. Thesis conceptual framework highlighting knowledge gaps addressed and tools developed in each manuscript and the respective scale of the research.

Chapter 2

Doody TM, Benyon RG. 2011. Quantifying water savings from willow removal in Australian streams. *Journal of Environmental Management*, **92**, 926-935.

Chapter 2 addresses the need for improved information on willow water use dynamics to aid management decisions relating to willow removal. A detailed literature review highlights the need to undertake an intensive field based water balance study in Australia. The study quantified the various components of willow water use in two semi-arid locations over three years and examined whether water savings could be achieved by willow removal. Total evapotranspiration of invasive willows, native riparian vegetation and unshaded open water were compared to estimate water savings from willow removal and replacement with native vegetation.

Chapter 3

Doody TM, Benyon RG, Theiveyanathan S, Koul V, Stewart L. 2013. Development of pan coefficients for estimating evapotranspiration from riparian woody vegetation. *Hydrological Processes (*DOI: 10.1002/hyp.9753*)*.

Chapter 3 included additional field measurements of willow water use for one year at two cool temperate sites for a second willow species and presented data on how willow transpiration is related to stomatal conductance and leaf area index. This and data reported in Chapter 2 are used to calibrate and validate the Penman-Monteith model of evapotranspiration. The validated Penman-Monteith model is run for two willow species using 30 years of climate data at each of 30 locations across seven biogeoclimatic zones of Australia to produce tables of monthly pan coefficients for each location. These pan coefficients provide a simple method for water resource managers to estimate long-term monthly and annual willow evapotranspiration based on local measurements of pan evaporation. Coupled with a simple model of open water evaporation derived from field data, potential water savings for each location can be calculated. This chapter addresses the need to scale from local to regional measurements by extrapolating from the field study sites to other regions within Australia, enabling improved cost-benefit analysis of willow removal. The method developed may have global application.

Chapter 4

Doody TM, Lewis M, Benyon RG, Byrne G. 2013. A method to map riparian exotic vegetation (*Salix* spp.) area to inform water resource management. *Hydrological Processes* (DOI:10.1002/hyp.9916).

Chapter 4 examines the utility of high resolution satellite remote sensing to economically map willow distribution. A method to discriminate willow canopy area from surrounding vegetation is described and tested. Used in conjunction with the look-up tables presented in Chapter 3, this relatively low cost mapping tool will enable weed and water managers to make accurate regional estimates of willow evapotranspiration and water savings for mapped target areas. In addition, the remote sensing tool provides an approach to allow catchment managers to monitor willow distribution spatially and temporally, using a method which has global application.

Chapter 5

Doody TM, Nagler PL, Glenn EP, Moore GW, Morino K, Hultine KR, Benyon RG. 2011. Potential for water salvage by removal of non-native woody vegetation from dryland river systems. *Hydrological Processes*, **25**, 4117–4131.

Chapter 5 provides a global perspective on the water resource impacts of invasive species in riparian zones, focusing on the potential to realise water savings from weed removal. This manuscript uses the contrast between two case studies (saltcedar in the United States and willows in Australia) to derive a generalised conceptual understanding of the ecohydrological circumstances under which removal of riparian weeds is likely to provide a net water saving. It concludes that water savings are possible when the invasive species occupy unused niches, increasing total riparian canopy area. The impacts on water savings in gaining and losing streams are discussed and a globally applicable generalized checklist is presented to enhance understanding of circumstances which may lead to water savings from riparian weed removal.

Chapter 6

Chapter 6 (Discussion and Conclusion) provides an overview of the research results and synthesises the knowledge acquired. It discusses the significance of the findings, limitations and potential future areas for progression of research in the context of the thesis findings.

Appendix

It is important to ensure transpiration measurements undertaken using sap flow measurements represent xylem flow accurately in order to account for under or over estimation of tree and plot water use to provide scientific rigour to the results. Chapter 2 reports the results of a cut-stem validation technique for *Salix bablylonica*, showing a slight underestimation. The same technique however, was less successful for *Salix fragilis*. The Appendix therefore presents a laboratory validation technique to validate sap flow of both *S. babylonica* and *S. fragilis*. This component is not presented in other Chapters due to word limitations enforced by publishers.

CHAPTER 2

Quantifying water savings from willow removal in Australian streams

Doody, T. & Benyon, R. (2011) Quantifying water savings from willow removal in Australian streams. *Journal of Environmental Management, v. 92(3), pp. 926-935*

NOTE:
This publication is included on pages 59-68 in the print copy of the thesis held in the University of Adelaide Library.

It is also available online to authorised users at:

http://doi.org/10.1016/j.jenvman.2010.10.061

CHAPTER 3

Development of pan coefficients for estimating evapotranspiration from riparian woody vegetation

Doody, T., Benyon, R., Theiveyanathan, S., Koul, V. & Stewart, L. (2013) Development of pan coefficients for estimating evapotranspiration from riparian woody vegetation.
Hydrological Processes, v. 28(4), pp. 2129-2149

NOTE:
This publication is included on pages 71-91 in the print copy of the thesis held in the University of Adelaide Library.

It is also available online to authorised users at:

http://doi.org/10.1002/hyp.9753

CHAPTER 4

A method to map riparian exotic vegetation (Salix spp.) area to inform water resource management

Doody, T., Lewis, M., Benyon, R. & Byrne, G. (2013) A method to map riparian exotic vegetation (Salix spp.) area to inform water resource management.
Hydrological Processes, v. 28(11), pp. 3809-3823

NOTE:
This publication is included on pages 95-109 in the print copy of the thesis held in the University of Adelaide Library.

It is also available online to authorised users at:

http://doi.org/10.1002/hyp.9916

CHAPTER 5

Potential for water salvage by removal of non-native woody vegetation from dryland river systems

Doody, T., Nagler, P.L., Glenn, E.P., Moore, G.W., Morino, K., Hultine, K.R. & Benyon, R. (2011) Potential for water salvage by removal of non-native woody vegetation from dryland river systems. *Hydrological Processes, v. 25(26), pp. 4117-4131*

NOTE:
This publication is included on pages 113-127 in the print copy of the thesis held in the University of Adelaide Library.

