AN EXAMINATION OF DEFICIT IRRIGATION IN AUSTRALIAN COTTON SYSTEMS USING BIOECONOMIC MODELLING AND FINANCIAL AND RISK ANALYSES

A Thesis submitted by

Hanan Hassan Shukr

M.Sc, B.A. in Agricultural Economics

For the award of

Doctor of Philosophy,

2020

Abstract

Cotton is an important crop in Australia, where around 99% of the domestic crop is exported. In order to achieve the high yields and fibre quality for which Australian cotton is known, production systems require precise crop and field management, which includes irrigation management. Most Australian cotton is irrigated and more than 80% of irrigated cotton farms are located within the Murray-Darling Basin (MDB). Water resources in the MDB are however, subject to high demand and partial market forces, leading to generally increasing prices.

Scarce water for irrigation is however a limitation on production. Previous studies have reported that deficit irrigation (DI) practices are among solutions that can be employed to ameliorate limited water availability. These studies have generally focused on the application of DI on cotton crops to improve WUE and maintain yield, with very little research investigating the adoption of DI in terms of short and long term investment decisions. Nor is there much research comparing DI under different irrigation systems. The aim of this thesis was to investigate the economic impacts of using DI under flood (FI), overhead sprinklers (OSI) and sub-surface drip (SDI) irrigation systems at both the field and enterprise scales. Biophysical simulations and economic modelling were carried out to achieve the objectives of this study.

Goondiwindi, Moree, Narrabri, and Warren in the MDB were the study locations. The Agricultural Production System Simulator (APSIM) model was employed to simulate the impacts of different levels of DI practices for irrigation systems on lint yield, WUE and marginal water use efficiency (MWUE). The outputs of the APSIM model were used to calculate gross margins (GM/ha), (GM/ML), on average and for 10-years. The

10-year net present value (NPV) was also estimated. Bio-economic modelling was also used to investigate the economic investment required for the adoption of DI for the three irrigation systems at the enterprise scale. This was done through analyses including the estimation of equivalent annual annuity (EAA), payback period, and annual cash flows (ACFs).

The results showed that WUE and MWUE were maximised when applying between 40% and 80% of full irrigation (TF) across the three irrigation systems, but lint yield was maintained under the OSI and SDI systems for most locations by applying 80% of full irrigation (TF). Under the FI system, DI had no benefit in terms of increasing yield but showed marginal gains in terms of WUE, and MWUE. The results suggest that over time the OSI system offers the most economic benefits from using DI. By applying 40% of TF under the OSI system, the highest annual lint yields and the highest EAA were achieved. This system also attained the shortest payback period, with initial capital costs recovered within three years for all study locations compared to the FI and SDI systems at enterprise scale.

The results from the modelling suggest that there is a net benefit from adopting DI under OSI and SDI, however the overwhelming majority of cotton is produced under FI systems, which showed little benefit. Therefore, realization of any significant gains in terms or either or both, increased returns on water used and less water used in the MDB, from DI would first require changes in irrigation systems.

Certification of Thesis

This thesis is entirely the work of **Hanan Hassan Shukr** except where otherwise is acknowledged. The work is original and has not previously been submitted for any other award, except where acknowledged.

Principal supervisor: Professor Geoff Cockfield

Associate supervisor: Associate Professor Keith Pembleton

Associate supervisor: Dr Andrew Zull

Student and supervisors signatures of endorsement are held at the University.

Acknowledgements Statement

"In the name of Allah, the beneficent, the merciful"

I would like to initiate the acknowledgment with Allah (God) who has provided me with the strength and wisdom to finish my thesis.

Special thanks to the Prime Minister's Office of the Higher Committee for Education Development in Iraq for providing me with the scholarship to pursue this research. The financial support from the ministry is appreciated.

This research has been supported by an Australian Government Research Training Program Scholarship.

My deepest gratitude and specific thanks go out to my supervisors: Professor Geoff Cockfield, Associate Professor Keith Pembleton, and Dr Andrew Zull. We worked together as one team and they provided me with the guidance, encouragement, and advice to complete my study objectives successfully in a reasonable time. Their efforts are highly appreciated.

Thanks, must also go to the University of Southern Queensland's (USQ) School of Commerce, Centre of Agricultural Engineering (CAE) and Centre for Sustainable Agricultural Systems (CSAS) for providing me with the facilities, technical assistance, and funds to carry out the research.

I also wish to acknowledge Graham Harris, James Hagan, Shirley Mullens and all staff in the Department of Agriculture and Fisheries (DAF, Queensland) in Toowoomba for providing me with trustworthy data related to my research topic. Many thanks to Mr David Johnston from CSIRO who supported and advised me with using the APSIM model. I would like to thank the late Professor Steven Raine for his assistance in explaining some of the technical concepts of irrigation systems through this research study. I also want to express my sincere gratitude to Associate Professor Joseph Foley and Diogenes Antille in the Centre of Agricultural Engineering (CAE) who provided me with knowledge about cotton crop and Australian irrigation systems. I am grateful to Dr Rachel King for technical support with using the program R. My special thanks to Dr Barbara Harmes and Dr Douglas Eacersall for their helpful proofreading service. Finally, special thanks to my father, mother, brother and sisters who also supported me in my PhD journey. I am greatly indebted to all of you.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

A	Area of enterprise (1000 hectare)
APSIM	The Agricultural Production Systems Simulator
AUD	Australian dollar
CV	Coefficient of Variation
CRDC	Cotton Research & Development Corporation, Australia
DAF	Department of Agriculture and Fisheries, Australia, Qld
DI	Deficit irrigation
DW	DurbinWatson test
EAA	Equivalent annual annuity
FI	Furrow irrigation system
GM	Gross margin
GRDC	Grains Research and Development Corporation
MDB	Murray-Darling Basin
ML	Mega-litre
MWUE	Marginal water use efficiency
NPV	Net present value
NSW	New South Wales
OSI	Overhead sprinkler irrigation system
PAWC	Plant available water capacity
PP	Payback period
Qld.	Queensland State, Australia
ROA	Return on assets
SA	Sensitivity analysis
SDI	Subsurface drip irrigation system
π	Annual profit
USQ	University of Southern Queensland
VC	Variable costs
WUE	Water use efficiency

List of Publications

Unpublished paper: Drafted

1. Shukr, H, Pembleton, K, Cockfield, G, & Zull, A (2020) Effects of deficit irrigation on water use efficiency and yield in cotton irrigation systems (Paper drafted and ready to submit).

2. Shukr, H, Pembleton, K, Cockfield, G, & Zull, A (2020) The use of deficit irrigation practices to maximise economic returns for three cotton irrigation systems (Paper drafted and ready to submit).

3. Shukr, H, Pembleton, K, Cockfield, G, & Zull, A (2020) The economics of long-term decisions by cotton farming enterprises when incorporating the use of deficit irrigation (Paper drafted and ready to submit).

Chapter 1. Introduction

1.1. Overview

This thesis examined the potential impacts of deficit irrigation (DI) practices on the economic productivity and profitability of Australian cotton farming based on simulation studies within the Murray-Darling Basin (MDB) using a bioeconomic modelling approach. This chapter presents an overview of the thesis and the background to the research problem. An outline of the thesis structure is presented with a brief description of each chapter.

1.2. Research background

Cotton (*Gossypium hirsutum L.*) is an economically important crop (Redfern 2015), with India being the largest cotton producer globally (~26%) followed by China (~25%) and the USA (~15%)(Kaur et al. 2019; Yadav et al. 2018). Although Australia's contribution to the global cotton supply is relatively small (4%), it is the third-largest cotton exporter in the world. Australia exports up to 66% of its national production, with the bulk of this export volume going to China (ABARES 2018; Williams et al. 2015). The cotton industry contributes approximately A$ 2.2 billion annually to the Australian economy, and provides employment for about 14,000 Australians (Azad and Ancev 2016). Deregulated and increasingly open water markets have been the mechanisms that have allowed for the expansion of the cotton industry (Adamson et al. 2009) have demonstrated improved water use efficiency (WUE), increased yield, and/or reduced water use (Cammarano et al. 2012; Luo et al. 2017; Peake et al. 2016; Qureshi et al. 2014; Rodrigues and Pereira 2009) .

Around 90% of Australian cotton is grown in Northern New South Wales (NSW) and Southern Queensland (Qld) (Mebrahtu et al. 2017). The majority (80%) of irrigated cotton farms is within the Murray–Darling Basin (MDB), which is Australia's largest river system (Williams et al. 2018).The most common irrigation system used for the Australian cotton crop is furrow irrigation (FI) because it is relatively inexpensive and requires a lower initial equipment cost; thus more than 83% of the cotton area is irrigated by FI (Gude 2016; Raine and Foley 2002). However, although it is inexpensive, this system is less efficient because of the extensive water loss (McGuire et al. 1998; Narayanamoorthy 2005). Some cotton growers have therefore started to adopt other approaches to irrigation (Peake et al. 2016). Other more efficient irrigation systems, such as overhead sprinkler irrigation (OSI) and subsurface drip irrigation (SDI) systems, are proposed as means of increasing WUE, thereby maximising economic returns (Roth 2010; Roth 2014; Smith et al. 2015).

Worldwide, irrigation water resources are becoming severely depleted and degraded owing to an unprecedented demand for water-derived commodities (Azad and Ancev 2016; Lorite et al. 2007; Roth 2014; Stiller and Wilson 2014). Uncertainty in water availability is a key issue for the agricultural sector because of the impact of climate change (Tilman et al., 2011, Mueller 2012; Elliott et al., 2014). However, other issues that relate to the rising demand for alternative uses of water include agriculture (other crops), the environment (climate change), and needs of domestic communities. Furthermore, seasonal variability in water supplies presents a planning challenge for industries such as irrigated cotton, and the issue of variability in supplies creates seasonal water scarcity (Cammarano et al. 2012). This has a significant effect on water markets and therefore presents a major challenge for growers (Kirda 2002; White 2007). Multiple competing uses are another issue, as these uses result in increased water costs, adding to the cost of water utilised for irrigation (Azad and Ancev 2016; Roth 2014; Stiller and Wilson 2014). For example, in Australia, the irrigated agricultural industries are under increasing pressure to keep farms economically viable in spite of reduced irrigation water allocations and increased competition for water (Braunack 2013; Cammarano et al. 2012; Maraseni 2012a; Roth 2010). In a dry year, the MDB irrigators cannot access adequate water to irrigate fully under traditional irrigation systems. Particularly over the past two decades, inflows have decreased which has resulted in increased competition for water (Cammarano et al. 2012). This in turn had implications for both national consumption and the agricultural sector, which has then led to pressure on farmers to increase WUE and/or water productivity (WP) (Qureshi et al. 2013b). Since water shortages can result in decreased crop yield per unit area (Luo et al. 2017; Roth 2010), the limited water needs to be carefully managed and the choice of the irrigation system is critical to both productivity and profitability (Enciso et al. 2015).

The key concerns for cotton growers regarding irrigation are the seasonal scarcity of water, reduced water allocation for irrigation and also uncertainty, competition and increased cost of water, owing to the combined effects of increasing relative scarcity of water (Linker et al. 2016). To avoid this issue, the use of advanced irrigation systems in the Australian cotton industry has increased with a noticeable development in the irrigation technologies in the last 20-30 years. However, the use of advanced irrigation systems is not enough to overcome the water scarcity issue. The Australian cotton industry can adopt several approaches to improve water use and increase WP in order to maintain its productivity of cotton crops. One of these approaches is deficit irrigation (DI), which is the application of water below the full crop-water requirements (Adeyemi et al. 2017; Fereres and Soriano 2006).

DI is the application of water below the full crop-water requirements (Adeyemi et al. 2017; Fereres and Soriano 2006). DI can be employed as an adaptation in drought years, or when water is limited for other reasons, or it can be employed more regularly as a means of improving WUE to ensure a more efficient and effective use of water without compromising crop yields substantially, thereby saving water and increasing economic returns (Geerts and Raes 2009; Linker et al. 2016). Several studies have confirmed that the adoption of DI plays a significant role in optimising water use in cotton crops without compromising yields, resulting in an increase in net income (Cammarano et al. 2012; Geerts and Raes 2009; Qureshi et al. 2013b). This implies increasing economic returns and minimising the total cost of water consumed (Expósito and Berbel 2017). Even where water availability is less constrained, the adoption of DI, can enable an increase in the area being irrigated, can or can provide more water for alternative uses (Chai et al. 2016a; Fereres and Soriano 2006). However, achieving these outcomes might depend not on the irrigation system's performance, but instead on the flexibility of the system, the irrigation scheduling adopted, the production costs and the consequent yields obtained (Rodrigues and Pereira 2009) .

In particular, studies should focus on the strategic benefits of DI in terms of short-term decision-making under different irrigation systems, such as FI, OSI and SDI

(Cammarano et al. 2012; Luo et al. 2017). Some studies have highlighted short-term (ignoring overhead and capital costs) and long-term decision- making. The potential for DI to increase irrigated areas and to improve enterprise total yields and net benefits for Australian cotton production, has also been articulated. However, there is a lack of comprehensive bio-economic studies of the outcomes from the long-term use of DI that include consideration of capital investment in different irrigation systems with DI. Therefore, this thesis focuses on the economic assessment of DI adoption, from both short and long term perspectives. This study also examines the economic benefits at the field scale, concentrating on maximising gross margins, using DI with three irrigation systems. Finally, this study investigates the economic benefits of investments in irrigation systems at the farm enterprise scale for using DI, under a 20-year time horizon. Bio-economic modelling, incorporating biophysical simulations and economic modelling, are used in this thesis. The findings presented in this thesis make an important scholarly contribution to growing body of knowledge and provide new insights to using DI under three different irrigation systems for Australian cotton production in different cotton farming areas within the MDB.

1.3. Thesis outline

The remainder of this thesis consists of five chapters (Figure 1.1). A brief overview of these chapters is presented below:

- Chapter 2 provides an overview of Australian cotton production, Australian cotton irrigation systems and the comparison between irrigation systems in terms of cotton yield and WUE. This chapter also presents an overview of DI practices and applications of DI on cotton crops for three irrigation systems. In this chapter, economic aspects of DI practices, the Agricultural Production Systems Simulator (APSIM), bio-economic models and the application of biophysical and bio-economic modelling to understand DI practices are reviewed. The summary of the literature and the research gap are presented, and the chapter also identifies the research problem, the research aim, the hypothesis of this study, and the research questions and research objectives.

- Chapter 3 investigates the impacts of various levels in the subsequent use of DI on lint yield, WUE and MWUE under three cotton irrigation systems across four locations within the MDB.
- Chapter 4 investigates the economic effects of different levels of DI for three irrigation systems on cotton production at the per unit area for short-term decisions across the study locations in the MDB.
- Chapter 5 investigates the economic impact of using DI to maximise net benefits at the enterprise scale for long-term economic investment decisions for three irrigation systems across the study locations in the MDB.
- Chapter 6 discusses the overall results of the previous three chapters in general and presents the overall outcomes and conclusions about the knowledge derived from this study. Further research that could address some of the identified limitations of the current research is recommended.

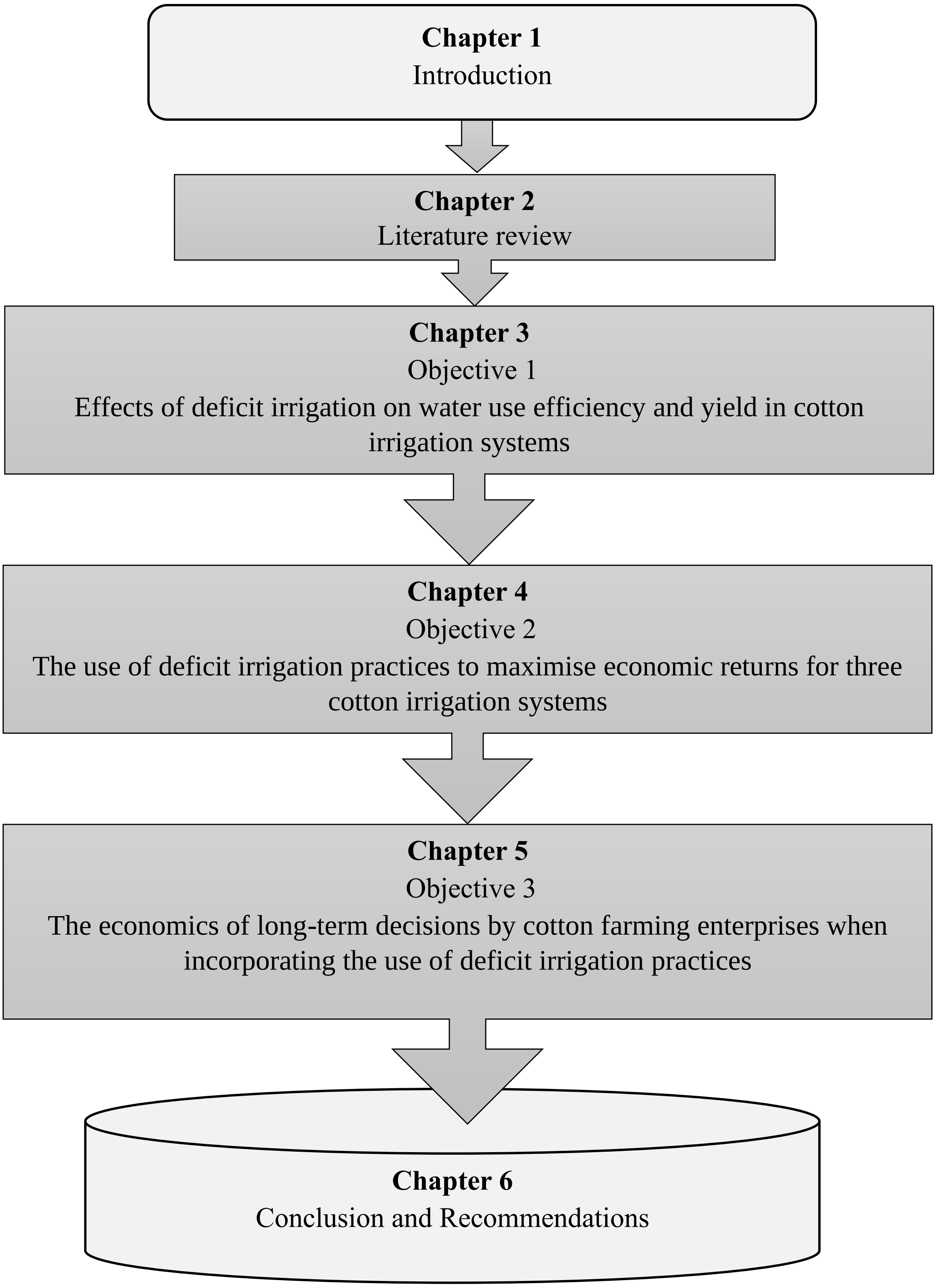

Figure 1.1*:* Block diagram outlining the thesis structure.

Chapter 2. A review of irrigation systems and deficit irrigation practices therein

2.1. Introduction

In the previous chapter, the importance of understanding the economic aspects of cotton production was outlined. The Australian cotton industry faces significant challenges due to increased climate variability associated with global climate change. This obviously exerts an impact on the amount of crop water required and the availability of water for irrigating crops. These challenges highlight the need for appropriate management decision making in terms of water use and water productivity for Australian cotton. The first part of this chapter provides an overview of the Australian cotton industry and reviews the literature related to cotton irrigation systems, yields and water use efficiency (WUE). Deficit irrigation (DI) practices are then touched on in as a potential approach to addressing challenges related to limited water availability. The second part of this chapter looks at bio-economic modelling. The Agricultural Production Systems Simulation (APSIM) is reviewed for its role as a farming systems biophysical model. This chapter concludes with a detailed review of relevant literature to identify the research gaps, from which the main aim of the research is stated, the hypothesis and the research objectives are presented, and the research questions are developed.