It is also available online to authorised users at:

http://doi.org/10.1002/hyp.8395

CHAPTER 6

Discussion

Introduction

The overarching goal of this thesis was to quantify how much water invasive willow species (Salicaceae: *Salix* spp.) consume, to determine if water savings can be achieved though removal of willows from creeks and streams in Australia. An additional goal was to determine whether estimated water savings would be maintained if willows were replaced with native riparian species. This research addresses a knowledge gap identified by the government bodies that funded the research. Accurate field evapotranspiration estimates address modelled regional water availability knowledge gaps and inform weed management strategies that are concerned with willow removal and potential to save water.

This thesis has contributed to the goal by investigating willow water consumption over four years, for two willow species (*Salix babylonica* and *Salix fragilis*) located in a semi-arid and cool, temperate climate representing typical regions where willows proliferate in Australia. In each climate zone, the comparative studies reported in Chapters 2 and 3 were undertaken to quantify whether estimated water savings were maintained, should willows be removed and replaced with native trees. The Penman-Monteith modelling of evapotranspiration described in Chapter 3 provided a simple method for water resource managers to extrapolate the field results to other climates and regions. The remote sensing of willow canopy area described in Chapter 4 provides a means to scale point estimates of willow evapotranspiration and water savings to whole regions based on remotely mapped willow locations and extent. Chapter 5 placed the results of the Australian studies in a global context and provided a conceptual understanding of the circumstances under which removal of riparian weeds will save water more generally.

The field studies described in Chapter 2 and Chapter 3 provide important new knowledge on willow water use dynamics in riparian zones. The results provided unexpected insights into riparian vegetation water use and water consumption in relation to niche occupancy. While willows located on stream banks maintained similar water use rates as co-located native species, willows situated within stream beds could maintain higher rates of water use. When located in stream beds, willows occupy an unused niche and increase total riparian canopy area, indicating that removal of in-stream willows will create a water saving.

Chapter 2 reported temporal and spatial water use dynamics of willows in response to heat stress, drought and attack by willow sawfly larvae (*Nematus oligospilus*) to further clarify situations when water salvage might be achievable. Chapter 3 investigated the ability of the Penman-Monteith model to estimate willow evapotranspiration and applied the validated Penman-Monteith model to derive monthly water use and pan coefficients across seven national climate zones. Field estimates of stomatal conductance were important to calibrate the model for each *Salix* species, while leaf area index for this deciduous tree appears less important than assumed prior to the study. Results provide insights into areas where willow invasion and spread should be avoided, based on climatic suitability, to prevent potential future impacts on water resources.

Chapter 4 investigated the utility of very high resolution satellite imagery (WorldView-2) to accurately discriminate willow stands from other riparian vegetation to provide a mapping method which can be used to detect and monitor willow invasions across the nation. In this investigation minimal spectral conflict with grass occurred as a result of buffering the riparian zone and manually removing errant pixels post-classification, using very high resolution aerial photography to guide decision making.

Chapter 5 investigates through review and case study, the ecohydrological drivers which make water salvage possible from willow removal in Australia and explains why, to date, water savings have not been realised in the United States.

Summary of specific contributions to knowledge

Water use of willows (Chapter 2)

The primary aim of Chapter 2 was to determine willow (*Salix babylonica* – weeping willow) and native riparian (*Eucalyptus camaldulensis* – River Red Gum) water use from intensive field water balance measurements over three years, in a semi-arid climate. The motivation was to provide evidence rather than anecdotal accounts, that removal of willows will create a water savings as willow evapotranspiration is higher than evaporation from open water. Prior to undertaking the study, it was assumed a water savings would result however it was the magnitude of the water savings that was unknown.

The study determined annual transpiration rates from *Salix* and *E. camaldulensis* stands using sap flow sensors. Rainfall, soil and shaded water evaporation, open water evaporation and canopy interception were also measured. The measurements were used to calculate annual evapotranspiration and water savings achievable from willow removal. Measurements of leaf area and stomatal conductance were collected for parameterisation of the Penman-Monteith model in Chapter 3.

An initial assumption that willows located along stream banks and those which had colonised within stream beds maintained similar rates of transpiration was rapidly proven inaccurate. Instead, it was demonstrated that riparian trees located on stream banks maintained low transpiration rates, similar to native vegetation nearby, while willows located within stream beds maintain significantly higher rates. Estimates of native riparian and willow evapotranspiration are provided for trees without permanent access to water situated along stream banks and willows located in-stream. A peak transpiration rate of 15.2 mm day^{-1} was recorded for in-stream willows compared to only 2.3 mm day^{-1} for water limited bank located willows. A comparable maximum of 15.2 mm day^{-1} for willow transpiration has not been reported in the literature to date. Evapotranspiration estimates indicate that removal of bank willows would not generate a water savings as evapotranspiration was less than open water evaporation. However, from a management perspective, removing and replacing bank willows with *E. camaldulensis* would not alter the water budget, but it would aid in eradicating an invasive weed species. Predictions of water savings are reported with removal of willows located in-stream which have permanent access to water. Willow evapotranspiration exceeded open water evaporation by an average of 550 mm $year^{-1}$ over the three years, thus 5.50 ML $year^{-1}$ per ha of willow canopy area could potentially be salvaged if in-stream willows were removed. It was specifically found that to achieve water savings, willows must have permanent access to water and be located within a perennial stream bed or along permanently saturated stream banks without water limitation. Water salvage from removal of in-stream willows is possible as native vegetation does not normally colonize within stream beds in Australia. Additional findings highlight a propensity for willows to recover rapidly from stress when not water limited, with stressors including extended periods of high temperatures and low humidity and defoliation by willow sawfly larvae. Severe drought reduced willow transpiration significantly because even trees in the stream bed became water-limited.