2.2. Australian cotton production

Cotton is one of the most important and profitable broadacre crops in Australia (Cammarano et al. 2012; Luttrell et al. 1994). *Gossypium hirsutum L* (*G. hirsutum L*) is the major species of cotton grown in Australia (Eskandari et al. 2017; Eskandari et al. 2018; Redfern 2015) constituting approximately 90% of the world cotton production, and is characterised by its relatively high quality (Liu et al. 2017; Sui et al. 2012). *G. hirsutum L.* is well suited to the range of growing conditions encountered in the main production areas. In Australia, cotton is grown under two systems, irrigated and dryland (Godfrey et al. 2019). There are 18 production areas within the Murray-Darling Basin (MDB) (CSD 2017), with the larger northern New South Wales (NSW) region accounting for about 66% of Austalian cotton production, while southern Queensland (Qld.) contributes about 33% of the production volume. The locations are largely a function of the historical availability of water for irrigation, the suitability of the climate, and the suitability of the soils (Williams et al. 2015). The total production area generally ranges between 200,000 and 300,000 hectares (DAF 2015) and this varies with seasonal conditions, consequent water availability of water for irrigation and cotton prices.

The majority of Australian cotton growing areas are located in the MDB (Hulugalle et al. 2016), in the south-east and central eastern inland parts of Australia (ABS 2012; ABS 2016). The MDB is the biggest river basin in Australia (1 million km^2) and accounts for more than 40% gross value of agricultural production in Australia (ABS 2012; Kirby et al. 2014). The MDB covers approximately about 14% of Australia land mass and extends across four states (Queensland, New South Wales, South Australia, and Victoria), and the Australian Capital Territory (Hulugalle et al. 2016; Quiggin

2001). The number of farms producing cotton in the MDB in 2015/2016 was 1094, with this number increasing to 1436 in 2017/2018 (Godfrey et al. 2019). The MDB is, however, affected by several issues prevalent in agricultural systems throughout Australia, drought is the most serious. Also, acid soils, dryland salinity, and a number of pests and invasive weeds are common challenges for agricultural producers (Adamson et al. 2007).

Given the impact of drought on the economic value of cotton , irrigation is part and parcel of growing cotton that significantly affects the commercial value (Reddy et al. 2020). The growing season in Australia typically takes place during the summer with several growing stages. It can be seen from

Figure 2.1 that Australian cotton crops are normally planted between mid-September and the end of November, with defoliation and harvesting occurring from March to May (Antille 2018 ; Hulugalle 2016). When irrigated, the initial irrigation is generally applied close to planting, with subsequent 4-5 irrigations occurring between November and February as the crop develops (DAF 2010). A final irrigation is normally applied before defoliation and harvesting (Monsanto et al. 2016). Overall, Australian cotton is considered to produce excellent crop in terms of quality and quantity. Unfortunately, under water scarcity conditions in the MDB, Australian cotton needs large quantities of irrigation water with higher resultant production costs per unit.

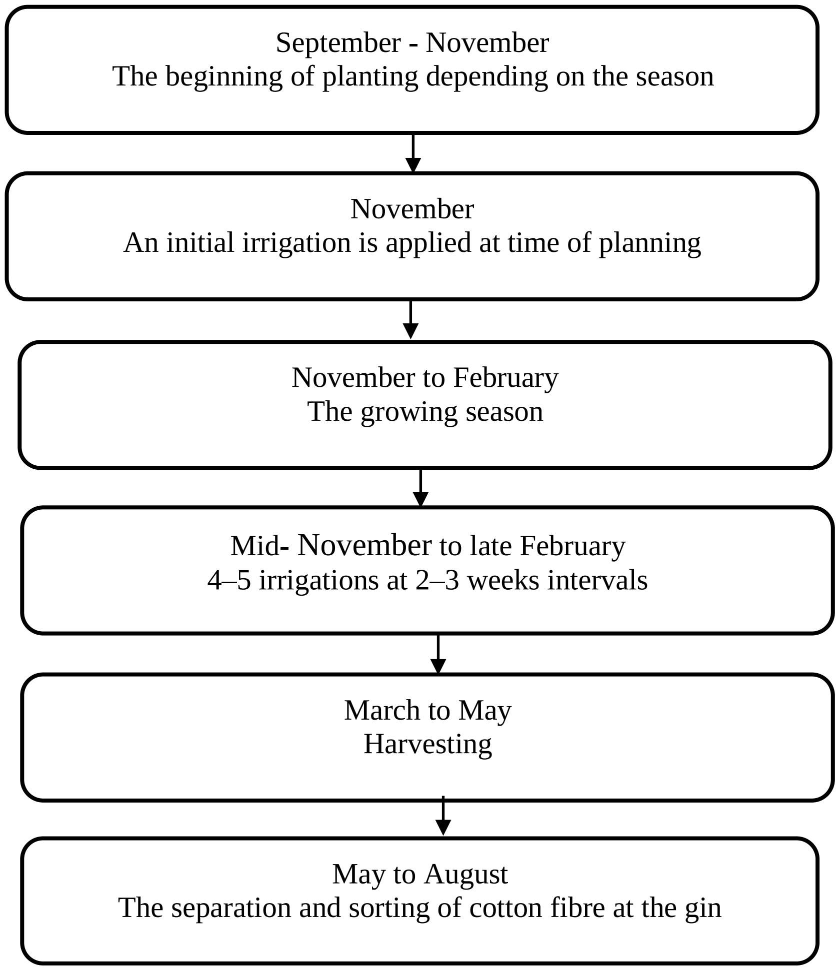

Figure 2.1: The stages of Australian cotton growing.

Source: Adapted from Cotton Australia (2019).

2.3. Australian cotton irrigation systems

As mentioned above, irrigated crop performance and productivity are directly affected by the irrigation system (Çolak et al. 2018). Irrigation supplies crops with supplementary water for growth (Cammarano et al. 2012). Worldwide, more than 53% of cotton farms use some form of irrigation and irrigated crops constitute approximately 73% of the global cotton production (Chapagain et al. 2006; Soth et al. 1999). River systems, particularly in the MDB, have however, become depleted (Kodur and Robinson 2014; Seidl et al. 2020; Wheeler et al. 2020) with increasing demand for scarce water (Zhou et al. 2012) and lower inflows due to an increasing number of relatively dry years. Around 20% of the MDB cotton area is not irrigated, and as such is a dryland production system (ABS 2012; Anwar and Darbyshire 2017; Turral et al. 2005). Irrigation requires significant financial investment and operating cost outlays, thus expected toincrease the productivity (yield/ha) substantially in order to enhance economic returns for growers (Payero and Khalilian 2017).

Three main irrigation systems used by Australian cotton growers are furrow irrigation (FI), overhead sprinkler irrigation (OSI), and subsurface drip irrigation (SDI). The FI is a gravity-fed surface irrigation method while OSI and SDI are pressurized irrigation systems (McCarthy 2010; Pratley 2003). Recent research and technological advancements have particularly focused on increased WUE in arid and semi-arid areas

(Deng et al. 2006). Overall, both OSI and SDI systems are new irrigation technologies and are increasingly used in Australia (McCarthy 2010). The majority of irrigated Australian cotton farms are ,however, still irrigated by FI system (Gude 2016; Raine and Foley 2002; Williams et al. 2018). Following in a detailed discussion of these three irrigation systems in terms of their performance, productivity, efficiency, advantages, disadvantages and production costs per unit area.

2.3.1. The furrow irrigation system

Furrow irrigation (FI) is one of the oldest and most common methods of surface irrigation and is appropriate for a range of crops, particularly row crops including cotton (Brouwer et al. 1988; Koech et al. 2014; Raine and Foley 2001). It is used on more than 83% of Austcotton farms (Conaty 2011; Roth 2014). In this system, water is applied to furrows which have a slight gradient to facilitate water flow. A furrow runs down between crop rows (Koech et al. 2014; Pereira 1999). Polyethylene pipes are commonly utilised to siphon water from a supply channel at the elevated end of a field into the furrows (Esfandiari and Maheshwari 1997) (Figure 2.2). The siphon pipes normally range between 5 m and 7 m in length and between 45 mm and 50 mm internal diameter (Koech et al. 2010). The siphoning action is normally started manually with one end of the pipe submerged in the supply channel water, while the other end is left to drain into the furrow at a lower level (Koech et al. 2010). Several factors can affect FI efficiency, such as furrow configuration, soil type, field slope and evenness, and the required wetting depth for the irrigation application (Walker 1989). Although, the water efficiency of the FI system can be as high as 60%,one of the adisadvantages of FI is that it has inherent water losses such as deep drainage, evaporation, and runoff into the tail – drain. Managing irrigation cut off based on the presence of water at the tail- drain can reduce run-off losses but cannot be considered in the irrigation application which reduces application efficiency (Antille 2018; McHugh et.al 2008). Advantages as well as disadvantages of the FI system are presented in Table 2.1. In brief, FI is the most commonly used in cotton irrigated areas in Australia because of its cheaper infrastructure compared to other systems. Nevertheless, when irrigation water is limited, the cost of irrigation water per unit area will be more expensive, which may lead to reduced economic returns. In addition, this system has less efficiency and water productivity, plus, its efficiency can be affected by many factors such as soil type and field slope.

Table 2.1: Advantages and disadvantages of the FI system.

Advantages	**Disadvantages**	**References**
Applicable to most soil types, except those which are highly permeable. A very reliable and flexible method that can improve WUE.	Erosion is a key concern. Salinity can be a large problem with salts tending to accumulate on the tops of the ridges.	(Burton 2010; Conaty 2011; Conaty et al. 2018)
	Limited/restricted access to farm machinery	(Antille 2018)
A relatively inexpensive method in terms of operating costs and energy requirements.	Higher water runoff.	(McGuire et al. 1998; Narayanamoorthy 2005)

Low operating energy costs Low maintenance and low capital setup costs.	High labour resource requirement.	(Narayanamoorthy 2005)
Lower initial cost of equipment. Lower pumping costs.	Higher labour costs. Lower application efficiency and water predictivity compared to other techniques.	(Antille 2018)

Figure 2.2: Furrow irrigation system at Goondiwindi (siphon method).

Source: Adopted by the researcher from a field day.

2.3.2. Overhead sprinkler irrigation system

The overhead sprinkler irrigation (OSI) system comprises a system of sprinklers that are normally supported by a moveable boom (centre pivot or lateral move) (Figure 2.3

). The OSI system is a self-driven system in which one pipeline propped up by a row of towers is suspended 2 m to 4 m above the ground (DAF 2018b; Heermann and Hein 1968; Omary et al. 1997). It consists of pump sprinklers and pressure regulators (CRDC 2012; Laurenson et al. 2018), and the traveling speed can be controlled according to the crop types and crop water requirements (Barbosa et al. 2018; Laurenson et al. 2018). Around 10% of Australian cotton farms use an OSI system (Smith et al. 2015). The key advantage of this system is that it provides higher irrigation efficiency, and saves a large amount of water, compared to FI system (Tarjuelo et al. 1999). The efficiency of OSI system increases when matching the amount, and rate of water application to soil conditions and crop demands (Dukes and Perry 2006; Foley and Raine 2002; Zhu et al. 2018). The water efficiency of the OSI system can be as low as 75%. However, although the OSI system can be more effective at applying the right amount of water to match crop requirements, that is, providing more than 80% of application efficiency compared to the FI system, there is still the potential for losses of water because of evaporation (Maas 2013). The OSI advantages and disadvantages are summarised in Table 2.2. Overall, the OSI system has a higher infrastructure cost per unit area, but in the long term, this system becomes cheaper, especially when irrigation water is limited. The system also has more efficiency in terms of WUE and WP, and it is of high economic viability.

Table 2.2: Advantages and disadvantages of the OSI system.

Advantages	Disadvantages	References
Well suited to soils with high infiltration rates. No flushing and no salt build up at irrigation zone The flexible system works either large field or small field System engineered to keep up with evaporative demand The ability to regulate soil moisture through the crop life cycle.	Higher operating energy and maintenance costs. Can be hard to match the booms to irregular shaped fields or plots.	(Brown 2008; Conaty 2011; Conaty et al. 2018; Grabham 2012)
Reduction in labour costs. Saving water and increasing WUE.	A lot of energy required to transfer water from the source to crop.	(Roth 2014)
Less labour intensive than other techniques. Low water runoff. Water coverage under the centre pivot is very even.	Greater chance of evaporation and wind drift. High maintenance cost. Trees have to be removed, increasing erosion.	(Spivey et al. 2018)

+20-year life	
	Highly saline water causes leaf burning when the temperature is higher than 95 F

Figure 2.3: Overhead sprinkler irrigation system at Goondiwindi.

Source: Adapted by the researcher from a field day.

2.3.3. Subsurface drip irrigation system

The drip irrigation (SDI) system is used in Australia and globally to irrigate a variety of crops including cotton (Lamm 2016; Perry et al. 2012). The SDI is a system of underground piping that delivers low amounts of water frequently (Wang et al. 2020). Asthe newest and most water efficient method of irrigation (Kalfountzos et al. 2007; Schmidt et al. 2018), SDI is particularly useful under limited availability of water supply and in drought conditions. Figure 2.4 illustrates the SDI system installed in a cotton field. The SDI system consists of a set of plastic tubes buried underneath the soil surface, along the crop row . Water emitters are embedded in the tubes at uniform spacing (Camp et al. 2000; Conaty 2011; Devasirvatham 2008). These tubes can be installed 20 mm– 45 mm directly underneath the centre of each crop row and discharge an average of 2 litres per hour at 1.41kPa (Ayars et al. 1999). The water efficiency of the SDI system can be as low as 90%. The efficiency of SDI systems in terms of water application is often higher than 90% (Amparo Martinez-Gimeno et al. 2017; Pendergast et al. 2014; Raine et al. 2000). Therefore, savings of approximately 23% of water can be achieved thanks to the SDI system compared to the OSI system (Martínez-Gimeno et al. 2018). By using SDI, evaporation is minimised which contributes to higher WUE (Irmak et al. 2016; Wang et al. 2018). Furthermore, it can save water and increase yields by 33% comparison with to the OSI system(Jacques et al. 2018). However, one of the disadvantages of the SDI system is the higher initial costs. Further performance of the SDI system can be affected by clogging, root pinching, root intrusion, termite damage, mechanical damage, and compaction (Abuarab et al. 2013; Lamm et al. 2012). Moreover, Its commercial life tends to last less than 11 years (Lamm et al. 2012). Complete details about this system's. advantages and disadvantages are delineated Table 2.3. Overall, SDI is an expensive system in terms of infrastructure costs, higher maintenance requirements, and limited system life per unit area when compared with other systems. This system, however, has advantages regarding using less water (saving water) and higher efficiency than other systems. Thus, it is possible to expand and increase the irrigated areas under the system through saving water and maximising economic returns.

Table 2.3: Advantages and disadvantages of the SDI system.

Advantages	Disadvantages	References
Can cope with small and odd-shaped fields. Potentially most efficient irrigation method available. Water savings Low runoff Enhanced fertiliser efficiency. Limits the spread of (water-borne) weeds.	High capital setup costs. Salt build up at irrigated/non-irrigated zone boundary; difficult to correct; reduced soil structure/porosity; soil amendments required and large volumes of high-quality water required	(Geerts and Raes 2009)
Reduces the need for manual labour throughout the year.	Needs a lot of energy to transfer water from the source to crop and transfer water to the machines in the underground pipes.	(Conaty 2011; Conaty et al. 2018; Grabham 2012)
Reduced topsoil evaporation. Lower labour demands.	Higher investment per unit area. Higher maintenance requirements and limited system life.	(Enciso et al. 2005; Wilde et al. 2009)
1 to 10-year life span	Reduced upward water movement: depending on installation depth and soil characteristics. This may	(Antille 2018)

be particularly troublesome on soils
With vertical cracking, salinity may be increased above the dripline.

Figure 2.4: Cotton field irrigated by the SDI system.

Source: Adopted by the researcher from a field day.

2.4. Comparing yields and water use efficiency between irrigation systems

The choice of irrigation system has a significant effect on not only the production costs of crops, but can also, to some extent, crop productivity (Camp 1998; McHugh et al. 2008).Viewed in this way, this section compares, the three irrigation systems in terms of cotton yield and WUE: furrow irrigation (FI), overhead sprinkler irrigation (OSI) and subsurface drip irrigation (SDI). For a better understanding of the following comparisons, some terms will be defined first a number of definitions have been discussed. WUE is a metric used to indicate how efficiently water is being converted to a measurable output in terms of crop production, with output signified by yield. The value calculated for the metric will be dependenton the input value, such as irrigation water only or irrigation plus rainfall. Irrigation water itself can be reported as the amount removed from a storage, or as the amount applied to a crop (Alghory and Yazar 2019; Steduto 1996). The three irrigation systems can be compared for both yield and WUE.

2.4.1. Cotton yield

Compared to dryland production, cotton crops can be supplied with water using frequent irrigation in order in order to significantly boost yields (Williams et al. 2018). The periods between irrigation events are usually long enough for the soil to dry to a point of mild water deficit stress (Loka 2012) which could then start to reduce yield potential. Under the FI system, in rare cases, depending upon soil conditions and prevailing weather conditions, the flooding of the crop during an irrigation event can conversely Other irrigation methods can also create prolonged saturated conditions (waterlogged) if the system is not managed well (Koech et al. 2014; Pereira 1999).

An OSI system should allow adequate water to be supplied to a cotton crop, provided the system is well designed (McCarthy 2010; Pratley 2003). With this system, the intervals between irrigations can be shorter than those with the FI system, thus reducing the risk of the crop suffering water stress (Loka 2012). On the other hand an OSI system can apply smaller amounts of water more evenly across a field, so it can a reduce the risk of the irrigation system causing waterlogging at any point in the cotton field (Foley and Raine 2002; Tarjuelo et al. 1999). However, a potential drawback of an OSI system is the risk of not being able to supply adequate water to a rapidly growing crop under hot, dry conditions. This, again, can be subject to the design of the system and capital outlay at the time of establishment.

Previous research has shown that SDI is capable of producing greater cotton yields than either the FI or the OSI systems. For instance, yield gains of up to 21% more than an OSI system (DAF 2018b) and 13%–29% higher than the FI system, have been reported (Darouich et al. 2014; Sorensen et al. 2011). Similarly, Colaizzi et al. (2004) also found increased cotton yields under SDI compared to an OSI system. These increases were attributed to more uniform soil water distribution within the root zone during the growing period under SDI, compared to FI and OSI systems (Sammis 1980). On top of that, irrigation through an SDI system can also play a significant role in preventing nutrient leaching from the soil profile, which could reflects positively on cotton yields compared to an FI system (Camp 1998; McHugh et al. 2008). Overall, the studies above showed that both OSI and SDI systems have produced higher yield than the FI system, but they did not compare profitability and, more particularly, not consider relative capital costs over time.

2.4.2. Water use efficiency (water productivity)

Water use efficiency (WUE), or water productivity (WP), refers to the dry grain yield per unit cropland divided by the amount of water consumed by the crop (ET, mm) to produce that yield (Fan et al. 2018). WP or WUE, expressed as an efficiency term, indicate the amount of marketable product in relation to the amount of input needed to produce that output. WUE is also known as the ratio of water used in plant metabolism to water lost by the plant through transpiration. WP describes the ratio between the quantity of an agricultural product (biomass, yield) and the amount of water depleted or diverted (Fan et al. 2018; Hatfield el al. 2019). In general, there is no difference between WP and WUE nor one definition that can be provided to distinguish them (Evans and Sadler 2008; Stewart and Steiner 1990). Irrigation engineers employ the term WUE to assess the efficiency of water delivery to a field or an irrigation unit, whereas agronomists, plant physiologists, and water resources managers use WUE to assess plant production over water use. The latter came up with the term water productivity to highlight the distinction between the two (Cha et al. 2016).

In an irrigation system, the efficiency is, amongst other things, a function of evaporation, deep drainage, runoff and crop water use through transpiration (Evans and Sadler 2008; Stewart and Steiner 1990). Improvements in irrigation technologies for the agricultural sector are often aimed at improving WUE (Al-Ghobari et al. 2015; Waterman 2017). They are driven by research and industry efforts utilising the emerging technologies to combat the problem of water scarcity and enhancing WUE in the agricultural sector, especially in cotton production (Qureshi et al. 2011; Stanhill 1986). The focus of research on WUE in irrigated cropping systems includes: (1) minimising water losses, and (2) applying water efficiently to a crop (Howell 2001; Huang et al. 2005). Improved WUE can be achieved by boosting the efficiency of water delivery and system application, as well as improving the timing of irrigation scheduling (Qureshi et al. 2011; Stanhill 1986). Many researchers (Pascale et al. 2011;

Farquhar and Richards 1984; Zhang et al. 1998) have found that optimised root growth will result in greater WUE.

Both the OSI and the SDI systems can have a higher WUE than the FI system (Camp 1998; McHugh et al. 2008). In particular, adopting an OSI system has been found to improve WUE, as OSI needs less than half of the water required for an FI system to achieve the same yield (Harris and Shaw 2007). In their work, Martínez and Reca (2014) concluded that an SDI system could improve WUE, and needed only 80% of the water required for FI. In the same vein, based on their study in India, Aujla et al. (2008) reported that irrigation by SDI triggered increased WUE of cotton crops by approximately 75%. Around 18%–42% of water can be saved when using SDI systems for cotton crops compared to using the FI system (Hutmacher et al. 2001; Ibragimov et al. 2007). More importantly, with the same amount of irrigation water,using the OSI and SDI systems can achieve higher yields than using the FI systems; that is, they givegreater WUE (Jha et al. 2016; Lowien and Gall 2106). In onther words, it could be concluded from the above findings that WUE can be more ameliorated under the OSI or SDI systems than under the FI system. Yet FI has been and remains by far the most dominant irrigation system forAustralian cotton, which suggesting that, either WUE and yield benefits are not as greatas was previously believed, or there may be other management benefits or economic benefits of FI. This confirms the water-saving potentials presented earlier. As recommended by the studies cited above, crop WUE could be significantly improved with a reduction in irrigation water. For example, using DI may increase yields and improve WUE. This development is driven by research and industry efforts utilising emerging technologies to combat the problem of water scarcity and improving WUE in the Australian agricultural sector with a focus on cotton production. Although there are a number of important factors affecting the feasibility assessment of the different irrigation systems, as was discussed previously, the focus of this chapter is directed only to the economic aspects of cotton production.

2.5. Water availability for irrigated cotton production in the MDB

Many of the world's agricultural systems and regions are confronting a drier future with an increased frequency of extreme weather events, such as droughts (IPCC, 2019). Cotton growers have recently faced a dramatic change in the form of droughts and warming temperatures, reduced irrigation water and a true decline in agricultural production prices, as well as the deterioration of rural community services (Wheeler 2020). This is especially true for Australia's MDB, a region already enduring a highly variable climate. Indeed, much of the MDB has been experiencing drought from 2017 onwards, leading to a rapid increase in permanent and temporary water prices (DELWP, 2019). The rapid rise of water prices means that water is sometimes one of the most valuable commodities owned by an irrigation grower in the MDB (Reba et al. 2014; Seidl et al.2020).

Irrigation devices have to be proven resilient to changing commodity markets and water availability (Iglesias el al.2015; Meyer el al. 2014). However, the tools needed to consider future market scenarios and climate-affected factors are not available in the case of irrigation in the MDB. The key finding was that a rise in total rainfall significantly promotes cotton growth and lessens the drought risk, while lower rainfall engenders the greater likelihood of drought risk and cotton growth reduction. Also a fluctuation in rainfall indicates an increased probability of extremely large or small rainfall, which significantly minimises the risk for growers (DEEDI 2011; Quigley 2017). Reduced rainfall, competition from other uses, policy requiring “environmental flows” and competitive water markets have resulted in higher water costs and concerns for the reliability of water supplies. If not for water trading, the uncertainty would be much higher and the cotton expansion may not have occurred (Roth 2014; Stiller and Wilson 2014).

Global growth in population, changing market demands, diminished productivity gains, future climate uncertainty and reductions in irrigation water availability (Elliott et al., 2014; Mueller 2012; Tilman et al., 2011,) are combining to change the operating environment of the agricultural systems. However, fluctuating temperatures and droughts in Australia have played an important role in growers’ decision-making, as this continent is severely affected by these fluctuations (Muhammad et al., 2010).

Irrigation water in the world has become more and more scarce owing to: (1) variability in the climate (Pitman and Läuchli 2002); and (2) higher demand for water for industry and urban consumption (Rao et al. 2016; Ünlü et al. 2011). In Australia, limited water availability for irrigation has resulted from changes in water policies, conflicting demands, climate uncertainties, and extreme and recurrent dry spells (Muhammad et al. 2010). The prospect of ongoing limited availability of irrigation water, particularly as drought conditions are predicted to worsen in Australia with climate change (Kirby et al. 2012; Qureshi et al. 2013b; Seidl et al. 2020), heightens the need for changes to irrigation management. However, these issues have been mentioned superficially, rather than addressed effectively. The case for significant improvements to WP (i.e., the more effective use of water to maximise profits) in cotton thus needs to be established more effectively (Camp 1998; McHugh et al. 2008). (DEEDI 2011; Quigley 2017).

The limited availability of irrigation water requires fundamental changes in irrigation management, and promotes the application of water saving techniques (Roth 2014; Stiller and Wilson 2014). FI is a good example. This irrigation system tends to over-irrigate croplands, resulting in a waste of water and low WUE (Muhammad et al. 2010; Yazar et al.2002b). By contrast, technology-based irrigation systems such as OSI and SDI, either spraying water on plants or dripping near their root zone, save 30%–70% of the irrigation water, and have gained increasing popularity in irrigated agricultural production (Ibragimov et al., 2007, Kang et al., 2012, Yazar et al., 2002b). With unique agronomic and economic advantages, these systems (OSI and SDI) also show the potential of precisely applying water and chemicals across croplands, which in turn reduces labour and energy inputs (Gärdenäs et al., 2005, Levidow et al., 2014). Comparative results regarding the irrigation effects on cotton have demonstrated that OSI and SDI systems lend support to increased yields and more efficient water use than FI (Bucks et al. 1988, Hodgson et al. 1990, Mateos et al. 1991;Reba et al. 2014).

In addition, while research into DI is not new, as is shown below, only limited literature compares the economic aspects of field scale and farm enterprises scale of adoption of DI for cotton production (Dağdelen et al. 2009). Australian cotton is considered to be the second-highest water-consuming crop (Williams et al. 2018), requiring an average of 5.2 mega-litres per hectare (ML/ha) (Conaty 2011; Cotton Australia 2019). These factors emphasise the need for the adoption of water saving technologies and practices, such as the refinement and application of DI (Dağdelen et al. 2009). In other words, there is a need for the more efficient use of irrigation systems that can not only save water but increase cotton production as well.

Water availability has been a limiting factor of yield for Australian cotton in recent years, as growers are reducing either the amount of water applied per hectare or the number of cotton plants, owing to water scarcity, particularly within the MDB. The increases in application efficiency as a result of irrigation optimisation would lead directly to increased yields rather than minimised production costs if fields were already fully irrigated. The fundamental issues of opportunity costs and trade-offs are driven by research and industry efforts utilising the emerging technologies to combat the problem of water scarcity in the agricultural sector, with a focus on cotton production. More research is required for economic analysis and risk mitigation in order to provide a critical discussion of where this work stands with regard to these concepts. This is because the DI is a strategy used in some scenarios rather than a solution that fits all problems generated from water scarcity in the agricultural sector.

2.6. Overview of deficit irrigation practices

Deficit irrigation (DI) is the application of irrigation below full crop-water requirements (Adeyemi et al. 2017; Fereres & Soriano 2006). DI is generally defined as an irrigation practice whereby a crop is irrigated with an amount of water below the full requirement for optimal plant growth (Zonta et al. 2016).The main aim of DI practices is to increase WUE or WP while maintaining, or even increasing, crop production under limited water conditions (Chai et al. 2016; Kirda 2002; Zhang et al. 2016). This leads to a reduced amount of water used for irrigating crops, improved responses of plants to a certain degree of water deficit,and reduced irrigation amounts or improved WUE (Bell et al. 2018; Jones 2004).

The sensitivity of the plant growth stage to water deficit can be affected by many factors such as climatic conditions, crop species and agronomic management practices (Grimes and Yamada 1982; Karam et al. 2006). The application of DI practices can facilitate more efficient water use, thereby extending the water supply during the growing season (Cortignani and Severini 2009). Also using DI practices can be of special help when water resources, including rainfall, are scarce or inadequate to meet normal crop-water requirements (Mebrahtu 2017b). The DI is thus considered a key water-saving practice for the efficient use of limited water resources (Abdel-Gadir et al. 2012; Guinn and Mauney 1984). Furthermore, it can save irrigation water by up to 20% -30% and increase WUE by up to 30% in favourable situations, with a minimal impact on crop yield (Bell et al. 2018; Jones 2004). DI has evolved as a deliberate strategy to achieve greater economic water productivity ($/ML) without substantially compromising crop yields (Bell et al. 2018; Jones 2004). For example, cotton is one of many crops that are suitable for the practice of DI (Kirda et al. 2002; White 2007). DI has been suggested as one strategy that uses an effective irrigation application during drought-sensitive growth stages (Azad and Ancev 2016; Chai et al. 2016a; Kirda et al. 2002; Zhang et al. 2016b). According to English (1990) and Zhang and Oweis (1999), the aim of DI is to stabilise crop yields by maximising crop water productivity rather than increasing yield under limited water availability (Chai et al. 2016a; Foley and Raine 2001; Zhang et al. 2016b). This means that using DI practices needs a detailed understanding of the yield response to less irrigation water and its economic impact (Loka 2012). This entails the aim of improving the ratio of yield to the WUE rather than increasing yield (Du et al. 2008). Therefore growers should understand that there are benefits of using DI practices effectively, and that it may not just stabilise productivity with dryland crops but it may also improve WUE and maximise the economic implications in terms of gross margin (GM).

It has been well-documented by many researchers (Chai et al. 2016a; Foley and Raine 2001; Zhang et al. 2016b) that one of the agronomic and economic responses of DI leads to maximising net income. However, these researches have also noted that maximising yields does not always equal maximising net income because the costs associated with the input used to achieve maximum yield are not always taken into account. Maximisation of the income is better than yield maximisation for water productivity management, regardless of the kind of agronomic management strategy (Du et al. 2008). Thus, the impact of DI practices on the grower's net income and profit in terms of unit area and enterprise level at a given DI is not supported by documentation. Yet DI is a strategy aimed at minimising the risk of profit loss as well as at coping with limited availability of supplementary water, which assumes that adequate crop growth can be maintained at other times as long as there is the availability of soil moisture from natural precipitation.

However, achieving this aim requires more comprehensive information about the agronomic and economic aspects governing the regulation of economic output (Mebrahtu 2017). Establishing a good irrigation schedule is critical in order to benefit from the positives that DI can deliver. Given the limited water availability within the MDB, approaches to reducing water use while maintaining agricultural production are needed. Overall, DI is considered a fundamental water-saving practice for the efficient use of limited water resources and may increase yields for both unit area and enterprise levels.

2.6.1. Deficit irrigation under furrow irrigation system

A number of studies (Ibragimov et al. 2007; Zonta et al. 2015; Zonta et al. 2017) have investigated DI under FI systems. Following Mateos et al. (1991), the application of DI under the FI system can improve cotton compared to full irrigation. In comparison with treatments using full irrigation allocation (TF), limiting water to 70% of that water volume (70% of TF) has been found to achieve higher cotton yield than full irrigation by 10%–19% (Ibragimov et al. 2007; Zonta et al. 2015; Zonta et al. 2017). Fereres and Soriano (2006) reported that WUE significantly increases when adopting DI under the FI system. However, as (Narayanan and Seid 2015), (2015) observe, there was a reduction in yields when applying DI at 85% of TF under the FI system. In their field trial comparing full and deficit irrigation (50% of TF) under the FI system for cotton crops in Turkey , Kaman et al. (2008),found no significant difference in cotton yield between treatments, but was almost doubled with DI in terms of WUE. In India, field trials using a FI for cotton farming showed that DI can reduce evapotranspiration by 20% – 40% (Pahlow et al. 2015). Another field experiment by Kifle and Gebretsadikan (2016) concluded that the use of DI reduced water use by 25% during the growth period, and did not significantly affect the lint yield.

These variations in research results reflect how greatly the dynamics of the system being studied can affect the outcomes. There can be negative effects to yield and WUE under FI. For instance Pabuayon et al. (2019) found that cotton yield decreased considerably-by approximately 40%-when less experienced irrigation managers inappropriately applied DI. Also, Golzardi et al. (2017) and Domínguez et al. (2012) found that applying DI resulted in yield reductions of 10%–76%. In a similar vein, Temesgen et al. (2018) found that DI at 75% of TF during the growing stages and maturity results in yield reduction, by approximately 7.5%–16%, while full irrigation under the FI system achieves better crop performance (biomass, yield, bulk weight, marketable yield, and unmarketable yield). Overall, the above results indicate that there can be benefits of using DI under the FI system in terms of yield and WUE, but there still exist many factors, particularly timing and level of deficit, to be considered. Although the above studies have declared that there is no benefit in using DI under the FI system, results from previous research indicate that there can be benefits of using DI under the FI system in terms of yield and WUE if many factors, especially timing and level of deficit, are taken into consideration.

2.6.2. Deficit irrigation under overhead sprinkler irrigation system

Deficit irrigation under an OSI system can save water, which engenders a reduction in pumping cost (Wang and Nair 2013). Using DI encourages cotton root growth and increases the capacity for water extraction and resilience to water deficits during reproductive development, enabling in increased yield (Thorp et al. 2017). Evans et al. (2006) reported that crop yields may increase considerably when using different levels of DI practices under the OSI system. Remarkably, both WUE and cotton yield have been found to improve significantly under DI compared to OSI and FI systems (Raine 2008). Other researchers (Heeren et al. 2011; Lamm et al. 2009; Montgomery and Wigginton 2008; Rodrigues et al. 2003) also pointed out that DI under the OSI system can be used to improve WUE and increase crop productivity when compared to a full irrigation treatment. The lint quality can be enormously enhanced when adopting DI under the OSI system (Wample and Smithyman 2002). The DI at 75% of TF under the OSI system was found to improve WUE, and achieve higher yields (Schneider and Howell 1998).

In contrast other researchers (Howell et al. 1995; Mulu and Alamirew 2012) reported that, compared to full irrigation treatments, DI under the OSI systems did not show any significant differences in terms of yields. Also, field research undertaken in the USA by O'Brien et al. (2001) showed the same finding when compared to full irrigation and DI treatments (85% of TF). Shehata (2009), likewise, reported that significant difference in crop yields was not found when applying DI at different levels under the OSI system compared to full irrigation treatment. It can be concluded from the above studies that the evidence for the benefits of DI under OSI systems is quite inconsistent. Even so, this review clearly showed that, to some extent, there were some benefits to use of DI under the OSI. However, there is a dearth of research that has explored Australian cotton productivity under OSI with different levels of DI practices.

2.6.3. Deficit irrigation under subsurface drip irrigation

The majority of the previous research on DI under SDI systems has involved crops other than cotton. For example, in drought conditions, adopting DI under the SDI system can be a powerful tool to improve WUE and yield for corn, cotton, and tomato (Ayars et al. 1999; Del Amor and Francisco 2007; Zaccaria et al. 2017). For research in cotton, the DI practices of 60% to 80% of full irrigation, achieved higher cotton yield when compared to full irrigation treatments (Kalfountzos et al. 2007). DeTar (2008) reported by that using DI could improve WUE through an increase in cotton yield noted for arid and semi-arid trial sites (Howell 2001; Howell et al. 2004). The quality of cotton yield can also be favourably influenced when adopting DI under the SDI system (Snowden 2012).

The application of DI under an SDI system, particularly during the vegetative period (i.e., 20–45 days after sowing), can ameliorate cotton yield and WUE. The favourable influence on root growth during this phase of crop development is a probable factor in these gains (FAO 2002). In regions where water sources are limited, appropriate application of DI under the SDI system may result in cotton yields being maintained, thus providing growers with more flexibility in managing their crops, maintaining profits and minimising water costs (Enciso et al. 2003).

In contrast, other study (Snowden et al. 2013) found that there was no significant difference in cotton yield or WUE when applying moderate DI practices compared to full irrigation treatments. Therefore, if there are no yield differences under full and deficit irrigations, then the water productivity must be higher under DI as it uses less water to produce the same yield than under full irrigation. Basal et al. (2009) reported that by using different levels of DI under the SDI system, such as only applying 25%, 50%, and 75% of the total water applied for a full irrigation treatment, there are decreases in cotton yields by 45%, 40% and 8%, respectively. The review of the literature above indicates that the use of DI under SDI systems does not guarantee higher yields or better WUE, but the evidence is that carefully and appropriately applied DI has the potential to give positive results. The timing and level of induced soil water deficits and their effects on crop growth are critical factors in determining the final outcome. Overall, like OSI, there are varying findings about the benefits of DI under the SDI system. However, research on using different levels of the DI under SDI of the Australian cotton industry is still in its infancy.

2.7. Economics of deficit irrigation practices

The majority of the previous research on the use of DI has been done in the form of field experiments while some has included agronomic modelling. Both of them of mainly focus on yield benefits and penalties. There is limited literature relating to the optimum level of DI from an economic viewpoint. This section highlights what research has been undertaken to assess the economic impacts of DI application for crop production. According to Capra et al. (2008), with DI, economic returns can be maximised by decreasing applied water volumes per unit area while increasing the irrigated area. Ali et al. (2007) reported that using DI for wheat crops, in terms of different measurements including yield, WUE and net returns, could maximise net returns when water resources were limited. Likewise, (Geerts and Raes 2009) have confirmed that DI can play a significant role in optimising water use by cotton crops without a decline in the yields but with an increase in the net income. Profitability , expressed by economic return for the amount of irrigation water used, can achieve the highest profits when DI is used to reduce the amount of water applied compared with full irrigation practices (Capra et al. 2010; Cusicanqui et al. 2013). In Southwest Texas, Wen et al. (2013) pointed out that, compared to full irrigation practices in terms of economic return DI increased WUE, cotton production, and economic returns. Analogously, (García-Vila et al. 2009) found that the economic returns of cotton farms can be maximised by adopting DI. Applying DI may result in a slight reduction in irrigation costs, which implies a boost to the net income (Shock and Feibert 2002). As Kirda (2002) put it, the key advantage of DI is greater net economic gains rather than increasing cotton production per unit of water. Economic water productivity, which is expressed by economic return for the amount of irrigated water used, can achieve the highest profits with an intermediate and low level of water applications (Capra et al. 2010; Cusicanqui et al. 2013).

In contrast, other studies (Lorite et al. 2007; Rodrigues and Pereira 2009) found that the impacts of DI on yields and related economic returns can be negative. Particularly, Rodrigues and Pereira (2009) assessed field experiments using OSI systems for DI for three crops including corn, sunflower and wheat. They found that, in terms of economic water productivity, while excessive irrigation applications with DI resulted in non-economical water use. Similarly, Rodrigues et al. (2013) reported that using DI generally is not economically feasible for either OSI or SDI systems. The above finding proves review provides evidence that DI can increase income per unit area, yet consideration should be given to applying DI practices for Australian cotton production. While a number of studies considered the economics of DI under one particular system, no direct comparisons among all three irrigation systems were made. This gives rise to the need for economic assessment proper in helping to understand the dynamics and relate to the concept of optimal production for maximum profit. This is because incorporating agronomic knowledge that is geared to maximum yield under uncertain farming and marketing conditions is the key challenge. In other words, this issue is in need of economic assessment- understanding relating to marginal value product and associated risk-weighted returns under limited water within the MDB area.