Modelling willow evapotranspiration using the Penman-Monteith Model (Chapter 3)

The aim of Chapter 3 was to calibrate and validate the Penman-Monteith model using data collected and outlined in Chapter 2, to develop monthly pan coefficients (the ratio of mean evapotranspiration to mean pan evaporation) for *Salix babylonica* across seven biogeoclimatic regions in Australia. Collection of additional field data from a cool climatic region was requested and funded by the North East Catchment Management Authority to expand willow water use knowledge further and develop pan coefficients for *Salix fragilis*. The motivation behind this component was to address the need to understand willow evapotranspiration across broader scales and varying climatic zones, providing a simple, economical method to estimate the potential impacts of willows on water resources. Additionally, evapotranspiration models have not previously been used to model willow evapotranspiration in Australia and globally there are no reports of willow pan coefficients.

The study involved the collection of additional field measurements of sap flow and water balance components, incorporating a second comparative study with native riparian tree species (predominantly *Eucalyptus camaldulensis*) from two field locations in cool temperate Victoria. Stomatal conductance and leaf area measurements were collected for Penman-Monteith model calibration. All trees had permanent access to water. The Penman-Monteith model was calibrated incorporating leaf area and stomatal conductance measurements to predict evapotranspiration of *S. babylonica* located in-stream and validated against field data. A second model was calibrated to predict in-stream *S. fragilis* evapotranspiration and validated against field data. Meteorological data from 1980-2010 including mean pan evaporation for 30 key reference locations, within seven climatic zones combined with the validated models, produced unique monthly pan coefficients for each key location, from which mean annual evapotranspiration can be estimated. A simple relationship between field-determined open water evaporation and pan evaporation was developed to estimate annual open water evaporation at each key location. Water savings were estimated as the difference between annual willow evapotranspiration and open water evaporation.

Field data indicate possible average water savings of 390 mm year^{-1} from removal of *S. fraglis*, situated in a cool climate, located within the stream bed. Evapotranspiration rates of bank located willows and eucalypts were not significantly different from each other or from in-stream willow. This is in contrast to the semi-arid environment where bank willows and Red Gum were water limited. Modelling results indicate that field data collected to calibrate each Penman-Monteith model were appropriate, providing high correlations between model and field results (r^2=0.88 *S. bablylonica* and r^2=0.99 *S. fragilis*). A vapour pressure deficit parameter derived from the literature for *Eucalyptus* trees was proven acceptable for modelling willow evapotranspiration. Use of a constant mean willow leaf area instead of seasonally variable leaf area gave reasonable predictions of evapotranspiration and thus willow evapotranspiration appears to be driven by available energy, enabling simplification of model input parameters in this study. Pan coefficients were developed for both willow species for 30 key locations. Evapotranspiration and water savings estimates using these pan coefficients should provide reasonable indicators of areas in Australia where willow spread should be avoided or controlled, based on climatic suitability to spread.

Mapping willow distribution using WorldView-2 imagery (Chapter 4)

The aim of Chapter 4 was to develop a method to accurately map willow distribution along riparian zones. The research was motivated by a need to integrate the results and tools developed in Chapter 2 and Chapter 3, to extrapolate willow evapotranspiration and water savings estimates to regional scales, providing total estimates within defined catchment areas.

The study required tasking WorldView-2 satellite imagery at a time which was representative of maximum willow leaf area but also minimum understorey grass cover to reduce spectral confusion. The 25 km^2 study area overlapped the region containing the field sites used in Chapter 3 in a cool climatic area of Victoria. Very high resolution (0.15 m) aerial photography and a digital elevation model (0.15 m) were used to represent ground truth data and provide a means to delineate stream channels. Discriminant analysis, spectral angle mapper (SAM) and maximum likelihood supervised classifications and spectral noise reduction techniques were employed to differentiate willows from other vegetative cover in the study region.

Discriminant analysis defined WorldView-2 bands 1 ('coastal blue'; 400-450 nm), 5 ('red'; 630-690 nm), 6 ('red edge'; 705-745 nm), and 8 ('near infrared'; 840-1040 nm) as optimal bands to discriminate willow canopies. The best differentiation of willows was obtained using a maximum likelihood classification after minimum noise fraction and 5 x 5 median filtering, discriminating between a willow category and a category of combined 'other' land cover classes (*kappa* = 0.92, willow user's accuracy 94%, overall accuracy 97%). The process was further simplified with a small loss of accuracy, by only applying the 5 x 5 median filter (*kappa* = 0.91, willow user's accuracy 93%) to provide a simpler repeatable technique for management authorities. Overall results provide a significant improvement to a bi-seasonal remote sensing method reported by Noonan and Chafer (2007). Finally, a digitised stream channel generated using a digital elevation model, delineated in-stream willows from bank willows to demonstrate the utility of a simple, economical mapping method to aid willow and water management and water accounting. Total riparian vegetation area of 59 ha occurs within the 25 km^2 study area, with 19 ha of that area occupied by willows. The total area if in-stream willows within the 25 km^2 study area, was 10.4 ha or approximately 20% of the total riparian area. Total water savings from removal of these in-stream willows is estimated as 41 ML $year^{-1}$ if it is assumed that *S. fragilis* is the dominant species, where removal will potentially realise 390 mm $year^{-1}$ ha^{-1} of willow canopy projected area.

Ecohydrological setting which enhance the potential for water salvage (Chapter 5)

The aim of Chapter 5 was to improve our understanding of the ecohydrological drivers that might potentially lead to water being returned to the environment following the removal of woody weeds. This component was motivated by the need to provide a global understanding of how invasive species in riparian areas impact on water resources. Additionally, similar international research informs managers about knowledge gaps not addressed in this thesis, related to improving our understanding of situations which might reduce the potential to salvage water in Australia. These include hydrological setting, specifically losing and gaining stream scenarios.

This study was undertaken as a review of literature providing a detailed case study comparing invasive willows in Australia to invasive saltcedar (Tamaricaceae: *Tamarix* spp.) in the United States of America.

The study demonstrated that willows in Australia occupy an unused ecological niche (with respect to woody vegetation) by invading and colonising stream beds. In doing so, willows increase the total canopy area of riparian vegetation present, compared to occupancy by native species only. In contrast, saltcedar in the United States colonise along riparian corridors at similar densities but not within an unoccupied niche. Rather, saltcedar displace native riparian species or coexist with them. In general, saltcedar are unlikely to increase total riparian canopy area and maintain similar rates of evapotranspiration to those of native species. As a result, studies to date in the United States to demonstrate actual water savings have not realized the expected increases in flow or groundwater storage. This result is specifically related to hydrological setting of woody vegetation and niche occupancy. It does not take into consideration removal of emergent non-wood macrophytes. The study concluded that the chance and magnitude of salvaging water from removal of invasive riparian species was highly variable and site specific. It is hypothesised that water savings would be realised in Australia with removal of in-stream willows as they increase total riparian canopy area and occupy an unused niche. As a result of the review, a checklist is presented to provide a global perspective on the ecohydrological settings that will potentially demonstrate actual water salvage from removal of invasive riparian species.

With respect to saltcedar removal studies in the United States, the area of vegetation removed might have represented a relatively small proportion of the catchment area. Bosch and Hewlett (1982) suggest at least 20% of catchment area requires conversion from forest to grassland to be detected as changes in stream flow. Therefore, water salvage from saltcedar removal may be possible over larger scales.

Validation of sap flow (Appendix)

Results presented in the Appendix add rigour to the transpiration measurements reported in Chapter 2 and 3. Mean error of ± 7% is reported for *Salix*, less than the overall error of 35% for the heat pulse velocity technique when applied to *Fagus grandifolia* (American Beech; Steppe *et al*., 2010). Of note, is the importance of applying a wound correction when using heat pulse sensors (Steppe *et al*., 2010). This correction is reported in Chapter 2 to be 3.0 mm for both *Salix* and *Eucalyptus camaldulenis*. This was later confirmed to be accurate by examining drilled wood sections under a microscope and measuring wound width from discolouration of damaged xylem cells.

Willow management in Australia

Prior to the research presented in this thesis, little was known about willow water use. Catchment and weed managers removed willows to return watercourses to more natural states as open flowing water bodies which are not heavily shaded by exotic vegetation. It was assumed that willow removal might reduce evaporative losses as well as reduce impacts to aquatic ecology related to willow invasions.

Studies suggest potential negative impacts of willow occupancy for bird, terrestrial and aquatic assemblages (Lester *et al*., 1994; Greenwood *et al*., 2004; Holland-Clift *et al*., 2011). Stream geomorphology is altered as thick root mats divert water outside the natural stream channel (Bunn *et al*., 1993) causing bank erosion. Water quality is reduced, resulting from bank erosion, root mats clogging channels, reducing flow and large inputs of organic material in autumn following willow senescence as opposed to annual leaf fall of evergreen native species (Gregory *et al*., 1991; Baldy *et* *al*., 1995; Schulze and Walker, 1997; Janssen and Walker, 1999; Wilson, 2001). Water temperature is potentially altered as large, dense canopies shade entire stream surfaces when willows are located in-stream, altering aquatic primary production (Lester *et al*., 1994, Van Kirk and Benjamin, 2001). Schulze and Walker (1997) suggest bank located willows inhibit understorey growth which affects terrestrial biodiversity.

The research in this thesis provides evidence that water savings are possible from in-stream willow removal in southeastern Australia. However, it is important to understand that at a whole of catchment scale, the water savings are likely to be quite small, as the area of in-stream willows is quite small in comparison. Willow removal is also likely to benefit aquatic and terrestrial ecology. These benefits however, must be weighed against the cost of removal and disposal of willow material and stream bank stabilisation that willows provide. As willow removal programs have been undertaken for many years, catchment managers have a very good understanding of the costs involved. These costs can now be considered against the additional benefit provided from returning water resources to creeks and streams across different climatic zones. Monitoring costs are also likely to be reduced by the development of a remote sensing monitoring tool which allows temporal willow monitoring in the future. Monitoring is currently undertaken by field assessment or from within a boat, incurring considerable costs in time and effort with unknown accuracy. In addition, monitoring accuracy will improve with application of the remote sensing tool reported. Cost benefit analysis relating to willow removal is a case by case process; however catchment managers can be better informed by applying the tools and knowledge of willow water use presented within this thesis.

Limitations

Several limitations of the research presented in this thesis must be acknowledged. Statistical confidence intervals surrounding field estimates of evapotranspiration, open water evaporation and water savings are discussed in Chapters 2 and 3. Sap flow measurement errors reported in the literature range from 5 to 25% (Barrett *et al*., 1995; Hatton *et al*., 1995). The 95% statistical confidence intervals for evapotranspiration of 20% for *S. babylonica* and 13% for *S. fragilis* reported in Chapters 2 and 3 falls within these previously reported error margins. Field experiments employed the heat pulse technique to determine transpiration rates, which is reported to be the most accurate of common sap flow methodologies (Steppe *et al*., 2010), increasing confidence in the results. Confidence intervals of approximately 20% are associated with open water evaporation estimates.

This research also assumes evapotranspiration and water savings presented are representative of the common *Salix* species in Australia. Caution is warranted when applying results to *Salix* species other than *S. babylonica* and *S. fragilis*. Quantifying actual water returns and improvements to hydraulic efficiency resulting from willow removal were beyond the scope of this study. To examine temporal and spatial variability within and between willow stands, three years of data was collected for *S. babylonica* and two field locations were used for each species. It was not possible to examine temporal variability of *S. fragilis* due to funding constraints. Additional field studies would further improve understanding of the temporal and spatial influence on willow evapotranspiration. This research has not quantified the ecological impacts of willows or their removal. Such research was beyond the scope of the project.

Additionally, spectral confusion creates error within the remote sensing method described, which maps willow distribution. Willows which form an understorey to *Eucalytpus* or other native species are not fully mapped, so underestimates in area can be expected in this situation. Since the majority of willows exist in-stream or on previously uncolonised stream banks, this does not pose a significant problem, as willows are mapped very well in these situations. The method described does not distinguish between willow species. The ground truth investigation was only undertaken in one relatively small study region where water balance of *S. fragilis* was measured. Very high resolution (0.15 m) aerial photography provides a suitable surrogate to ground truth data, but does not allow differentiation of willow species.