2.8. Agricultural systems modelling

Traditionally, agricultural research has been underpinned by physical field experiments. However, thanks to the development of computers and mathematical models, experimentations based on computer simulation experiments are also feasible (Jones et al. 2017; McCown et al. 2002; Robertson et al. 2015). The use of computer simulation experiments has proven cost effective and informative, and allows much more diverse and long-term experiments to be conducted than would be possible if relying solely on field experiment trials (Jones et al. 2017). Computer simulation experiments can also be used to identify and optimise inputs and management decisions.

Of the many biophysical modelling systems available around the world, two systems stand out as the most used agricultural modelling systems: The Decision Support System for Agrotechnology Transfer (DSSAT) and Agricultural Production Systems sIMulator (APSIM) (Van Ittersum and Donatelli 2003). The Decision DSSAT is one of the preeminent biophysical modelling systems used globally (Jones et al. 2003). This modelling system has been developed in the USA and has simulation models for about 42 crops. The CSM-CROPGRO-Cotton model (Abbas et al. 2020; Pathak et al.

2007; Zamora et al. 2009), which was embedded in DSSAT, has been widely used to simulate both dryland and irrigated cotton production at many locations around the world. These simulation studies have included analysis of yield components and WUE. For instance, Modala et al. (2015) and Cammarano et al. (2012) used the DSSAT cotton model in their studies on cotton irrigation strategies for cotton growing regions in Texas, USA, and the MDB in Australia. Focusing on cotton yield and net return of irrigation, these two studies found that commodity prices, variable input costs such as water, and production efficiencies all influenced the optimum irrigation strategy identified for yield or net return (Cammarano et al. 2012; Modala et al. 2015). They also concluded that irrigation strategies to maximize yield did not always maximize WUE or economic returns. Another study by Spivey et al. (2018) also used DSSAT's CROPGRO-Cotton in their evaluation of the economic feasibility of investing in irrigation systems for cotton production.

The other widely used agricultural modelling system is the APSIM (Holzworth et al. 2014). This modelling system was developed in Australia by the agricultural production systems research unit (APSRU) (Keating et al. 2003) and simulates in excess of 30 agricultural crops, including cotton. The APSIM system is a modelling framework which is used to simulate biophysical processes in agricultural production (Thorburn et al. 2010). It is under constant development with updates released at regular intervals.

Agricultural modelling systems generally have similar minimal requirements for simulation setup, which includes location details, daily meteorological observations, soil characteristics, farm management practices, and crop cultivar parameters (Spivey et al. 2018). Simulations of agricultural systems developed under the APSIM modelling system have been used to analyse decisions relating to crop types and soil characteristics, fertilisers, crop defoliation and harvesting, and crop irrigation (see Figure 2.5) (Holzworth et al. 2014; Keating et al. 2003).

According to McCown et al. (1996), APSIM may provide better predictive modelling in numerous situations than other agricultural models, based on a number of factors. These factors include a focus on the soil being the core integrating model component rather than the crops that are produced from it, a requirement that crop models have sufficient sensitivity to environmental extremes in order to allow analysis of economic risks, and use of advanced software that allows for adjustments of the modelling system by research teams. Robust predictive modelling is provided by APSIM (McCown et al. 1996) as it integrates models derived from agricultural research. This enables research from one discipline to be transferred to the benefit of another discipline, and also integrates modules or sub-models on a common platform, allowing for the long-term simulation of whole farming systems (Holzworth et al. 2014; Keating et al. 2003). The capability of APSIM to predict yields of a wide range of crops has previously been validated using field experiment data (Keating et al. 2003).

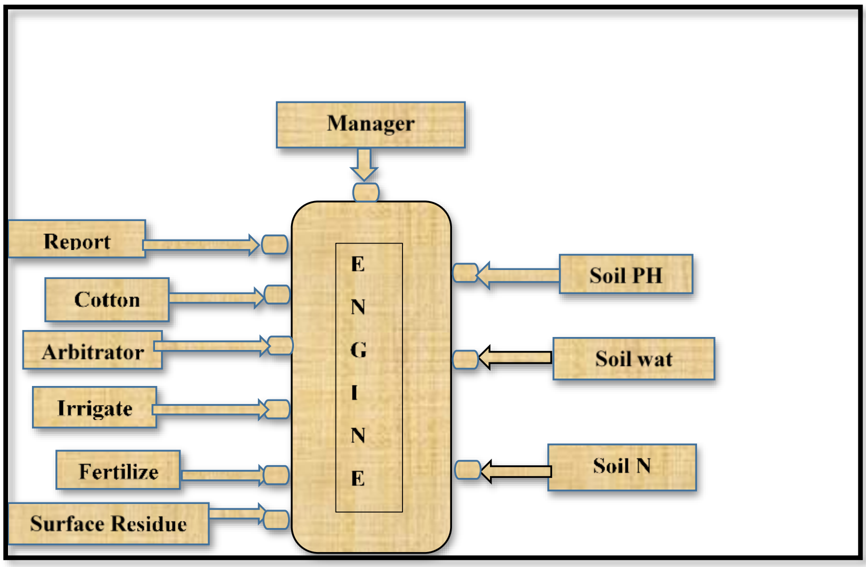

Figure 2.5: Schematic of the Agricultural Production Systems Simulator framework (APSIM).

Source: Adapted from Keating et al. (2003).

The APSIM model outputs can assist growers to gain more certainty in planning and decision-making (Carberry et al. 2009). By using the APSIM model, it is possible to predict the performance of the crop at a level close to reality through the description of the resources available to the crop which is being simulated, particularly the soil water and nitrogen resources (Carberry et al. 2009). The APSIM system supports simulation of farming decisions such as sowing, fertilising, and irrigating via management rules which allows crop performance responses. The APSIM model has been employed to simulate cotton yield and other crop growth variables which helps inform famers to make effective crop management decisions (Thorp et al. 2014). The cotton model in APSIM has been adapted from the Australian OZCOT cotton model (Hearn 1994) and allows simulation of both dryland and irrigated cotton production. In summary, the APSIM modelling system offers a way to investigate the impact of using different levels of DI on cotton crops, and this study will extend this analysis to include economic and farm enterprise financial analyses. These simulated experiments will generate the data that will be analysed in an effort to answer the research questions presented in this research.

2.9. Overview of economic and bioeconomic modelling

This section reviews the common economic models that are widely used for analysis in agricultural systems. These models include the Cobb-Douglas (CD) production function, the cost benefit analysis (CBA) and the positive mathematical programming (PMP).

The CD production function is an economic function that is dependent on two main variables: capital variable, and labour variable (Debertin 2012). It focuses solely on these two factors and overlooks other inputs. The function assumes that constant returns to scale, and the parameters limit identification of all economic implications (Zhang et al. 2016a). However, the optimal allocation of economic resources should include all elements of production such as land, labour capital, management and regulation (Zhang et al. 2016a). The research undertaken by the CD approach was thus not beyond challenge and has been questioned in terms of whether, over a number of years, it is credible to assume that the relative factor shares for capital and labour would remain fixed (Salahuddin and Gow 2016). This means that the estimates for capital and labour factor shares are extremely sensitive to the inclusion or otherwise of certain data points. In fact, the same measurement of these inputs of capacity utilisation is likely to vary over time (Fraser 2002). More importantly, the CD function is inflexible in its functional form (Yang et al. 2016). An inflexible functional form often prescribes the values, or at least the range of values, of critical parameters (which should ideally be included) (Hossain et al. 2012). Given this, flexibility of functional form is desirable because it allows the data the opportunity to provide information about critical parameters.

In addition to the above criticisms, a CD approach is not without its shortcomings. First of all, it cannot handle a large number of inputs. Second, the function is based on restrictive assumptions of perfect competition in the factor and product markets. Third, serial correlation and heteroscedasticity are common problems that beset this function too. Fourth, labour and capital are correlated, and the estimates are bound to be biased. Fifth, the unitary elasticity of substitution is unrealistic. Sixth, its form is inflexible for the optimal allocation of water resources. Finally, single equation estimates are bound to be inconsistent. (Salahuddin and Gow 2016; Yang et al. 2016). Overall, the CD model has a limited capacity for establishing the optimal allocation of water resources; while commonly used, it was deemed unsuitable for this research.

The CBA model is a financial analysis tool that offers the greatest benefits in the public and private sectors (Scott et al. 2013) such as commercial transactions, business or policy decisions (particularly public policy), and project investments (Misuraca, 2014). However, the major drawback of the CBA model is that it is just one specific, controversial way of expressing and weighing costs and benefits – based on the monetisation of individual benefits. In practice, the evaluation of benefits and costs often means ecosystems against economics (Cartwright 2000). The CBA also presents a number of disadvantages:(i) potential inaccuracies in identifying and quantifying costs and benefits; (ii) inaccurate calculations of present value resulting in misleading analyses; (iii) increased subjectivity for intangible costs and benefits; and (iv) the possibility of CBA turning into a project budget (Hafeez et al. 2008). To recap, the greatest limitation of CBA and CD is that they are both are either not comprehensive enough or too inflexible. In light of this, these methods are of limited use for the optimal allocation of water resources.

The PMP model has been used to analyse the economics of irrigated agriculture, as this approach works well with a multitude of resources such as the policies and environmental constraints found in industry (Qureshi et al. 2013). The utmost advantage of the PMP model is that it needs to be calibrated against a base over one year, or as an average over several years (Howitt 1995). The PMP model includes the basics of agricultural production economies through both inputs' distribution and water demand (Graveline 2016). The power of the PMP approach can be characterised by its response to changes in constraints (Howitt 1995). However, the key issue of using PMP with a single calibration observation is that it is not sufficient to infer the value of model parameters that directly control the way that the model responds to changes in price conditions (Cortignani and Severini 2011). Despite its increasing popularity in economic analysis, the PMP model generally fails to include the activities that were not observed in the reference period (Qureshi et al. 2014). In particular, when water availability decreases, or water cost increases, farmers could find it convenient to introduce DI (i.e., with low unitary water uses) that was not profitable. Water availability was observed under pre-reform conditions, in order to overcome this difficulty (Cortignani and Severini 2009). This study used an approach that allowed to simulate the adoption of DI, and to switch from irrigated to dryland crops. Furthermore, it used an innovative bio-economic model for optimising profitability and productivity in an irrigation command area, with conjunctive water use options. The development of optimum land use, water allocation plans and operable water delivery schedules is valuable for irrigation schemes in irrigated and dryland regions.

The main issues raised by bio-economic models include relationships between bio-economic models and economic models, characteristics of economic production functions, dynamic approaches (CD) to modelling, structure and main characteristics of biophysical and economic models (Blanco Fonseca and Iglesias Martinez 2005). The PMP model is useful for the purpose of policy assessment, but it also has some limitations, as was mentioned previously. Innovative approaches such as PMP may help to deal with specific economic problems, while multi-purpose dynamic models (CD) can be used for assessing policies that deal with applicability to a single farming system (or single region) (Frahan et al. 2007). Furthermore, bio-economic modelling can cover a group of regions (multiple regions or multiple scenarios). In fact, because of the use of PMP, calibration has become no longer crucial in bio-economic models, especially when dealing with the scale of applications in a single region or a group of regions. The PMP model does have greater possibilities for integration with bio-physical models than other economic models: in this way, a wider set of policies affecting the environment and sustainability issues can be considered.

Bio-economic modelling is the real link between biophysical and economic models. It is integrated into biophysical models with specific goals. For example, the bioeconomic modelling used by the various models differs with regard to specific elements of a sustainable economy: soil and water management. The CD is presented as individual models, which explains an interesting and innovative dynamic optimisation problem. It details all the elements involved in selecting and estimating a suitable production function. Nevertheless, the main problem is in estimating job parameters, and, when looking at statistical inference, non-technical aspects of the observed cases are identified in the model, such as heterogeneous "labour input" and/or "capital input". The PMP and CD models are complex and are not able to consider the real status of the available natural resources, nor predict realistic outcomes for the longer term. Rather, they do work for short periods. In addition, the application of a complex approach such as PMP does not necessarily produce better results. For instance, Qureshi et al. (2016) reported that both complex and simple approaches provide more or less similar outcomes. The approach of this study made clear that bio-economic models applied to cotton farming systems are a new frontier for growers to assess the impact of farm decisions on the environment, water management and natural resources. Given the increased pressure on water availability, there is a need for an increase in crop production and maximising economic returns.

2.10. The application of biophysical and bio-economic modelling to understanding deficit irrigation practices

The term "bio-economic modelling" has no single definition in either applied biology or economics (Cacho 2005), and the candidate used Allen's (1984) definition as "the use of mathematical models to relate the biological performance of a production system to its economic and technical constraints" (p. 55). Although optimisation models are often used, it is not imperative for decision theory to achieve the highest expected utility. To ameliorate this situation, the candidate added a section to the review of the economic models that explained why PMP was not an appropriate approach in this study. This is accomplished by expanding the discussion in the sections pertaining to technical discussions such as irrigation practices and simulation modelling in order to establish a sound conceptual basis, including a demonstrated technical understanding, that is then drawn on in the subsequent discussion in the data analysis chapters. The observations and trends presented in the literature have been evaluated and compared with one another. While there is a number of single approach techniques that are followed in the literature, such as PMP and CD, these approaches were deemed unsuitable for this study owing to the requirement for real data with a high level of specificity. In addition, single approach studies are normally applied for a specific purpose, such as optimisation, and they make a better fit for multiple crop types because of strong dynamic links between the biophysical modelling and economic analysis.

Existing local and global studies of DI practices for cotton under different irrigation systems are presented in Table 2.4. These studies found that using DI can have both benefits and drawbacks for crop production in terms of yield and WUE. A few studies used the APSIM cotton model with DI to simulate cotton production but did not simulate different levels of DI for Australian cotton irrigation systems. With respect to economic modelling, little research has reported the economic analysis of cotton production in either Australia or other parts of the world. Other studies have reported investment assessment of irrigation systems, but have excluded the use of DI practices (Spivey et al. 2018).

In summary, the literature review highlighted the importance of economic returns associated with using DI. Hence there is a need for financial analyses to evaluate investments in irrigation systems for both short-and long-term decisions in relation to Australian cotton production. This creates a gap in the research to be undertaken in Australia in the area of DI application in cotton production. With this said, the present study was designed to bridge this gap through the use of bio-economic modelling, which included both biophysical modelling and economic analysis, in order to investigate the impacts of using various scenarios of DI practices on cotton production. More details are provided in the following chapters.

Table 2.4: Summary of previous studies on DI practices for cotton under different irrigation systems.

References	Locations	Crop	System/ Field Modelling	Focus (yield, economic return, WUE, ET, etc.)	Practices	Findings/Outcomes
Cammarano et al. (2012)	Australia (NSW+ Qld.)	Cotton	FI system with using CROPGRO-Cotton simulation model)	Yield & profit	< 50%	The amounts of water required to maximise yield and maximise profit are different
Farahani et al. (2009)	Northern Syria	Cotton	SDI system with using simulation model (AquaCrop) and field experimental of 2006	Evapotranspiration & biomass accumulation, yield	40%, 60%, 80%, &100%	Increasing yield with 10%
Liu et al. (2017)	North China	Cotton	FI &SDI systems	Yield, WUE & fibre quality	Deficit irrigation during growth stages of plant	Decreased fibre strength & fibre length increase WUE & yield
Zhang et al. (2016b)	China (Xinjiang in the dry land)	Cotton	SDI system	Yield and fibre quality	Full, regular & deficit irrigation	Using DI practices increased plant density, gave greater yield, saved water by 20% & increased irrigation water productivity (IWP)

Rao et al. (2016)	India	Cotton	SDI & FI systems	Seed cotton yield & water productivity	100%,80% & 60%	Increased yield & saved water under drip irrigation at 80% scenario
Meng et al. (2016)	China Huang-Huai-Hai region	Coton	Under rain- proof shelter condition	Water-saving, high yield, high quality and efficiency of cotton crops	light deficit (LD) Moderate deficit (MD)& severe deficit (SD)	Moderate deficit practice was a suitable & effective approach for root and shoot in the cotton plant.
Yang et al. (2015)	China Northwest	Cotton	Aid system	Yield,WUE, & CWP	100%,85%, 70%, 55% & 45%	Decreasing water led to decreased yield (45%)
Wang and Nair (2013)	USATexas High Plains,	Cotton	OSI &SDI systems	Water-supply & net return	100%, 80% & 40%	All scenarios received a basal dose of 45 kg N/ha and that reported lint yields are calculated at 60 % open balls

Suleiman et al. (2007)	USA	Cotton	SDI system	The different developmental stages	40%, 60% & 90%	The least irrigated scenarios corresponded to 40% IT & the most irrigated corresponded to 90% IT.
Wen (2017)	Southwest Texas	Cotton	OSI system	Lint yield & soil water content	100%,80%,70%, 60% & 50%	The relationship between lint yield and soil water can be defined content through linear approach better than the spatial autocorrelation model

2.11. Summary and research gaps

This chapter reviewed the relevant literature on irrigation systems, deficit irrigation practices, water use efficiency, agricultural modelling and economic modelling. The main concepts of deficit irrigation as well as its the economic aspects were reviewed. FI, OSI, and SDI are three irrigation systems used in Australia, with FI being by far the most common despite the potential advantages for OSI and SDI suggested by both international and Australian studies. Furthermore, there is a scarcity of information from Australia enabling comparisons of all three systems under DI. From the above discussions, the research gaps in the application of DI generally, and for three irrigation systems particularly, can be identified as:

- Most of the previous studies have used the DI on cotton crops other than Australian cotton, and have focused on a range of measurements, agronomic practices and economic conditions that are not directly applicable to Australian cotton production.

- There is a lack of economic framework and risk analysis for decision making (short and long) relating to the optimum level of DI under three irrigation systems for Australian cotton growers at unit area and enterprise scales.

- Work is needed to investigate the predictions for increasing Australian cotton yields and improving WUE per unit area under different levels of DI for the three irrigation systems.

- At the unit area, bio-economic and risk analyses are also needed to identify how using DI can reduce the amount of water applied to Australian cotton crops while also maximising economic returns and minimise risks for growers.

- The economic impacts and financial investment decisions at enterprise scale relating to the use of DI practices for Australian cotton irrigation systems have not been conclusively identified in the literature.

- At the enterprise scale, work is also needed to evaluate the financial benefits of capital investment and risk analysis in each of the three irrigation systems in order to identify how using DI can benefit the Australian cotton industry.

2.12. Aim, hypothesis and research questions

The aim of this study was to employ biophysical, financial, and risk modelling to investigate the impacts of deficit irrigation practices under three irrigation systems in terms of short and long-term decisions in the MDB, Australia.

The hypothesis of this research can be formulated as:

> *The application of deficit irrigation practices, considered in terms of short and long-term decisions, may maximise the profitability of cotton production in the study areas in the MDB.*

The main research question can be formulated as:

> *What is the optimum level of DI to achieve the highest yield and profitability, for both short and long-term economic decisions under each of the three irrigation systems for the study locations within the MDB?*

Based on the main research question above, three research sub-questions are:

1- *Can the application of DI achieve higher lint yield (per unit area), improve WUE, and marginal water use efficiency (MWUE) for any of additional irrigation water for the three irrigation systems across the study locations in the MDB?*

2- *Can the application of DI with current farm infrastructure increase financial returns and minimise risks in cotton production in the short-term under any of the three irrigation systems across the study locations in the MDB?*

3- *Which level of DI practice and irrigation system can maximise net benefits and minimise risks for long term investment in capital infrastructure at the enterprise scale under any of the three irrigation systems in the MDB?*

2.13. Research objectives

The sub-questions were addressed through the following specific objectives:

1. To investigate the impacts of DI on lint yield and economic water productivity of cotton and risk analysis under three selected irrigation methods across four locations within the MDB of Australia using APSIM- cotton model.