Recommendations for further research

It is recommended that large-scale willow removal studies be undertaken to specifically evaluate if water is actually returned to watercourses as flow. This would require detailed monitoring of gauged river flow before and after willow removal, linked with diurnal observation of groundwater bores, upstream extraction amounts and an understanding of stream character (gaining or losing stream). Observations over several years are required to ensure water savings are long-term.

It is suggested that additional field-based studies to quantify water use of *Salix babylonica* in a cool temperate climate and *Salix fragilis* in a semi-arid climate are undertaken as well as additional measurements for other common willow species. This would further address temporal and spatial influences on willow evapotranspiration estimates and provide additional validation and rigour to results of Penman-Monteith modelling.

It is important to consider investigating the potential to apply existing open water evaporative models reported in the literature, to estimate open water evaporation and develop a new model to specifically address open water evaporation from narrow water courses. This would reduce uncertainty related to estimates of open water evaporation.

It is recommended that a method is developed to discriminate between willow species using remotely sensed imagery by undertaking a detailed spectral response field study. Such research would allow differentiation between willow species to potentially highlight different water use patterns across willow species and therefore differences in potential water savings estimates. It would be important to assess whether timing of senescence can be used as a technique to discriminate between species.

Evapotranspiration algorithms specific to Australia such as that developed by Guerschman *et al*., (2009) could be tested for accuracy against field measurements using WorldView-2 imagery (or other fine resolution imagery) to provide simpler, economical solutions to monitoring catchment willow evapotranspiration and estimating potential water savings. It is recommended that research be undertaken to investigate the utility of very high resolution remote sensing imagery to estimate willow evapotranspiration within a whole catchment. This would provide *Salix* catchment area and evapotranspiration estimates and allow calculation of potential water savings per hectare of willow canopy removed. Previous studies applied an EVI (enhanced vegetation index) to MODIS imagery (Nagler *et al*., 2005; Glenn *et al*., 2007, 2010). However, the spatial resolution of MODIS is too coarse for willow estimates. Noonan and Chafer (2007) suggest 10 m resolution is possibly suitable for mapping willow distribution and thus calculation of evapotranspiration, however Chapter 4 indicates the spectral resolution of 2m provided only by World-View2 is essential for willow discrimination.

Conclusion

Invasive willows in Australia are considered to be a serious environmental threat in riparian areas and current policies include removal. Resource management policy to protect water resources and environmental assets require a sound scientific basis. Prior to the research presented in this thesis it was assumed that willow removal would result in net water saving, but this had not been tested.

This thesis presents evidence that water savings are possible from the removal of invasive willow species located within stream beds in Australia. The presence of willows in an unoccupied riparian niche in the permanently saturated stream bed, increases overall riparian canopy area. Removal of these willows will likely return water to the environment. Extensive field studies indicate potential water savings of approximately 5.5 ML year^{-1} ha^{-1} of willow canopy area removed for *Salix bablylonica* and 3.9 ML year^{-1} ha^{-1} for *Salix fragilis*. These field data were used to produce tools to assist with future monitoring and management of willow invasions, highlighting key areas across Australia where invasions should be controlled and avoided, to prevent water resource impacts. The methods reported here are applicable globally for similar investigations of the water use of invasive woody riparian species. This research addressed deficiencies in water accounting by enabling robust estimates of riparian evapotranspiration along perennial and intermittent streams for inclusion in future estimates of catchment water availability.

References

Adair RJ, Groves RH. 1998. Impact of environmental weed on biodiversity: A review and development of a methodology. Report for the Director of the National Parks and Wildlife, Environment Australia, Canberra. http://www.weeds.gov.au/publications/books/pubs/bioimpact.pdf

ANCA (Australia Nature Conservation Agency). 1996. A Directory of Important Wetlands in Australia, Second edition. Australia Nature Conservation Agency, Canberra.

Agriculture & Resource Management Council of Australia & New Zealand (ARMCANZ) 2001, Weeds of National Significance Willow (*Salix taxa*, excluding *S. babylonica*, S. x *calodendron* and *S.* x *reichardtii*) Strategic Plan, National Weeds Strategy Executive Committee, Launceston.

Armstrong JL, Kingsford RT, Jenkins KM. 2009. The Effect of Regulating the Lachlan River on the Booligal Wetlands – The Floodplain Red Gum Swamps.' University of NewSouth Wales: Sydney. www.wetrivers.unsw.edu.au/Booligal_Lachlan_River_Report.pdf

Baldy V, Gessner O, Chauvet E. 1995. Bacteria, Fungi and the breakdown of leaf-litter in a large river. *Oikos*, **74**, 93–102.

Barrett DJ, Hatton TJ, Ash JE, Ball MC. 1995. Evaluation of the heat pulse velocity technique for measurement of sap flow in rain-forest and Eucalypt forest species of South-Eastern Australia. *Plant, Cell & Environment*, **18**, 463-469.

Bosch JM, Hewlett JD. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology*, 55, 3-23.

Brown RL, Peet RK. 2003. Diversity and invasibility of Southern Appalachian plant communities. *Ecology*, **84**, 32-39.

Bunn SE, Pusey BJ, Price P. 1993. Ecology and Management of riparian zones in Australia: An introduction. In: Proceedings of the Ecology and Management of riparian zones in Australia.Marcoola, Queensland, 1–20, The Land and Water Resources Research and Development Corporation and the Centre for Catchment and in-stream research, Griffith University.

Busch DE, Ingraham NL, Smith SD. 1992. Water Uptake in Woody Riparian Phreatophytes of the Southwestern United States: A Stable Isotope Study. *Ecological Applications*, 2(4), 450-459.

Busch DE, Smith SD. 1995. Mechanisms associated with decline of woody species in riparian ecosystems of the southwester U.S. *Ecological Monographs*, 65(3), 347-370.