2. To evaluate the economic outcomes and risk analysis from adopting DI associated with short-term decisions by using the bio-economic modelling of DI at per unit area level using current farm irrigation infrastructure for each of the three irrigation systems across the study locations in the MDB.

To evaluate, using bio-economic modelling and risk analysis, long-term decisions of investment in capital infrastructure at the enterprise scale and incorporating DI for three irrigation systems in order to maximise the profitability of cotton farms at the study locations in the MDB. The next chapter will investigate the impacts of adopting different levels of DI under the three cotton irrigation systems using APSIM model simulations. Simulation experiments using the APSIM modelling system are commonly used in Australia, as referenced in this review, to predict cotton crop growth and yield in order to make informed decisions about irrigation management practices and production potentials. Management options, which include irrigation choices and production potentials, will allow the economic analysis of the consequences of management decisions.

Chapter 3. Effects of deficit irrigation practices on water use efficiency and yield of cotton irrigation systems

Abstract

Irrigated cotton growers in the Murray-Darling Basin (MDB), Australia, are challenged by limited water availability. Deficit irrigation (DI) practices can improve water use efficiency (WUE), and marginal water use efficiency (MWUE) and may increase cotton lint yield, for furrow irrigation (FI), overhead sprinkler irrigation (OSI) and subsurface drip irrigation (SDI) systems. To demonstrate this, we validated the Agricultural Production System sIMulator (APSIM) against observed cotton lint yield and crop biomass accumulation for different management practices and locations. The APSIM cotton model had correlation coefficients of 0.93 and 0.82 against observed cotton crop biomass accumulation and lint yields, respectively. The APSIM cotton model was then used to explore the impacts of different levels of DI on lint yield, WUE and MWUE across cotton growing locations in the MDB (Goondiwindi, Moree, Narrabri, and Warren). Lint yield was maximized under the OSI and SDI systems for most locations by applying 80% of full irrigation. In a few locations, applying 60% of full irrigation under the SDI system maximized yield. Modelling identified that WUE was however, maximised at 60% of full irrigation for OSI and SDI systems, while MWUE was maximised at 80% of full irrigation under OSI system, and 40% of full irrigation under SDI system for all locations. For FI, DI had no benefit in terms of increasing yield, while DI showed marginal gains in terms of WUE, and MWUE in some situations. The results suggest that in the northern MDB, water savings could be

realised for cotton production under both OSI and SDI systems if DI were adopted to a limited extent, depending on location and irrigation system.

3.1. Introduction

Approximately 90% of the Australian cotton (*Gossypium hirsutum L.*) crop is grown in the Murray-Darling Basin (MDB), particularly in northern New South Wales (NSW) and southern Queensland (Qld.) in both irrigated and dryland cropping systems (Azad and Ancev 2016; Cammarano et al. 2012; Stiller and Wilson 2014). Approximately 83% of cotton grown within the MDB is irrigated, with the remaining 27% being dryland (Roth et al. 2013; Seidl et al. 2020; Wheeler et al. 2020). Irrigation is used to mitigate the risk of inadequate rainfall, particularly during the vegetative stages of cotton growth (Perry et al. 2012). Water availability is one of the most important determinants of the total area of cotton grown under irrigation in the MDB (Kodur and Robinson 2014; Qureshi et al. 2013b). During severe droughts, such as occurred during 2003/04 and 2007/08, water availability for irrigation was significantly reduced which affected total cotton production within the MDB (An-Vo et al. 2019; Cammarano et al. 2012; Qureshi and Whitten 2014).

In the MDB, 80% of irrigated cotton is grown using furrow irrigation (FI), 14% using overhead sprinkler irrigation (OSI) and 6% using subsurface drip irrigation (SDI) (McCarthy et al. 2010; Raine and Foley 2002). In the MDB, 80% of cotton growers use the FI system, 12% use OSI system and 6% use SDI system (Brouwer et al. 1988; Foley and Raine 2002; Koech et al. 2014; Roth et al. 2013; Uddin et al. 2018). The FI, has significantly lower capital and energy costs, ease of operation and possibly management costs compared to the other systems (Uddin et al. 2018). The OSI and SDI systems allow cotton crops to be grown with less irrigation water, which can result in higher water use efficiency (WUE) and higher marginal water use efficiency (MWUE) (Darouich et al. 2014; Lowien and Gall 2016).

Restricted water availability and the cost of water have resulted in researchers seeking to improve WUE through zero or minimum tillage, crop rotations, new cotton varieties or better management practices such as deficit irrigation (DI) (Dağdelen et al. 2009). The aim of DI practices is to maintain soil water at a level that does not affect crop yield while not completely filling the soil profile (Chai et al. 2016b). Whilst the concept of DI practices for cotton was proposed in the 1970s (Capra et al. 2008), to date in the MDB, it is not a common practice. Nor is there clear-cut evidence in favour of DI, with a number of studies having shown that DI practices can increase yield per hectare and improve WUE while other studies did not show such improvements (Chai et al. 2016b; Kirda et al. 2002; Zhang et al. 2016b).

Mangalassery et al. (2019) and Wen (2017) reported that DI is a useful strategy for maintaining crop yield and impoving WUE. Properly managed, DI can sustain profits while reducing irrigation water use during periods of reduced water availability (Suleiman et al. 2007). This can be demonstrated in situations where water is saved by not applying additional irrigation when additional irrigation results in little yield improvement (Chai et al. 2016b; Kirda et al. 2002).

Biophysical modelling can be used to identify optimum management practices (including water application strategies) and the impact of seasonal variation on crop yields (Williams et al. 2018; Yang et al. 2014).The Agricultural Production Systems sIMulator (APSIM) is a biophysical crop model used for exploring complex crop, resource and management interactions within cropping systems (Richards et al. 2008). This model operates on a daily time step integrating the supply and demand of resources (water, nutrients, light and heat) to predict crop growth, development and yield processes (Holzworth et al. 2014). It has a pedigree in simulating cropping systems and the interactions between farm resources (soil properties, water, nutrients, and weather) and crop management practices in Australia. The model includes modules for a range of crops (including cotton), soils, climate, irrigation management, and crop management practices (Carberry et al. 2009; Holzworth et al. 2014) making it an ideal tool to investigate complex farming systems questions such as irrigation practices. Using APSIM,we tested the proposition that using DI can decrease per unit area water use without at least decreasing lint yield and increase WUE and MWUE. The objective of this research is to model different levels of DI using APSIM cotton model under three different irrigation systems across four locations within the MDB to determine the effects on lint yields, WUE, and MWUE.

3.2. Materials and methods

3.2.1. APSIM cotton modelling

The Agricultural Production Systems sIMulator (APSIM platform; Version 7.9) (Holzworth et al. 2014) with the cotton module (Hearn 1994) was used to simulate irrigated cotton production in this study (crop biomass accumulation and lint yield). Input parameters for each simulation contained soil information, a description of crop management including irrigation, and meteorological inputs. The APSIM model was validated for cotton crop biomass accumulation and lint yield against observed field experiments (Cammarano et al. 2012) and regional cotton trial data (CSD 2017), prior to modelling the impact of DI across irrigation systems and locations in the MDB. There was a challenge to collect recent real-time data from farmers, and therefore relied on historical data in this study. The approach used in this thesis was based on modelling, rather than questionnaires or interviews. The use of historical data was proven to be useful and reliable in many studies (e.g., CSD 2017; Cammarano et al. 2012; Conaty et al. 2018; Nguyen et al. 2018). Most of the information and data were taken from industries that work with field farmers.

3.2.2. Validation data

To validate the APSIM cotton model for DI, figures describing cotton crop biomass accumulation under contrasting irrigation regimes, presented in Cammarano et al. (2012), were manually digitised. There were 139 data points from two growing seasons (2007/08 and 2009/10) at Oakey, Qld. in Australia (27.4034^{o}S, 151.7413^{o}E; 431m a.m.s.l) under four irrigation treatments (Table 3.1). Irrigation treatments occurred when soil moisture was depleted to 50% of plant available water capacity (50% of PAWC), 60% of PAWC, 70% of PAWC and 85% of PAWC. For the validation simulations of crop biomass, soil parameters were sourced from data provided in Cammarano et al. (2012). Daily meteorological patch point data were sourced from SILO (2017). Crop management was set to reflect the management described with each treatment given in Cammarano et al. (2012). The variability in crop yields from APSIM simulations was compared with the data from the field. Cammarano et al. (2012) also validated APSIM-simulated yields by comparing them with yields from the data field in order to increase farmers' confidence in modelling outcomes. Therefore, this led to show the difference between this work and the work conducted by Cammarano et al. (2012).

Table 3.1: Summary of four different irrigation regimes at Oakey, Qld. in Australia over two cotton growing seasons 2007/08 and 2009/10 (PAWC: plant available water capacity).

Treatments at:	**Irrigation water applied**	**Number of irrigation applications (events)**
50% of PAWC	228 mm	6
60% of PAWC	83 mm	3
70% of PAWC	82 mm	2
85% of PAWC	0 mm (not irrigated)	0

The data used to evaluate predictions of lint yield by APSIM across a range of locations and management practices were sourced from annual reports of the Cotton Seed Distributors variety trial results (CSD 2017). This field experiment data set covered 27 locations and 111 individual cotton crops over a seven-year period (from 2009 to 2015) and recorded crop management information and lint yield. For the simulations of lint yield, soil parameters to run simulations for each 27 locations were sourced directly from the APSoil database. crop simulations covered the full cropping cycle (from sowing and harvest). Management parameters were set to reflect the actual crop management practices at each location as described in (CSD 2017).

3.2.3. Statistical analysis of validation simulation outputs

In the first instance, modelled outputs were visually compared with observed data for accumulated crop biomass from Cammarano et al. (2012) and lint yield from CSD (2017). To assess the accuracy with which APSIM predicted cotton crop biomass and lint yield, several statistics were also calculated. The first was R^2 (coefficient of determination), which measures the proximity of data to the regression line (Tedeschi 2006). The second statistic was the mean bias as an assessment of the difference between the mean of observed values and mean of modelled values (Tedeschi 2006). Third, model efficiency was calculated as an assessment of the predictive power of model to explain the variation between observed and modelled values (Tedeschi 2006). Fourth, root mean square error (RMSE) was calculated as an assessment of the estimate of the amount of error between modelled values and observed values (Willmott and Matsuura 2005). Finally, the concordance correlation coefficient was calculated as an assessment of the precision and accuracy of the model (Tedeschi 2006).

3.2.4. Simulation of deficit irrigation (DI) practices

To assess the impacts of DI on cotton crops, we ran a series of single season simulations for four locations from the north to the middle area of the MDB (Goondiwindi, Moree, Narrabri, and Warren), spanning 41 years from 1977 to 2017. These locations are representative of four cotton growing areas located within the MDB in Australia (Figure 3.1). Three cotton irrigation systems were represented. These were furrow irrigation (FI), overhead sprinkler irrigation (OSI), and subsurface drip irrigation (SDI) systems. Management parameters for the DI simulations were sourced from a range of industry publications (DAF 2018a; Luo et al. 2016; Luo et al. 2015b; Nguyen et al. 2018). Sowing depth was consistent across all four locations at 65 mm (DAF 2018a). The crop management used reflected the current industry best practice within the MDB. The cotton cultivar Sicot 71BRF (Conaty et al. 2018; Nguyen et al. 2018) was used for all four study locations. For Goondiwindi, Moree, Narrabri, and Warren, sowing dates were October 23, October 15, October 11, and October, 13 (Luo et al. 2016; Luo et al. 2015b), respectively, and plant densities were 9.5, 9, 10.5, and 10 plants/m^2, respectively (DAF 2018a). For all locations, nitrogen fertiliser as urea was applied at planting (100 N kg/ha), with 50 N kg/ha top dressings on 15 December, and 25 January (CSD 2008; Hulugalle et al. 2016). Daily meteorological data from 1977 to 2017 for each location were obtained from the SILO Patched Point Dataset (Jeffrey et al. 2001) https://beta.longpaddock.qld.gov.au/silo/ . Soil definitions, including plant available water capacity (PAWC), were obtained from the APSoil database (Dalgliesh et al. 2006) and are described in Table 3.2. Soil water properties are the total from the surface to 1.8 m soil depth.

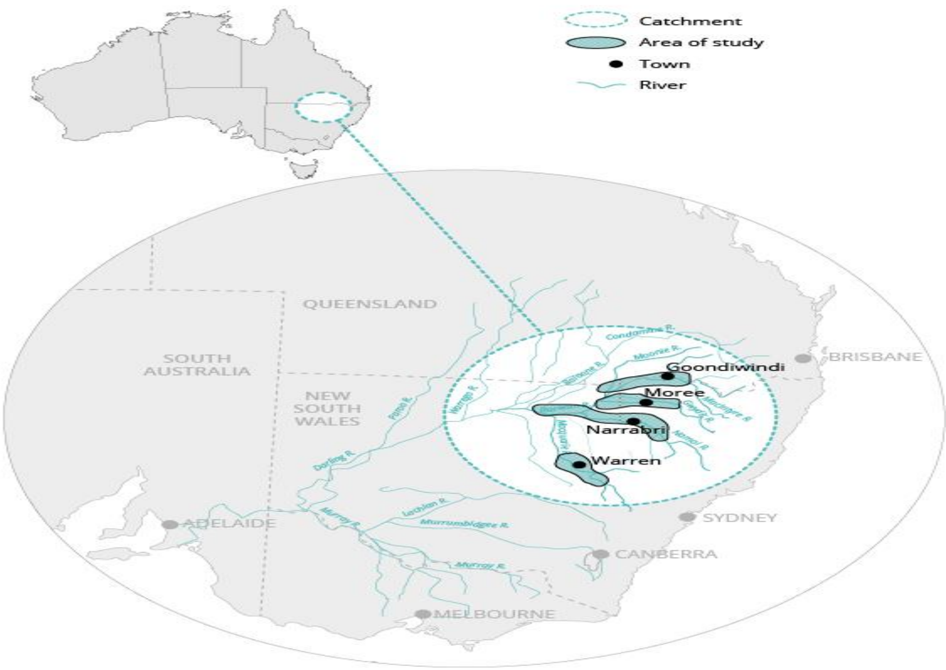

Figure 3.1: The four cotton growing areas in the Murray-Darling Basin, Australia.

Source: Adopted by the researcher from (Hulugalle et al .2016).

Table 3.2: Summary of soil type and climate details for each location used in the DI simulations. Soil water properties: drained upper limit, (DUL; mm); soil water capacity at 1500 kPa drained lower limit (DLL; mm); and plant available water capacity (PAWC; mm). Soil water properties are the total from the surface to 1.8 m soil depth and monthly climatic averages are for the 41 years from 1977 to 2017.

Locations	**Lat./Long**	**APSIM soil number**	**Soil type**	**DUL**	**DLL**	**PAWC**	**Average annual rainfall**	**Total annual evaporation**	**Maximum and minimum mean monthly temperatures (^oC)**											
									Jan.	Feb.	Mar.	Apr	My	Jun.	Jul.	Aug.	Sep	Oct.	Nov.	Dec.
Goondiwindi (Qld.)	-28.54S/ 150.3E	219	Clay vertisol	481	280	253	614	2054	32 20	32 21	31 18	27 14	21 10	19 6	19 5	21 6	25 9	28 14	31 17	33 19
Moree (NSW)	-29.48S/ 149.83E	870	Clay vertisol	562	316	372	594	2178	30 20	21 20	31 17	27 11	22 9	19 6	18 5	19 5	24 9	26 12	31 16	33 19
Narrabri (NSW)	-30.34S/ 149.75E	125	Clay vertisol	628	350	279	652	2005	31 19	22 12.	19 6	18 12	23 8	19 6	16 4	20 5	24 8	27 12	31 16	32 17
Warren (NSW)	-31.78S/ 147.76E	705	Medium clay vertisol	454	257	234	487	2038	30 17	33 19	30 16	26 12	21 8	17 5	16 4	18 4	22 7	26 11	30 15	32 17

DI practices were used for FI, OSI, and SDI systems reflecting the different capabilities of each system. Suitable DI practices for the three irrigation systems were obtained from interviews with two irrigation researchers: Executive Director of the University of Southern Queensland's Institute for Life Sciences and the Environment, the late Professor Steven Raine (Personal Communication, 2017 and 2018) and Associate Professor Joe Foley (Personal Communication, 2019). The FI system was simulated by applying infrequent irrigation events of comparatively large volumes of water. The trigger point of the FI system under full irrigation treatment (TF) was a soil water deficit of 100 mm. DI under FI in simulations by skipping specific number of TF irrigation events as described in the Table 3. 3. The OSI and SDI systems were simulated by applying frequent applications of small volumes of water. The trigger points for an irrigation application under the TF treatment were soil water deficits of 50 mm and 20 mm for the OSI and SDI systems, respectively. Treatments levels were 20%, 40%, 60% and 80% of TF application volumes.

Table 3.3: Summary of irrigation treatments under the FI, OSI and SDI systems across four locations. Full irrigation treatment (TF) represents irrigation to refill soil profile when soil water deficit reaches 100 mm, 50 mm and 20 mm, for FI, OSI and SDI systems, respectively. For FI, DI treatments are achieved by skipping one or more TF irrigation events, e.g. T5 irrigates 3 out of 4 TF applications and skips one. For both OSI and SDI systems, DI treatments are achieved by applying a percentage of the TF applications on all occasions, e.g. 80% treatment applied 80% of TF water on all irrigations occasions.

Code	**FI treatments**	**Code**	**OSI and SDI treatments**
TF	Full irrigation treatment	TF	Full irrigation treatment
T1	Irrigated 1 out of 4 TF irrigation events	20%	Irrigated 20% of TF application
T2	Irrigated 1 out of 3 TF irrigation events	40%	Irrigated 40% of TF application
T3	Irrigated 1 out of 2 TF irrigation events	60%	Irrigated 60% of TF application
T4	Irrigated 2 out of 3 TF irrigation events	80%	Irrigated 80% of TF application

T5	Irrigated 3 out of 4 TF irrigation events		
0%	Dryland	0%	Dryland

3.2.5. Calculation of water use efficiency, marginal water use efficiency and statistical analysis of simulations outputs

Water use efficiency (WUE; kg/mm) was calculated (Bhattarai et al. 2008; Chai et al. 2016b) as

$$\mathbf{WUE} = \frac{Y}{T_W} \quad (1)$$

where Y represents cotton lint yield (kg/ha) and T_W represents total water applied (in-crop rainfall plus irrigation) (mm/ha).

Marginal water use efficiency (MWUE) was calculated as the difference between irrigated yield and dryland yield relative to irrigation water applied. The MWUE was calculated as (Chai et al. 2016b):

$$\mathbf{MWUE} = \frac{(Y_i - Y_d)}{W_I} \quad (2)$$

where Y_i represents lint yield (kg/ha) with irrigation, Y_d represents lint yield (kg/ha) without irrigation and W_I represents water irrigation applied (mm).

To determine if a system or location had a significant effect on the relationship between lint yield and total water (rainfall plus irrigation), polynomial and linear regressions were fitted to the data. To test the best model fit, ANOVA was used to determine if the addition of fixed terms for irrigation system and location improved model fit. Factors and terms were added to the model until no significant improvement to the model was identified. To assess the normality of the WUE and lint yield data prior to fitting the regressions, we used Quantile-Quantile plots (QQ-plots) (Ghasemi and Zahediasl 2012). We also used the non-constant variance (NCV) test to check the WUE data for heteroscedasticity (Saunders et al. 2009). As the WUE data failed to meet the assumptions of normality there was no attempt to fit regressions to it. For each irrigation treatment the coefficient of variation (CV) was used as a measurement of relative variability, comparing the degree of difference relative to the means (Abdi 2010). All statistical analyses were performed using R (R Core Team 2019; version 3.3.5) and figures were produced using the ggplot2 package (Wickham 2016).

3.3. Results

3.3.1. Model validation

Validating the APSIM cotton model against biomass data given by Cammarano et al. (2012) showed that the model was capable of predicting cotton biomass accumulation under a range of irrigation practices (Figure 3.2). The summary statistics comparing modelled biomass to observed biomass were R^2: 0.68, mean bias: 1476, model efficiency: 0.72, root mean square error: 2655, and concordance correlation coefficient: 0.82. These values demonstrate the model's ability to produce an acceptable level of accuracy in the prediction of crop biomass.

The APSIM model well-represented lint yield across the range of different environments, years, and crop management practices (Figure 3.3). There was a slight overprediction of yield at lower yields and slight underestimation of lint yield at higher yields. Compared to observed biomass data, the APSIM model tended to underestimate crop biomass accumulation in both the 2007/08 and 2009/10 seasons. There was also a tendency to overestimate the final crop biomass in the 2010/11 season, in which there were late season, heavy rainfalls. The summary statistics comparing modelled yield to observed yield were R^2: 0.86, mean bias: 32, model efficiency: 0.99, root mean square error: 280 and concordance of the correlation coefficient: 0.93.

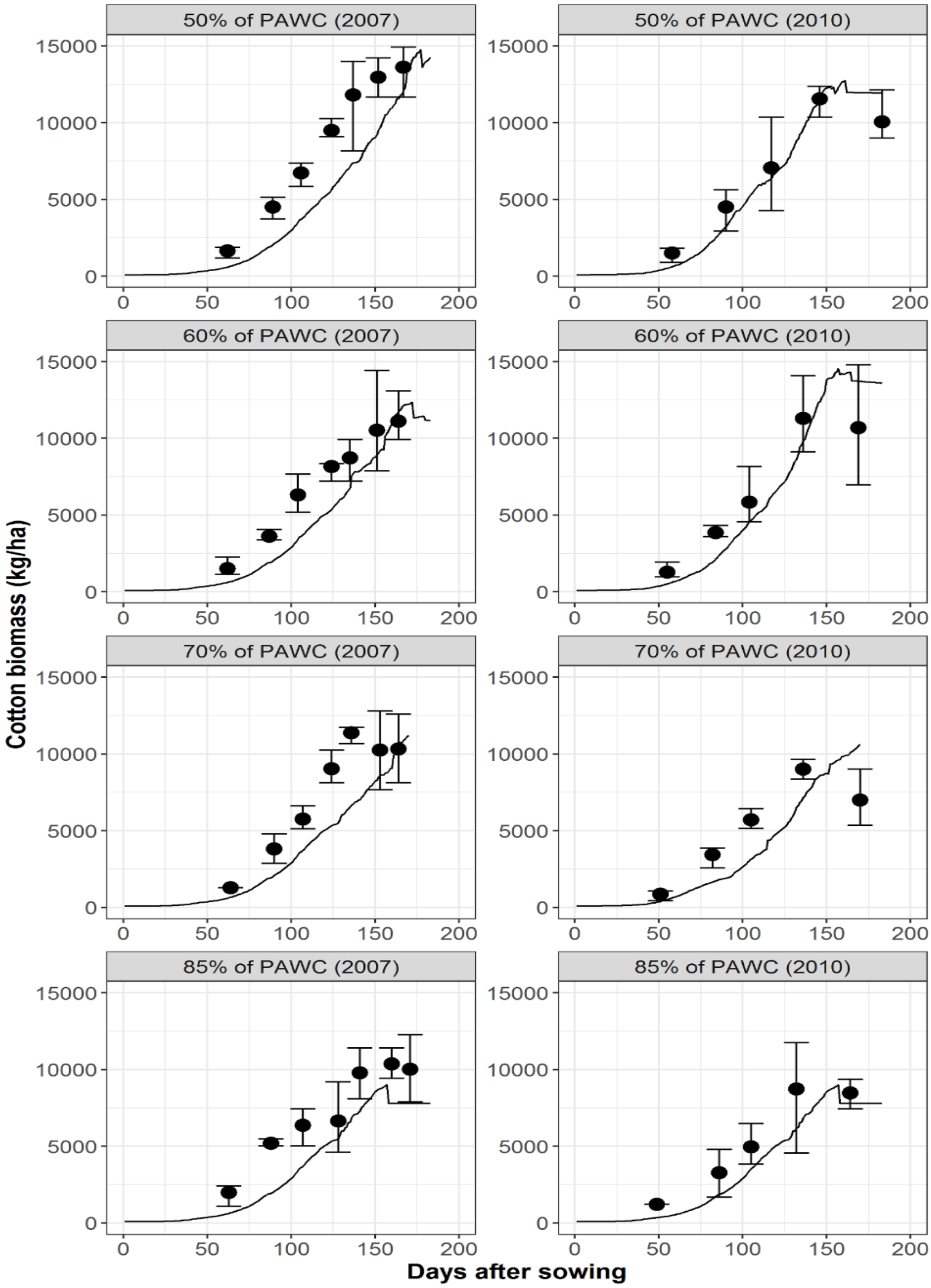

Figure 3.2: Observed cotton (close dots) biomass accumulation for cotton grown at Oakey in Qld. for 2007/08 and 2009/10 seasons under the four irrigation treatments (Cammarano et al. 2012) and APSIM modelled (solid line). Irrigation treatments occurred when soil moisture was depleted to 50% of plant available water capacity (50% of PAWC), 60% of PAWC, 70% of PAWC and 85% of PAWC. Each point represents the mean with the range in observed values represented by the error bars.

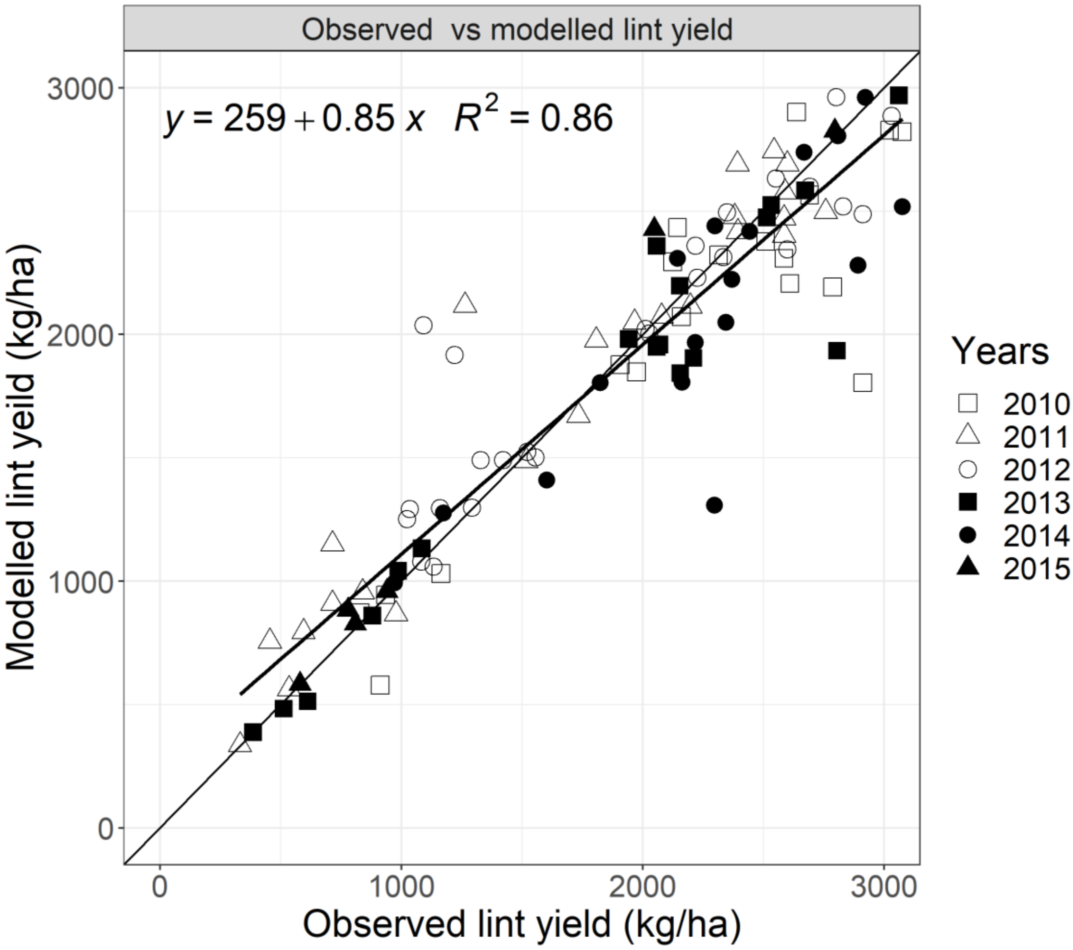

Figure 3.3: Modelled lint yield (kg/ha) compared to observed lint yield (CSD 2017) at 27 locations across northern NSW and Qld. for growing seasons from 2009/10 to 2014/15.

3.3.2. Simulation of cotton lint yield and water use efficiency with different irrigation systems and locations

Regression analysis identified that the relationship between lint yields and total water applied (in-crop rainfall and irrigation) was nonlinear (Figure 3.4). Lint yield per ML of water was consistent for each irrigation system, across all four locations up to 10 ML of total water applied. For the FI system, applications above 10 ML/ha at Warren resulted in lower yields when compared to Goondiwindi Moree and Narrabri. Under the OSI system, applications above 10 ML/ha resulted in higher yields at Goondiwindi and Warren compared to Moree and Narrabri. For the SDI system, greater differences were simulated between locations for applications over 10 ML when compared to other irrigation systems. Lint yield at Warren, the southern-most location with lowest average rainfall, decreased noticeably with water applications over 10 ML/ha. Under all three irrigation systems and across all locations there was no consistent relationship observed between total water applied (ML/ha) and WUE (kg/mm) (Figure 3.4).

In fact, the data for this relationship was not normally distributed based on observations of the QQ-plots test and an NCV test (P-value < 0.0001). Across all locations and under all irrigation systems, WUE improved as volumes of water increased up to 5 ML/ha. As total water increased from 5 ML/ha to 10 ML, the WUE decreased. The effect that location had on the relationship between total water (ML/ha) and lint yield (kg/ha) was statistically significant (Table 3.4a). The effect that irrigation system had on the relationship between water applied (ML/ha) and lint yield (kg/ha) was also statistically significant (Table 3.4b).

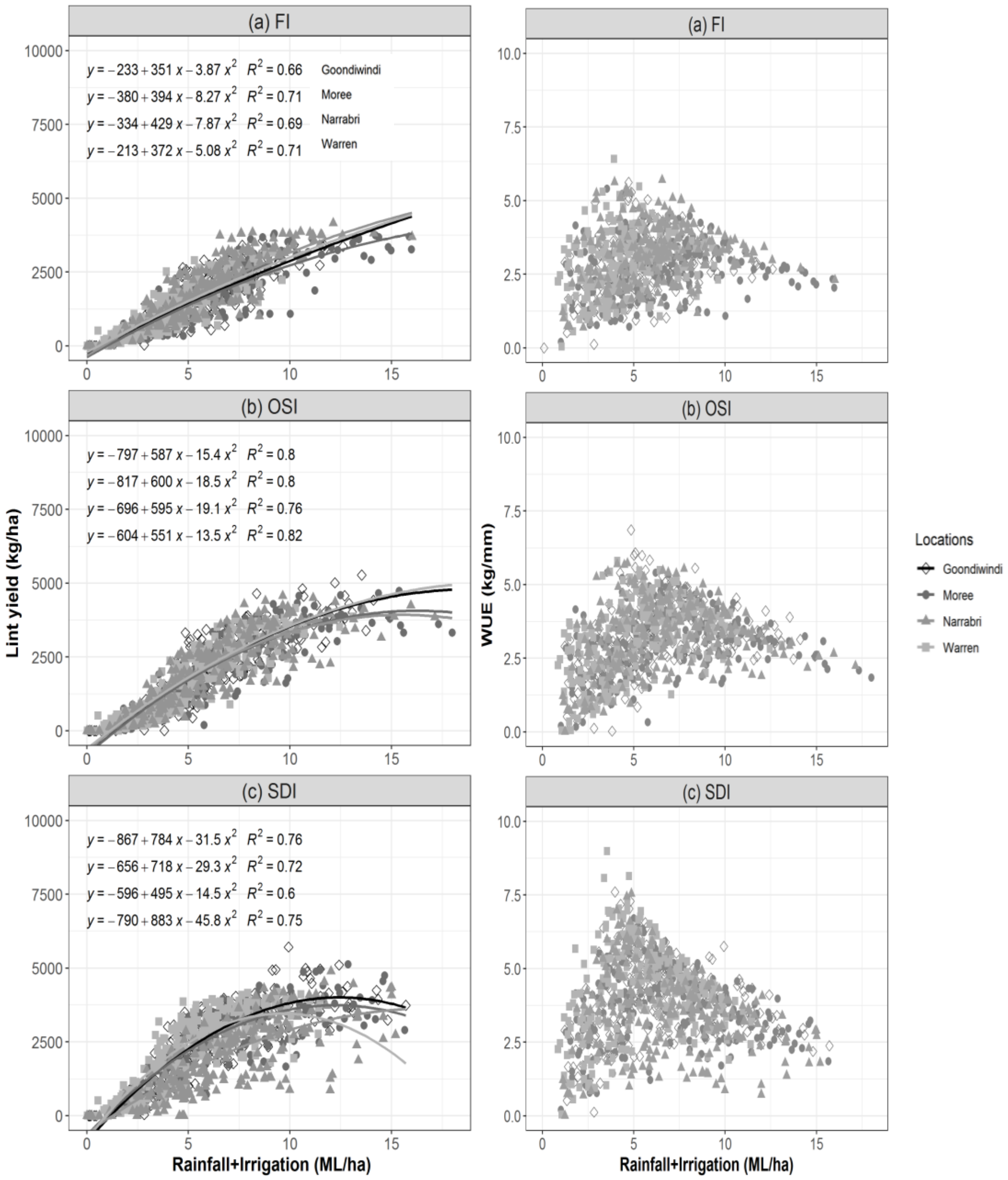

Figure 3.4: Cotton lint yield (kg/ha) versus total water (in-crop rainfall plus irrigation; ML/ha) with regressions for each location (left hand plots). Water use efficiency (WUE; kg/mm) versus total water (in-crop rainfall plus irrigation; ML/ha) (right hand plots). Plots (a) furrow irrigation (FI), (b) overhead sprinkler irrigation (OSI), and (c) subsurface drip irrigation (SDI) systems, across four locations: Goondiwindi, Moree, Narrabri and Warren during 41 years from 1977 to 2017.

Table 3.4: Summary of the statistical analysis of DI for three cotton irrigation systems and four locations. Two analyses are presented: (a) for locations against irrigation systems and (b) for irrigation systems against locations. Statistical measures presented are: R^2, P-value, ANOVA P-value factorial model R^2 and factorial model P-value. The y values represent lint yield and x values represents total water applied.

Locations (a)	**With all systems**	**R^2**	**P-value**	**Effect of system ANOVA (P-value)**	**Factorial model R^2**	**Factorial model P value**
Goondiwindi	$y = -633 + 554x - 14.6x^2$	0.71	< 0.001	< 0.001	0.79	< 0.001
Moree	$y = -603 + 551x - 16.9x^2$	0.70	< 0.001	< 0.001	0.76	< 0.001
Narrabri	$y = -466 + 538x - 17.3x^2$	0.65	< 0.001	< 0.001	0.66	< 0.001
Warren	$y = -521 + 567 - 16.5x^2$	0.72	< 0.001	< 0.001	0.80	< 0.001

Systems (b)	**With all locations**	**R^2**	**P-value**	**Effect of location ANOVA (P-value)**	**Factorial model R^2**	**Factorial model P value**
FI	$y = -313 + 402x - 8.08x^2$	0.70	< 0.001	< 0.001	0.71	< 0.001
OSI	$y = -797 + 587x - 15.4x^2$	0.79	< 0.001	< 0.05	0.79	< 0.001
SDI	$y = 588 + 713x - 30x^2$	0.68	< 0.001	< 0.001	0.70	< 0.001

3.3.3. The effects of deficit irrigation practices on lint yield

For FI, the TF treatment achieved the greatest lint yield across all locations (Figure 3.5). For this treatment, the median lint yields at Goondiwindi, Moree, Narrabri and Warren were 2427, 2667, 2800 and 2089 kg/ha, respectively; the average total water applied was 7.35, 8.93, 8.47 and 6.3 ML/ha, respectively. As the amount of water increased, the CV of lint yield tended to decrease. The lowest CVs for Goondiwindi, Moree, Narrabri and Warren were 36% (TF), 33% (TF), 27% (T5 and TF) and 27% (T5), respectively. Under FI, the greatest median lint yield was achieved with the TF treatment. This treatment also had the lowest CVs for two of the four locations.

For the OSI system, the greatest median lint yield was achieved with the 80% of TF treatment across all study locations. For this treatment, the median lint yields at Goondiwindi, Moree, Narrabri and Warren were 3374, 3334, 3231 and 3179 kg/ha, respectively; the average total water applied was 7.95, 9.35, 8.8 and 7.22 ML/ha, respectively. Lint yields were higher than for the FI with TF simulations. There were savings of 1.33, 1.4, 1.2 and 1.38 ML/ha of water compared to the TF treatment for Goondiwindi, Moree, Narrabri and Warren, respectively, but the water applied was a little higher than the FI with TF. As the amount of water increased under OSI, the CV of lint yield tended to decrease. The lowest CVs for Goondiwindi, Moree, Narrabri and Warren were 26% (80% of TF), 24% (80% of TF and TF), 23% (60% and 80% of TF) and 20% (80% of TF), respectively. In summary, with the OSI system, the greatest median lint yield was achieved with the 80% of TF at all locations and with the lowest CVs for three of those four locations.

For the SDI system, the greatest median lint yield was achieved with the 80% of TF treatment at Goondiwindi and Narrabri, and 60% of TF treatment at Moree and Warren. For these treatments, the median lint yields at Goondiwindi, Moree, Narrabri, and Warren were 3568, 3470, 3296 and 3279 kg/ha, respectively; the average total water applied was 8.5, 7.85, 9.38 and 5.9 ML/ha, respectively. There were savings of 1.28, 3.1, 1.03 and 2.45 ML/ha of water compared to the TF treatments for Goondiwindi, Moree, Narrabri and Warren, respectively, while maximising median lint yields. As the amount of water increased, the CV of lint yield tended to decrease. The lowest CVs for Goondiwindi, Moree, Narrabri and Warren were 20% (60% of TF), 18% (60% of TF), 34% (80% of TF) and 16% (60% of TF), respectively. Under the SDI system, the greatest median lint yields were achieved with the 80% of TF treatment at Goondiwindi and Narrabri, and 60% of TF treatment at Moree and Warren. The lowest CV for three of the four locations was achieved at 60% of TF treatment. Overall, yields under the SDI system were higher than FI and OSI systems.

3.3.4. The effects of deficit irrigation practices on water use efficiency

For the FI system, the greatest median WUE was achieved with the TF treatment at Goondiwindi, Moree and Warren, and T5 treatment at Narrabri (Figure 3.6). For these treatments, the median WUE was 3.0, 2.9, 3.5, and 3.5 kg/mm, at Goondiwindi, Moree, Narrabri and Warren, respectively; the average total water applied was 7.34, 8.97, 7.57 and 6.42 ML/ha, respectively. As the amount of total water applied increased, the CV of WUE tended to decrease. The lowest CVs for Goondiwindi, Moree, Narrabri and

Warren were 31% (T5 and TF), 25% (TF), 23% (TF) and 19% (TF), respectively. Under the FI system, the greatest median WUE was achieved with the TF treatment at Goondiwindi, Moree and Warren, and the T5 treatment at Narrabri. The lowest CV for three of the four locations was achieved at TF treatment.