Colloff MJ, Baldwin, DS. 2010. Resilience of floodplain ecosystems in a semi-arid environment. *The Rangeland Journal*, **32**, 305–314.

Council of Australian Governments (COAG). 2004. Intergovernmental agreement on a national water initiative. Council of Australian Governments, Canberra.

http://www.nwc.gov.au/__data/assets/pdf_file/0019/18208/Intergovernmental-Agreement-on-a-national-water-initiative2.pdf

CSIRO. 2008. Water availability in the Murray-Darling Basin. A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project. CSIRO, Australia. www.csiro.au/mdbsy.

Cunningham SC, Thompson JR, Read J, Baker PJ, Mac Nally R. 2010. Does stand structure influence susceptibility of eucalypt floodplain forests to dieback? *Austral Ecology*, **35**, 348–356. doi:10.1111/ j.1442-9993.2009.02043.x

DeFerrari C, Naiman RJ. 1994. A multi-scale assessment of the occurrence of exotic plants on the Olympic Peninsula, Washington. *Journal of Vegetation Science*, **5**, 247-58.

Ede FJ, Ainsworth N, Hunt TD. 2010. Managing weeds in riparian zones. 17th Australasian weeds conference. New frontiers in New Zealand: together we can beat the weeds. Christchurch, New Zealand, 26-30 September, 311-314

Farrell B. 2003. Strategic Planning for Willow Management in Tasmania, Tasmania.

Froend RH, Drake PL. 2006. Defining phreatophyte response to reduced water availability: reliminary investigations on the use of xylem cavitation vulnerability in *Banksia* woodland species. *Australian Journal of Botany*, **54**, 173–179.

Glenn EP, Huete AR, Nagler PL. 2010. Vegetation index methods for estimating evapotranspiration by remote sensing. *Surveys in Geophysics*, **31**, 531-555.

Glenn EP, Huete AR, Nagler PL, Hirschboek KK, Brown P. 2007. Integrating remote sensing and ground methods to estimate evapotranspiration. *Critical Reviews in Plant Sciences*, **26**, 139-168.

Greenwood H, O'Dowd DJ, Lake PS. 2004. Willow (*Salix* x *rubens*) invasion of the riparian zone in south-eastern Australia: reduced abundance and altered composition of terrestrial arthropods. *Diversity and Distributions*, **10(5-6)**, 485-492.

Gregory SV, Swanson FJ, McKee WA., Cummins KW. 1991. An ecosystem perspective of riparian zones: focus on links between land and water. *BioScience*, **41**, 540-51.

Guerschman JP, Van Dijk AIJM, Mattersdorf G, Beringer J, Hutley LB, Leuning R, Pipunic RC, Sherman BS. 2009. Scaling of potential evapotranspiration with MODIS data reproduces flux observations and catchment water balance observations across Australia. *Journal of Hydrology*, **369 (1-2)**, 107-119.

Hancock CN, Ladd PG, Froend RH. 1996. Biodiversity and management of riparian vegetation in Western Australia. *Forest Ecology and Management*, **85**, 239-50.

Hatton TJ, Moore SJ, Reece PH. 1995. Estimating stand transpiration in a Eucalptus populnea woodland with the heat-pulse method – measurement errors and sampling strategies. *Tree Physiology*, **15**, 219–227.

Holland-Clift S, O'Dowd DJ, Mac Nally R. 2011. Impacts of invasive willow (*Salix* x *rubens*) on riparian bird assemblages in south-eastern Australia. *Austral Ecology*, **36**, 511-520.

Hood WG, Naiman RJ. 2000. Vulnerability of riparian zones to invasion by exotic vascular plants. *Plant Ecology*, **148**, 105-14.

James CD, Landsberg J, Morton SR. 1995. Ecological functioning in arid Australia and research to assist conservation of biodiversity. *Pacific Conservation Biology*, **2**,126-42.

Janssen MA, Walker KF. 1999. Processing of riparian and wetland plant litter in the River Murray, South Australia. *Hydrobiologia,* **411**, 53–64.

Jayawardana JMCK, Westbrooke M, Wilson M, Hurst C. 2006. Macroinvertebrate communities in willow (*Salix* spp.) and reed beds (*Phragmites australis*) in central Victorian streams in Australia. *Marine and Freshwater Research*, **57**, 429–439.

Kutscha NP, Sachs IB. 1962. Color tests for differentiating heartwood and sapwood in certain softwood tree species. Report. United States Forest Products Laboratory 2246, 13 pp.

Leblanc M, Tweed S, Van Dijk A, Timbal B. 2012. A review of historic and future hydrological changes in the Murray-Darling Basin. *Global and Planetary Change*, **80-81**, 226-246.

Lester PJ, Mitchell SF, Scott D. 1994. Efffects of riparian willow trees (*Salix fragilis*) on macroinvertebrate densities in 2 small central Otago, New Zealand streams. New Zealand Journal of *Marine and Freshwater Research,* **28(3)**, 267–276.

Lonsdale WM. 1999. Global patterns of plant invasions and the concept of invasability. *Ecology*, **80**, 1522-1536.

McCarthy EL. 1934. Mariotte's bottle. *Science*, **80**. P100.

Mac Nally R, Cunningham SC, Baker PJ, Horner GJ, Thomson JR. 2011. Dynamics of Murray-Darling floodplain forests under multiple stressors: The past, present and future of an Australian icon. Water Resource Research, 47, W00G05, doi:10.1029/2011WR010383.

MDBA (Murray-Darling Basin Authority). 2010. Guide to the Proposed Basin Plan: Overview, Murray-Darling Basin Authority, Canberra.

Millennium Ecosystem Assessment. 2005. Ecosystems and human well-being: synthesis. Island Press. Washington DC, USA.