For the OSI system, the greatest median WUE was achieved with the 80% of TF treatment at Goondiwindi and Warren, and 60% of TF treatment at Moree and Narrabri. For these treatments, the median WUEs at Goondiwindi, Moree, Narrabri and Warren were 4.0, 4.0, 4.2, and 4.3 kg/mm, respectively; the average total water applied was 7.69, 7.57, 7.37 and 7.21 ML/ha, respectively. There were savings of 1.49, 3.18, 2.7 and 1.4 ML/ha of water compared to the TF treatment for Goondiwindi, Moree, Narrabri and Warren, respectively. As the amount of total water increased, the CV of WUE tended to decrease. The lowest CVs for Goondiwindi, Moree, Narrabri and Warren were 22% (60% of TF), 20% (80% of TF and TF), 21% (60% and 80% of TF) and 16% (80% of TF), respectively. Under the OSI system, the greatest median WUE was achieved with the 80% of TF treatment at Goondiwindi and Warren and 60% of TF at treatment Moree and Narrabri. These treatments resulted in low CVs for these locations.

For the SDI system, the greatest median WUEs were achieved with the 40% of TF treatment at Goondiwindi, Moree and Narrabri and 60% of TF treatment at Warren. For these treatments, the median WUEs at Goondiwindi, Moree, Narrabri, and Warren were 5.2, 5.2, 5.4 and 5.6 kg/mm, respectively; with the average total water applied 5.74, 6.47, 5.96 and 5.97 ML/ha, respectively. There were savings of 4.08, 4.43, 4.44 and 2.4 ML/ha of water compared to the TF treatment for Goondiwindi, Moree, Narrabri and Warren, respectively, while maximising the median WUE. As the amount of total water applied increased, the CV of WUE tended to decrease. The lowest CVs for Goondiwindi, Moree, Narrabri and Warren were 20% (60% of TF), 18% (40% and 60% of TF), 22% (40% of TF) and 20% (80% of TF), respectively. Under the SDI system, the greatest median WUE was achieved with the 40% of TF treatment at Goondiwindi, Moree and Narrabri, and 60% of TF treatment at Warren. These treatments resulted in low CVs for these locations.

3.3.5. The effects of deficit irrigation practices on marginal water use efficiency

For the FI system, the greatest median MWUE was achieved with the T5 treatment at Goondiwindi and Narrabri, and TF treatment at Moree and Warren (Figure 3.7). For these treatments, the median MWUEs at Goondiwindi, Moree, Narrabri and Warren were 4.5, 3.6, 5.2 and 4.6 kg/mm, respectively; the average irrigation water was 3.16, 5.25, 3.97 and 3.82 ML/ha, respectively. As the amount of irrigation water increased, the CV of MWUEs tended to decrease. The lowest CV for Goondiwindi, Moree, Narrabri and Warren were 40% (T5), 58% (T4), 30% (TF) and 29% (TF), respectively. Under the FI system, the greatest median MWUE was achieved with the T5 treatment at Goondiwindi and Narrabri and TF at Moree and Warren. These treatments had low CVs for those locations.

For the OSI system, the greatest median MWUE was achieved with the 80% of TF treatment at Goondiwindi and Warren, and 60% of TF treatment at Moree and

Narrabri. For these treatments, the median MWUEs at Goondiwindi, Moree, Narrabri and Warren were 6.2, 5.9, 6.1 and 5.7 kg/mm, respectively; the average irrigation water was 4.14, 3.95, 3.66 and 4.51 ML/ha, respectively. There were savings of 1.17, 3.05, 2.61 and 1.31 ML/ha of water compared to the TF treatment for Goondiwindi, Moree, Narrabri and Warren, respectively. As the amount of irrigation water increased, the CV of MWUE tended to decrease. The lowest CVs for Goondiwindi, Moree, Narrabri and Warren were 29% (60% of TF), 29% (TF), 42% (80% of TF) and 15% (80% of TF), respectively. Under the OSI system, the greatest median MWUE was achieved with the 80% of TF at Goondiwindi and Warren, and 60% of TF Moree and Narrabri.

For the SDI system, the greatest average MWUE was achieved with the 40% of TF treatment across all locations. For this treatment, the median MWUEs at Goondiwindi, Moree, Narrabri, and Warren were 10.1, 9.1, 9.5 and 9.1 kg/mm, respectively; the average irrigation water was 2.22, 2.76, 2.32 and 2.09 ML/ha, respectively. There were savings of 3.63, 4.36, 4.14 and 3.55 ML/ha of water compared to the TF treatment for Goondiwindi, Moree, Narrabri and Warren, respectively. As the amount of irrigation water increased, the CV of MWUE tended to decrease. The lowest CVs for Goondiwindi, Moree, Narrabri and Warren were 25% (40% of TF), 25% (40% of TF), 43% (40% of TF) and 18% (60% of TF), respectively. Under the SDI system, the greatest median MWUE was achieved with the 40% of TF treatment across all study locations and resulted in the lowest CVs for three of the four locations.

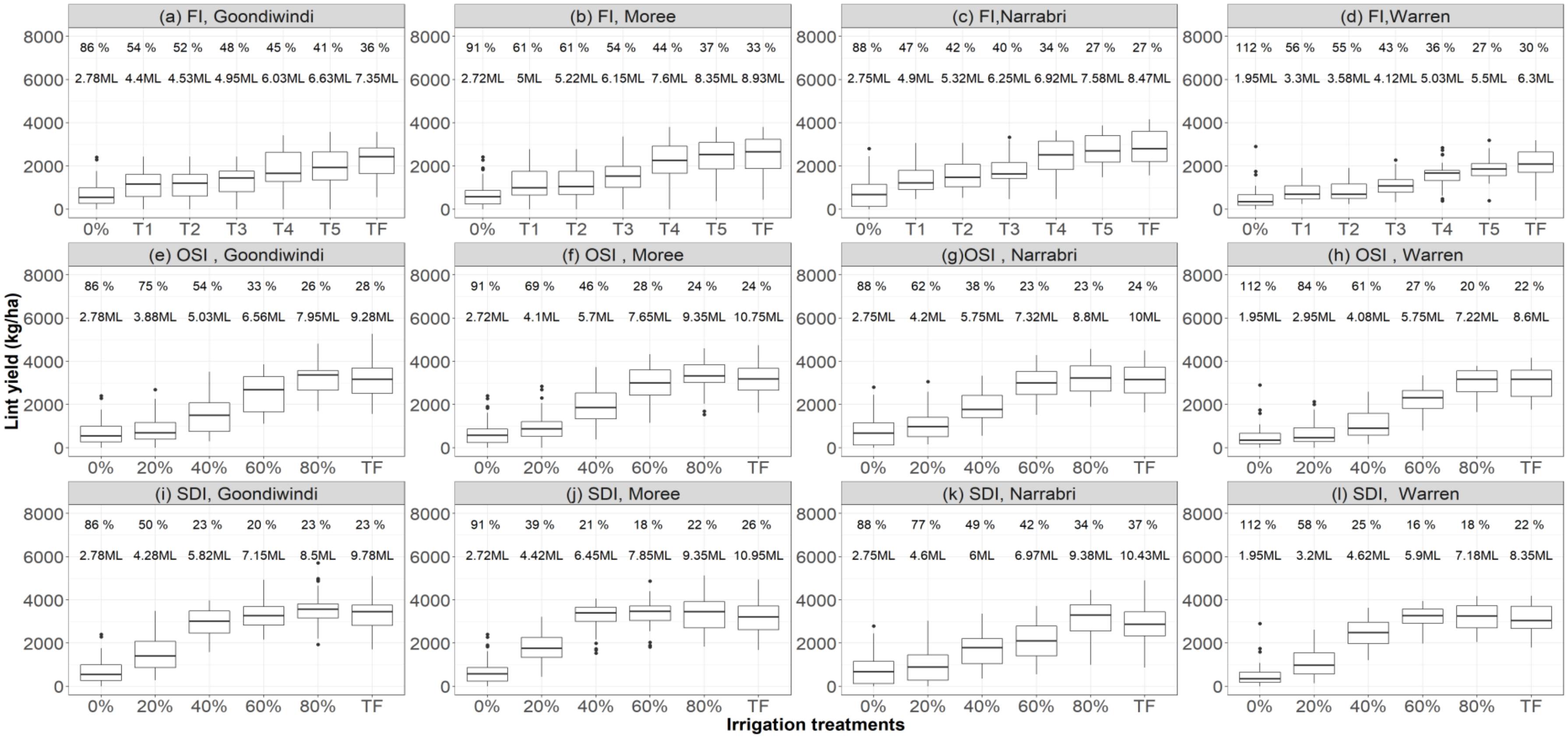

Figure 3.5: Cotton lint yield (kg/ha) predicted using APSIM cotton model in response to irrigation treatments for furrow irrigation (FI), overhead sprinkler irrigation (OSI), and subsurface drip irrigation (SDI) for Goondiwindi, Moree, Narrabri, and Warren (1977/2017). FI treatments of irrigation events were dryland (0%) irrigation water, '1 out of 4' (T1), '1 out of 3' (T2), '1 out of 2' (T3), '2 out of 3' (T4), '3 out of 4' (T5) irrigation events, and (TF) full irrigation treatment. The treatments of OSI and SDI systems were 0% (dryland), 20% of TF, 40% of TF, 60% of TF, 80% of TF, and full irrigation treatment (TF). The percentages represent the coefficient of variation (CV). The numbers represent total water applied (in-crop rainfall plus irrigation; ML/ha) for each treatment.

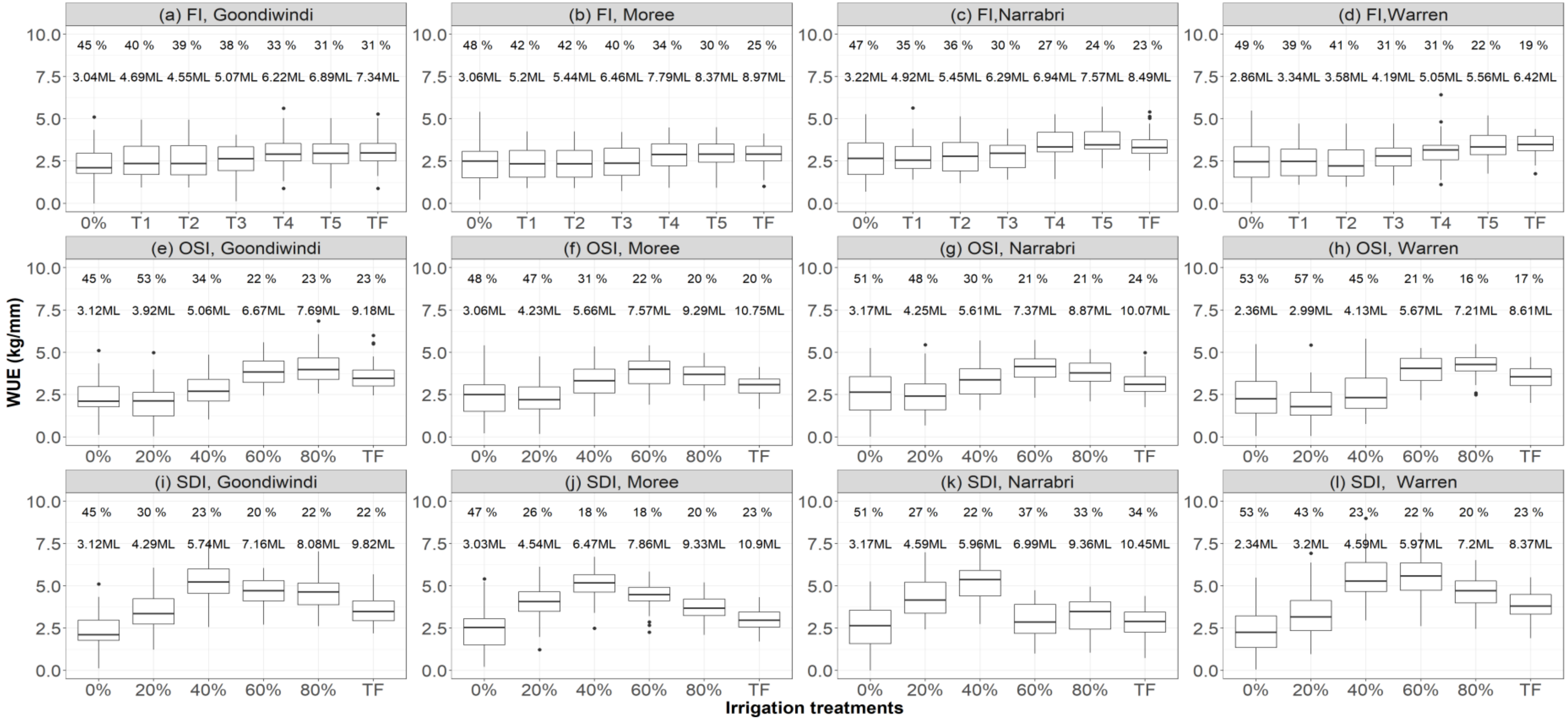

Figure 3.6: Water use efficiency (WUE; kg/mm) predicted using APSIM cotton model in response to irrigation treatments for furrow irrigation (FI), overhead sprinkler irrigation (OSI), and subsurface drip irrigation (SDI) for Goondiwindi, Moree, Narrabri, and Warren (1977/2017). FI treatments of irrigation events were dryland (0%) irrigation water, '1 out of 4' (T1), '1 out of 3' (T2), '1 out of 2' (T3), '2 out of 3'(T4), '3 out of 4' (T5) irrigation events, and (TF) full irrigation treatment. The treatments of OSI and SDI systems were 0% (dryland), 20% of TF, 40% of TF, 60% of TF, 80% of TF, and full irrigation treatment (TF). The percentages represent the coefficient of variation (CV). The numbers represent total water (in-crop rainfall plus irrigation; ML/ha) for each treatment.

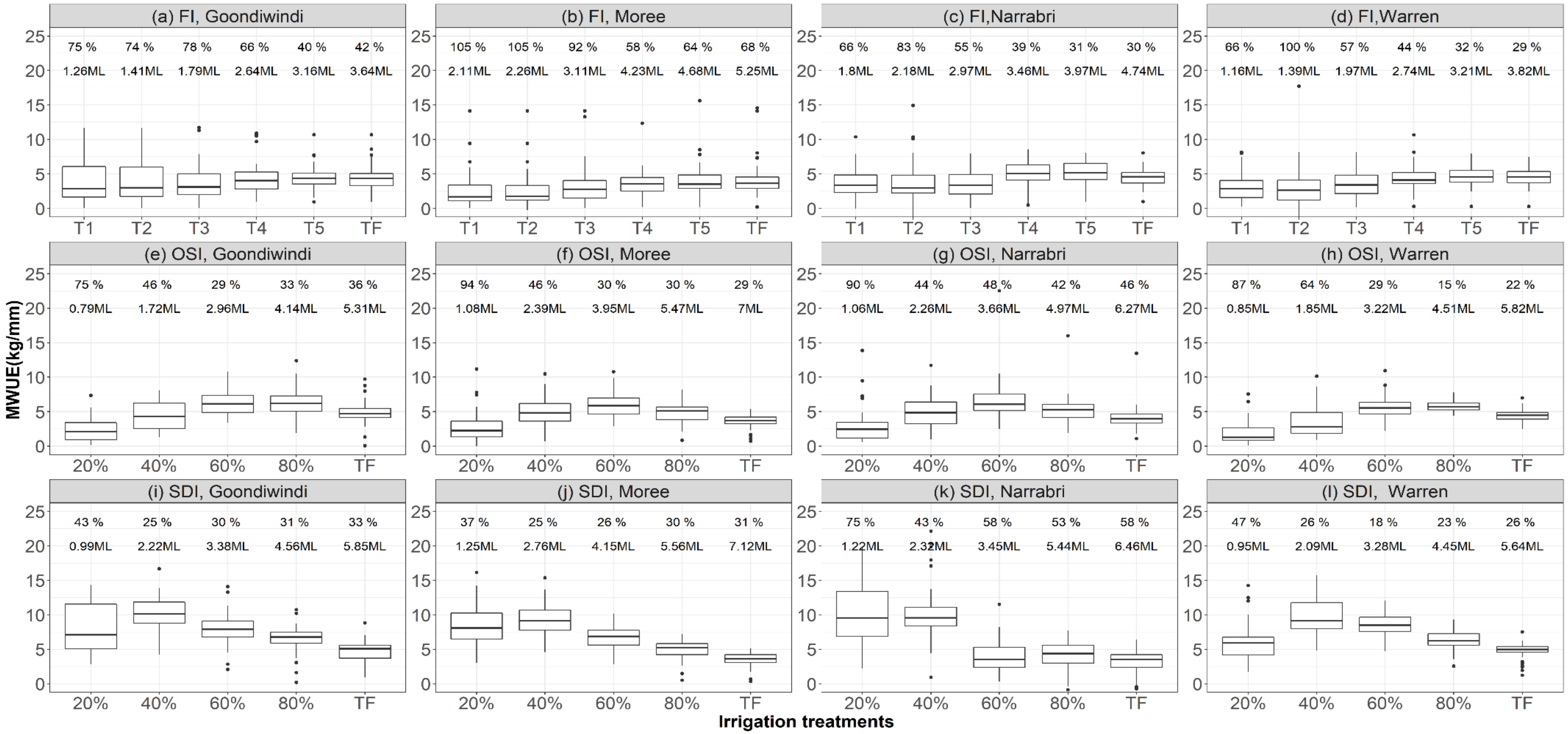

Figure 3.7: Marginal water use efficiency (MWUE; kg/mm) predicted using APSIM cotton model in response to irrigation treatments for furrow irrigation (FI), overhead sprinkler irrigation (OSI), and subsurface drip irrigation (SDI) for Goondiwindi, Moree, Narrabri, and Warren (1977/2017). FI treatments of irrigation events were '1 out of 4' (T1), '1 out of 3' (T2), '1 out of 2' (T3), '2 out of 3' (T4), '3 out of 4' (T5) irrigation events, and (TF) full irrigation treatment. The treatments of OSI and SDI systems were 20% of TF, 40% of TF, 60% of TF, 80% of TF, and full irrigation treatment (TF). The percentages represent the coefficient of variation (CV). The numbers represent median irrigation water applied (ML/ha) for each treatment.

3.4. Discussion

APSIM model was found to be adequate to accurately simulated a range of different crops including cotton grown at Dalby, Qld., Australia Carberry et al. (2009). Earlier versions of the APSIM cotton model (APSIM-OZCOT) accurately predicted lint yield in two locations in Xinjiang, northwest China (Yang et al. 2014). For this study, we validated the APSIM cotton model for its ability to model deficit irrigation (DI) through comparisons to observed crop biomass (Figure 3.2) and lint yield (Figure 3.3) from both experimental field data and industry production data across the MDB. We utilised APSIM cotton to investigate the use of DI practices under three irrigation systems for four locations within the MDB.

Our results showed that modelled lint yield, WUE and MWUE under the FI system were lower than for the SDI and OSI systems (Figures 3.5, 3.6 and 3.7). This finding is supported by Lowien and Gall (2016) who reported that field data from both OSI and SDI systems demonstrated greater yields (4% increase) and WUE (7% increase) compared to FI systems. Darouich et al. (2014) also ascertained that irrigation by SDI systems produced higher lint yields than FI systems for the same amount of water used. Our modelling suggests that the infrequent application of irrigations under FI systems results in periodic water deficit stress in the cotton crop which reduces plant growth and leads to a decrease in lint yield.

Our results also indicated no beneficial effects of DI for FI systems in terms of lint yield. The findings of Wen (2017) from field experiments in Southwest Texas, USA support our modelling results that there was no benefit for lint yield from DI practices under the FI system. However, there may be some improvement in WUE and MWUE with DI under FI. At Goondiwindi and Narrabri, the T5 treatment led to the best outcomes for each of these measures (Figures 3.5, 3.6 and 3.7). Kaman et al. (2008) reported that, when using DI in field experiments in Turkey, cotton yield was reduced, but WUE improved under a FI system. Their final conclusion supports our modelling results that the greatest lint yield is achieved under a FI system using the TF treatment. This result is also supported by other studies (Fereres and Soriano 2007; Geerts and Raes 2009; Kaman et al. 2008). We conclude that it is difficult to successfully apply DI practices with a FI system and not negatively impact lint yield due to the infrequency of irrigation application coupled with the large volumes of water applied which induce crop stress due to the periodic wet and drying cycles. For the FI system, the results do not support our hypothesis that DI practices increase lint yield. However, in some situations, our hypotheses that DI achieved improvements in terms of WUE and MWUE, were proved.