Murray–Darling Basin Commission and Brett Lane and Associates. 2005. Survey of River Red Gum and Black Box Health along the River Murray in New South Wales, Victoria and South Australia – 2004.

www.samdbnrm.sa.gov.au/Portals/7/AWMN/chowuploads/RRG_report_final%20.pdf

Nagler PL, Cleverly J, Glenn E, Lampkin D, Huete A, Wan Z. 2005. Predicting riparian evapotranspiration from MODIS vegetation indices and meteorological data. *Remote Sensing of Environment*, 94(1):17-30.

Noonan M, Chafer C. 2007. A method for mapping the distribution of willow at a catchment scale using bi-seasonal SPOT5 imagery. *Weed Research*, **47**, 173-181.

Parks CG, Radosevich SR, Endress BA, Naylor BJ, Anzinger D, Rew LJ, Maxwell BD, Dwire KA. 2005. Natural and land-use history of the Northwest mountain ecoregions (USA) in relation to patterns of plant invasions. *Perspectives in Plant Ecology Evolution and Systematics*, **7**, 137-158. Doi: 10.1016/j.ppees.2005.09.007.

Poff N, Allan J, Bain M, Karr J, Prestegaard K, Richter B, Sparks R, Stromberg J. 1997. The Natural Flow Regime. *BioScience*, **47**, 769-784.

Ramsar. 1971. Convention on Wetlands of International Importance especially as Waterfowl Habitat. Ramsar (Iran), 2 February 1971. UN Treaty Series No. 14583. As amended by the Paris Protocol, 3 December 1982, and Regina Amendments, 28 May 1987.

Richardson DM, Holmes, PM, Esler KJ, Galatowitsch SM, Stromberg JC, Kirkman SP, Pysek P, Hobbs RJ. 2007. Riparian vegetation: degradation, alien plant invasions, and restoration prospects. *Diversity and Distributions*, **13**, 126-39.

Robinson TW. 1958. Phreatophytes. United States Geological Survey. Water Supply Pap., 1423, 84 pp.

Rodd N. 1982. Salicaceae. In: Barlow B. George AS. (Eds.). Flora of Australia, vol. 8.Australian Government Publishing Service, Canberra, Australia, pp. 200e206.

Schulze DJ, Walker KF. 1997. Riparian eucalypts and willows and their significance for aquatic invertebrates in the River Murray, South Australia. *Regulated Rivers: Research & Management*, **13**, 557–577.

Smith, D. 1998. Water in Australia: resources and management, Melbourne: Oxford University Press.

Smith RE. 1991. The heat pulse velocity technique for determining water uptake of *Populus deltoides*, *South African Journal of Botany*, **58**, 100-104.

Steppe K, De Pauw DJW, Doody TM, Teskey RO. 2010. A comparison of sap flux density estimates using thermal dissipation, heat pulse velocity and heat field deformation methods. *Agricultural and Forest Meteorology*, **150** (7-8), 1046-1056.

Stohlgren TJ, Bull KA, Otsuki Y, Villa CA, Lee M. 1998. Riparian zones as havens for exotic plant species in the central grasslands. *Plant Ecology*, **138**, 113-25.

Stromburg JC, Tluczek MGF, Hazelton AF, Ajami H. 2010. A century of riparian forest expansion following extreme disturbance: Spatio-temporal change in *Populus/Salix/Tamarix* forests along the Upper San Pedro River, Arizona, USA. *Forest Ecology and Management*, **259**, 1181–1189.

Swanson RH. 1994. Significant historical developments in thermal methods for measuring sap flow in trees. *Agricultural and Forest Meteorology*, **72**, 113-132.

Tickner DP, Angold PG, Gurnell AM, Mountford JO. 2001. Riparian plant invasions: hydrogeomorphological control and ecological impacts. *Progress in Physical Geography*, **25**, 22-52.

Timbal B, Arblaster J, Braganza K, Fernandez E, Hendon H, Murphy B, Raupach M, Rakich C, Smith IKW, Wheeler M. 2010. Understainding the anthropogenic nature of the observed rainfall decline across South Eastern Australia. Centre for Australian Weather and Climate Research (CAWCR) Technical Report No. 026, pp.202.

Teskey RO, Sheriff DW. 1996. Water use by *Pinus radiata* trees in a plantation. *Tree Physiology* **16**, 273-279.

Thorp, JR. 2001. Willow Strategic Plan. For the National Weeds Strategy Executive Committee, Launceston. http://www.weeds.org.au/docs/wilstrat.pdf.

Van Kirk RW, Benjamin L. 2001. Status and conservation of salmonids in relation to hydrologic integrity in the Greater Yellowstone Ecosystem. *Western North American Naturalist* **61**, 359–374.

Vertessy RA, Hatton TJ, Reece P, O'Sullivan SK, Benyon RG. 1997. Estimating stand water use of large mountain ash trees and validation of the sap flow measurement technique. *Tree Physiology*, **17**, 747-756.

Wei Y, Langford J, Willet IR, Barlow S, Lyle C. 2011. Is irrigated agriculture in the Murray-Darling Basin well prepared to deal with reductions in water availability? Global Environmental Change, 21(3), 906-916.

Wilson ME. 2001. Organic matter dynamics in willow and eucalypt lined central Victorian streams, Thesis submitted in total fulfilment of the requirements for Doctor of Philosophy, School of Science, University of Ballarat, Victoria.

Yeates LV, Barmuta LA. 1999. The effects of willow and eucalypt leaves on feeding preference and growth of some Australian aquatic macroinvertebrates. *Australian Journal of Ecology*, **24**, 593–598.

APPENDIX

Laboratory validation of sap flow

Introduction

Heat based sap flow methods to determine leaf level or whole tree sap flux have a long history (Swanson, 1994), with three methods commonly employed; heat pulse velocity, heat field deformation and thermal dissipation (Steppe *et al.*, 2010). The key issue however for each technique, is accuracy. Within this study, the heat pulse velocity technique is used to calculate plot scale water use of willows, information which will potentially lead to decisions to remove willow stands from riparian areas in southeastern Australia. It is therefore important that errors associated with sap flow measurements are reduced to prevent over or under estimation of tree water use by validating measured sap flow against actual xylem flow. A common technique described in detail in Teskey and Sheriff (1996); Smith (1991); Vertessy *et al*., (1997) is the cut-stem experiment. This technique was applied in Chapter 2 to validate use of Greenspan sap flow sensors in *Salix babylonica* with some success; however it appears *Salix* are very sensitive to xylem flow disruption created by stem segmentation and although applied to validate *Salix fragilis* sap flow, it proved unsuccessful. The Mariotte's bottle laboratory technique described in Steppe *et al*., (2010) was thereafter applied to *S. babylonica* and *S. fragilis* stems in the laboratory to ensure water use estimates were accurate for each species.

Method

Sap flow measurements were validated on willow stem sections in the laboratory using a Mariotte's bottle system (McCarthy 1934; Steppe *et al*., 2010). The Mariotte's system holds flow rates constant by maintaining a constant water pressure head on a 30 cm stem segment. Four sap flow sensor sets were installed at sapwood depths of 5 and 10 mm in two *S. babylonica* stems (*S. babylonica* Stem A and *S. babylonica* Stem B) and one *S. fragilis* stem. Heat pulse velocity was measured every 3 minutes while simultaneously collecting and weighing the water passing through the stem using an electronic balance (VIBRA, SHINKO DENSHI CO, LTD, Tokyo Japan). Heat pulse velocity was converted to sap flux density using the method described for sap velocity in Chapter 2. Conducting wood area was determined using starch stains, in particular Methyl Orange as described by Kutscha and Sachs (1962). The volume of water passing through the stem was converted to sap flux density by dividing by stem conducting wood area. The pressure head was increased once during each calibration with the stem left to equilibrate for 30 minutes.

Results and conclusion

The heat pulse and gravimetric methods produced similar estimates of sap flux density in *S. babylonica* and *S. fragilis* stems (Figure 1 and Table 1). The heat pulse method did not consistently over- or under-estimate sap flux density. The mean error was close to zero and errors ranged from a 7% over estimate in *S. babylonica* Stem A at pressure head 1 to a 7 % under estimate in *S. babylonica* Stem B and *S. fragilis* at pressure head 1. Variation between the two methods shown in Figure 1 was similar to that noted by Steppe *et al*., (2010) for this sensor type, with less variability shown at lower flows.

Steppe *et al*., (2010) identify a slight underestimation of sap flux using the Greenspan heat velocity technique, however of the three methods analysed, heat pulse velocity sensors provided the most accurate sap flux estimates. Based on the laboratory analysis for *Salix* and results presented in Steppe *et al*., (2010), the heat pulse method employed to quantify water use of willows, appears to provide accurate estimates of sap flux in *S. babylonica* and *S. fragilis* stems.

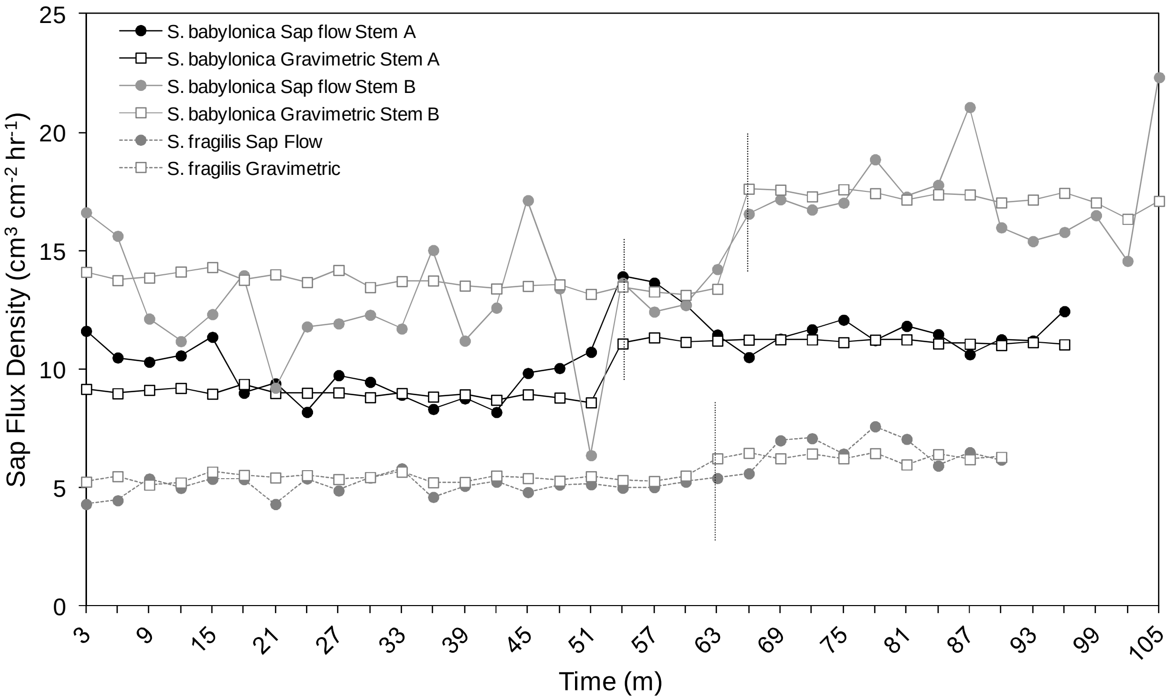

Figure 1. Comparison of sap flux densities measured by the heat pulse and gravimetric methods in three willow stems. Vertical dashed lines indicate pressure head increases.

Table 1. Comparisons of mean sap flux density determined from the heat pulse and gravimetric methods. Average sap flux densities are shown for three sample stems at two pressure heads (PH1 and PH2).

Stem Sample	**Mean sap flux density at PH1 (cm^3 cm^{-2} hr^{-1})**		**Mean sap flux density at PH2 (cm^3 cm^{-2} hr^{-1})**	
	Heat pulse	Gravimetric	Heat pulse	Gravimetric
S. babylonica Stem A	9.7	9.0	11.8	11.2
S.babylonica Stem B	12.8	13.7	17.4	17.3
S. fragilis	5.1	5.4	6.5	6.3