Deficit irrigation practices had a positive effect on predicted lint yield, WUE, and MWUE under the OSI system as the impact on yield was either positive or when negative was relatively minor compared to the reduction in T_w and W_I. Our results indicated that, under an OSI system, lint yields, WUE and MWUE were all optimised with 60% to 80% of the TF treatments volume of irrigation, with the study location having a direct effect on the actual optimisation point (Figures 3.5, 3.6 and 3.7). The 80% of TF treatment compared to the TF treatment, saved between 1.20 and 1.40 ML/ha of irrigation water across the four study locations with minimal negative impact on yield. Evans and Sadler (2008) reported that yield and WUE increased significantly when using deficit irrigation practices under the OSI system. Our modelling and the study conducted by (Evans and Sadler 2008) support our hypothesis that, under an OSI system, the use of DI practices to apply the optimum application of water can increase lint yields and can improve WUE and MWUE.

For the SDI system, DI practices had a positive effect on lint yield, WUE, and MWUE for all study locations, but there is some variation in the best DI treatment amongst locations. These differences may be dues to variation in average annual precipitation rates, especially lower summer rainfalls at Goondiwindi and Warren. Our results indicated that, under an SDI system, lint yields were maximised by the use of 60% to 80% of the TF treatment volume of irrigation, while WUE and MWUE were optimised with more restrictive applications of water, around the 40% to 60% of TF (Figures 3.5, 3.6 and 3.7). Field experiments investigating DI for cotton grown with SDI systems in Coimbatore, India identified that 80% of TF treatment achieved the greatest cotton yield (Sampathkumar et al. 2013). Our modelling and other findings support our hypothesis that, under SDI system, the use of DI can increase lint yields and improve both WUE and MWUE by applying the optimum application of water.

The results also suggest that the choice of system could change overall yields. Across the four study locations, using 4 ML/ha of irrigation water with the FI system produced 2.9 tonnes of lint without using DI practices, while the OSI and SDI systems produced 3.8t /ha and 5.2t/ha, respectively, for the same application of irrigation water using DI and reducing risk. If costs associated with water purchasing and delivery are low, then a practice of applying 80% of TF treatment should be the most financially beneficial practice under OSI and SDI systems, excluding the initial start-up costs which need to be further examined. However, if water is limited or costly and/or pumping costs are high, then a practice of applying 60% of TF might be the most financially beneficial practice for these systems. Alternatively, water saved could be used to irrigate more land, which would increase total cotton production.

3.5. Conclusions

Differences in lint yield and WUE, induced by the use of DI practices under three irrigation systems have been modelled across four Australian cotton growing locations, using the APSIM cotton model. Our results showed that FI systems result in lower yields, WUE and MWUE than both OSI and SDI systems in all locations. DI was found to be a useful strategy for OSI and SDI systems to further improve these efficiency indicators. Therefore, growers should consider OSI or SDI adoption with DI practices. With the use of DI, we identified the following implications for irrigation decisions: although FI is the most common approach for irrigating Australian cotton. According to the outcomes from this research, the use of DI does not improve lint yield, while WUE and MWUE show marginal gains under some situations, dependent upon rainfall and soil PAWC. These results suggest it might be possible to grow more cotton with the same amount of water and increase WUE, with the use of DI practices and OSI and SDI systems. In terms of CV, the optimal DI practices resulted in lower yield variation for these two systems across all locations suggesting that DI practices may also reduce risk. Water saving may be realised as reduced water consumption for a given level of lint production, or it may allow growers to increase the irrigated area, potentially increasing total cotton yield. However, given the overwhelming existing FI infrastructure across the industry, consideration of start-up/capital replacement costs and other costs should be considered in future research.

Chapter 4. The use of deficit irrigation practices to maximise economic returns and risk analysis for three cotton irrigation systems

Abstract

Cotton growers in the Murray-Darling Basin (MDB), Australia are affected by increasing water costs and decreasing water availability. One option to reduce these challenges is the use of deficit irrigation (DI) practices. This study developed a DI bio-economic model with focusing on short-term decisions to compare gross margins by unit area (GM: $/ha) and unit of water (GM: $/ML), sensitivity analysis, and net present values (NPV). This was undertaken for three irrigation systems: furrow irrigation (FI), overhead sprinkler irrigation (OSI) and subsurface drip irrigation (SDI) at four locations within the northern region of the MDB: Goondiwindi, Moree, Narrabri, and Warren. Applying 80% of full irrigation (TF) to the study locations maximised GM/ha and NPV for both the OSI and the SDI systems in all locations, whereas, for FI, GM/ha and NPV were maximised at full irrigation. However, under the SDI system, the greatest median GM/ML was achieved by irrigating with the 80% of TF treatment at three locations and the 60% of TF treatment at Narrabri. Cotton price was the most sensitive variable in terms of GM/ha for all treatments, systems and locations. This study identified opportunities for using DI in cotton production for two of the three irrigation systems considered, focusing on short-term decisions with respect to economic returns and risks. In situations of limited water, DI is a useful strategy to maximise GM/ha and GM/ML. These approaches are be applicable to other

locations within the MDB, to the Australian cotton industry generally and to irrigated cotton production systems elsewhere.

4.1. Introduction

Cotton is one of the most important economic crops, by value, to Australian agricultural production (Eskandari et al. 2018; Yadav et al. 2018). Meanwhile, Irrigation water for cotton crop is a critical input for agricultural production systems, particularly when water is limited. In a majority areas of the MDB, there is market-based competition for water MDB (Seidl et al. 2020; Wheeler et al. 2020). Given the scarcity and cost of irrigation water, DI is a possible strategy leading to increased water use efficiency (WUE), and water productivity, and maintaining income. The work presented in Chapter 3 established criteria for improving cotton production yields and WUE with DI, but it did not address the complex question related to economic returns.

In Australia, the MDB covers parts of four Australian states, and contains 90% of Australian cotton production, most of which is grown in New South Wales and Queensland (Azad and Ancev 2016; Cammarano et al. 2012; Stiller and Wilson 2014). (Uddin et al. 2018; Williams et al. 2018). Australian cotton production within the MDB are constrained by decreasing water availability and increasing water prices (Maraseni 2012b; Wheeler et al. 2020; Williams et al. 2018). For irrigated farming, a sufficient and reliable supply of water needs to be available (Payero and Khalilian 2017). The MDB is however subject to highly variable rainfall and consequent inflows resulting in floods and droughts (Azad and Ancev 2016; Stiller and Wilson 2014; Wheeler et al. 2020), which intensifines water scarcity, sometimes for several years. Therefore, more research needs on opportunity cost, trade-offs, and the uncertainty associated with the knowledge required for operating and managing precision irrigation when the crop response to field conditions and water availability (Azad and Ancev 2016; Stiller and Wilson 2014; Wheeler et al. 2020).

The Australian cotton industry is adopting several strategies in order to overcome limited water availability and to decrease irrigation costs. One strategy is DI (Cortignani and Severini 2009; Wen et al. 2013) whose goals of DI are to improve water productivity, and maximise gross margin (GM) (Ali et al. 2007), while also increasing growers' incomes and reducing financial risk (Fereres and Soriano 2007). Darouich et al. (2014). However, the aforementioned studies evaluated DI only in a single region or a single irrigation system while this study attempts to assess DI practices across different area within the MDB regions and irrigation systems.

There are three major irrigation systems used for cotton production in Australia. These are furrow irrigation (FI), overhead sprinkler irrigation (OSI) and subsurface drip irrigation (SDI). The most common system in the MDB is FI (Foley et al. 2006; Williams et al. 2018) because of its simplicity, lower energy requirements and lower capital costs compared with OSI and SDI (Antille 2018). Each system results in different water applications (amounts and timing) and different yields, but it is possible to model inputs and yields by a particular location.

Approaches for agricultural modelling, Cobb-Douglas (CD) production function, and positive mathematical programming (PMP) are generally adopted (Misuraca 2014). These approaches are complex, especially PMP does not result in a different outcome to the simpler approach which will use in our study (Qureshi et al. 2016). In addition, as explained in chapter 2, these models are not suitable for addressing the research questions of this study due to requirements for field data. While this study employs mixed methods by combining these data sources with the APSIM tested capability, the basic analytical tool for the research is able to be used with some degree of confidence such as Monte Carlo method. This method not only allows the further use of randomising potential future conditions, as opposed to relying on historical seasons only, but it also adds to the strength of the analytical approach apparently insufficient to obtain reliable outcomes (Tanaka et al. 2021). Thus, a simpler and more practical approach of combining APSIM and economic and risk analyses has been pursued in this work in terms of short term decision-making with three irrigation systems.

The agricultural production system simulator (APSIM) is a farming system simulation platform used around the world to assess complex interactions between components of farming systems (Chauhan et al. 2013; Keating et al. 2003). The APSIM framework uses sub-models describing soil, crop and farm management processes and integrates them with weather data in a mechanistic manner to simulate crop growth and development (Holzworth et al. 2014). Soil water and soil nitrogen dynamics are also simulated along with crop growth (Keating et al. 2003; Power et al. 2011). One major use of the APSIM framework is to explore short and long-terms questions about cropping systems (Luo et al. 2014; Wang et al. 2008). However, APSIM model does not cover the economic aspects pertaining to the physical modelling. Hence, a supplementary economic and risk analyses are required for the modelling outcome in order to produce a thorough evaluation of DI strategy.

In this study, economic and risk analyses were used to examine the implications of DI practices as a strategy for Australian cotton farms to adapt to limited water availability.

While GMs for cotton production are routinely estimated both in Australia and internationally (Luo et al. 2017; Peake et al. 2016; Rodrigues and Pereira 2009), there are few analyses of the impact of DI practices on GMs. Addressing this shortcoming this research investigated the impacts of different levels of DI practices on GM/ha and GM/ML, on the distribution and on variability of average GMs and the probability distributions of net present value (NPV) for short term using FI, OSI and SDI across four study locations (Goondiwindi, Moree, Narrabri and Warren) in the MDB.

This study addressed four specific research questions:

1- What are the GM outcomes (per ha and per ML water used) of cotton with DI practices under three different irrigation systems in four locations within the MDB?
2- What are the effects on GM/ha for Australian cotton producers of changing the input (water and labour) and output (cotton prices) by ± 10%, while adopting different levels of DI practices?
3- What are the distribution and variability of average GMs over a ten-year time horizon, using different levels of DI practices for three irrigation systems across four locations within the MDB?
4- What are the probability distributions of net present value (NPV) of cumulated GMs over a ten-year period, using different levels of DI practices for three irrigation systems across four locations within the MDB?

4.2. Materials and methods

4.2.1. Study areas and farming irrigation systems

This study focused on four major cotton farming locations within the MDB: running from north near the Queensland/NSW border (Goondiwindi) to about 450 kilometres into Central West NSW (Warren). The growing season (Summer rainfall) decreases towards the south, and Warren is the furthest inland site (so that overall rainfall is lowest at Warren) for three irrigation systems:

4.2.2. Deficit irrigation practices using the APSIM cotton model

Agronomic (biophysical) modelling using the APSIM version 7.9 was undertaken to simulate cotton yields and irrigation water requirements for the four study regions for the time period from 1977 to 2017. Data required to run the APSIM model included weather data and management data. Daily weather data from 1977 to 2017 for each location were obtained from the SILO Patched Point Dataset (Jeffrey et al. 2001) (https://www.longpaddock.qld.gov.au/silo/). Soil profile descriptions, including plant available water capacity (PAWC), were obtained from the APSoil database (Dalgliesh et al. 2006) and can be identified for each location by APSIM soil numbers. Other data and input requirements to run the ASPIM model were sourced from both industry databases and previous studies (DAF 2018a; Luo et al. 2016; Luo et al. 2015a). Simulations covered a range of DI practices under each of the three irrigation systems across the study locations.

Different levels of DI practices were simulated for the FI, OSI, and SDI systems, reflecting the different capabilities of each system. The FI system was represented by a simulating standard FI system, applying relatively infrequent irrigation events of comparatively large volumes of water. The trigger point of the FI system for the treatment-full (TF) irrigation was a soil water deficit of 100 mm. The DI practices for the FI system were simulated by skipping specific irrigation events of the TF treatment (Table 4.1). The OSI and SDI systems were simulated by assigning frequent applications of smaller volumes of water. The trigger points for an irrigation application under the TF treatments for the OSI and SDI systems were soil water deficits of 50 mm and 20 mm, respectively. The DI treatment levels of 20%, 40%, 60% and 80% of TF application were achieved by adjusting the irrigation volumes of each application, as presented in Table 4.1. The full irrigation (TF) treatment varied by irrigation system, but within each system it was the same for all locations in both timing and volume of water applied. Total water applied per irrigation event under the TF treatment was 100 mm for the FI system, 50 mm for the OSI system and 20 mm for the SDI system.

Table 4.1: Summary of different levels of deficit irrigation (DI) practices under the furrow irrigation (FI), overhead sprinkler irrigation (OSI) and subsurface drip irrigation (SDI) systems.

Code	FI treatments	Code	OSI and SDI treatments
T1	Irrigated 1 out of 4 TF irrigation events	20% DI	Irrigated 20% of TF application
T2	Irrigated 1 out of 3 TF irrigation events	40% DI	Irrigated 40% of TF application
T3	Irrigated 1 out of 2 TF irrigation events	60% DI	Irrigated 60% of TF application
T4	Irrigated 2 out of 3 TF irrigation events	80% DI	Irrigated 80% of TF application
T5	Irrigated 3 out of 4 TF irrigation events	TF	Treatment full irrigation
TF	Treatment full irrigation		

4.2.3. Bio-economic modelling: Gross margins analysis

As discussed in Chapter 2, there is a very strong link between the biophysical (APSIM) model and economic analysis that was utilized to make informed economic decisions. This study used APSIM version 7.9, which does not have a production function for economic analysis. In order to make up for this limitation, gross margin (GM) was used this study to determine profitability. GM analysis relies fixed and variable cost of the irrigation systems, however, the fixed cost will not be considered in this chapter. For example, overhead (fixed) costs common to all three irrigation systems were excluded from the analysis. Several studies such as (Rodrigues & Pereira 2009; Cammarano et al. 2012; Peake et al. 2016; Luo et al. 2017) have successfully applied some the economic functions applied in this study such as GM in determining the profitability of different cotton production. This study used Monte Carlo simulation to approximate probability distributions with a considerable number of randomised draws and improve the accuracy of a model's results. The main reason for running the Monte Carlo simulation was to expand the sample size of possible cumulative outcomes over time with a relatively small climatic data set of 41 to 100 data points.

The yield under different levels of DI practices was derived from APSIM's simulation outputs. The APSIM output data (lint yield, seed yield and irrigation water used) were taken from previous work (Chapter 3) as input data for this analysis. These outputs were then used to calculate GMs ($/ha and $/ML) at field scale. Overhead (fixed) costs common to all three irrigation systems were excluded from the analysis, as they were evaluating on-farm decisions with currently established irrigation infrastructure. Simulated production outputs were based on 41 years of climate data from 1977 to 2017. For a robust analysis of the GMs, larger sample sizes were required. To test the validity of such an approach, the Durbin Watson (DW) statistical test (Kabaila et al. 2018; Savin and White 1977) was employed to determine if there were autocorrelation between year to year annual rainfall for the simulation period from 1977 to 2017. The null hypothesis (that there is a correlation) would be rejected if the DW test statistic were between du, and 4-du. The degree of freedom (k =1) in the current analysis was 1, and du and 4-du were 1.54 to 2.45 for a 5% level of significance. If the DW test showed no autocorrelation between rainfall and years across any study location, then random sampling of annual production and associated GM was used for the Monte Carlo simulations to generate a range of net present values (NPV) over time.

The gross margin (GM; $/ha) for the analysis was calculated as:

4.1. $$\mathrm{GM}_{ijkt} = \left(Y_{L,ijkm}P_L + Y_{S,ijkm}P_s\right) - \mathrm{VC}_{ijkm}$$

where the irrigation systems were denoted by subscript $i = 1, 2, 3$ representing FI, OSI and SDI, the deficit irrigation practice used for all years was represented by j, the location of the enterprise was represented by k, and the year of production was represented by t ($t = 0,1,2,\ldots T$). The randomly selected annual cotton production yield (Y) for both cotton lint and seed yields (kg/ha) was represented by m ($m = 1,2,3 \ldots 41$) from the yield sample set, being 1977/2017. The year Y_L represents cotton lint yield (kg/ha), P_L represents price of cotton lint (\$/kg), Y_S represented cottonseed yield (kg/ha) and P_S represents price of cottonseed (\$/kg), VC_{ijkm} were the variable costs (\$/ha) for system i, DI practice j, location k and randomly selected sample year m. The randomly chosen sample year (m) was used throughout for Y_L, Y_s and VC in year t. Commodity prices, including production costs were obtained from the Queensland Government's Agricultural Gross Margin Calculator (https://agmargins.net.au/). Returns on irrigated water used ($GM/ML_{\text{irrigated}}$) were calculated by Eq. 4.1 divided by water applied in a given sample year. The coefficient of variation (CV) of the GM was calculated and used as a measure of relative variability for each irrigation regime. To help to choose the time horizon that this study examined, the distribution and variability of average GM was calculated over a range of time periods from 1 to 10 years.

4.2.4. Sensitivity analysis

A sensitivity analysis of the value of yields and the major production input costs was used to investigate the impacts of changing major input and output costs and prices on GM/ha across different levels of DI practices, irrigation systems, and locations. The sensitivity analysis approach was determined by varying cotton (lint and seed) prices, as well as water and labour costs, by ± 10%, while holding the other parameters constant.

4.2.5. Net Present Value

To assess the value of future GMs over time, this study used net present value (Aparicio et al. 2019; Coria et al. 2019). This was calculated according to (Eq.4.2) to determine the return income (future outcomes) for 10 years for different levels of DI under three cotton irrigation systems. The study looked at the distribution of cumulated GMs with a current value NPV. The research examined the compounded effects of good or bad years on net present value (NPV) with a discount rate (*r*) of 6.7% (Scott et al. 2013) as follows:

4.2 $$\mathrm{NPV}_{ijkn} = \sum_{t=1}^{T} \frac{\mathrm{GM}_{ijkt}}{(1+r)^t}$$

where *n* represented the number of iterations (*n* = 1,2,3 …*N*) for *N* = 100 for this analysis based on the gross margins (GM; Eq.4.1) for each irrigation system (*i*), deficit irrigation practice (*j*) and location (*k*). The time horizon was *T* = *10-years* and *t* represented the random sample gross margin (GM; Eq.4.1) along the time horizon. All economic analyses were undertaken by using Microsoft Excel 2016. All figures were created using R (R Core Team 2019; version 3.3.5), and were produced using the ggplot2 package (Wickham 2016).

4.3. Results

4.3.1. The effects of deficit irrigation practices on gross margin per hectare

For FI, the greatest median GM/ha was achieved with the TF treatment across all locations. This treatment also had the lowest CV for three of the four locations (Figure 4.1). That is, under FI, a grower would achieve the highest gross margins over time by staying with full irrigation as understood at the time of the study. In addition, that strategy would have the lowest variation in net income in most locations. The median GMs/ha under this treatment were Goondiwindi $3644, Moree $3983, Narrabri $4326 and Warren $3127; the average irrigation water used was 3.9, 5.15, 5.15 and 3.62 ML/ha, respectively. As the irrigation deficit decreased through less severe DI practices, the CV of GM tended to decrease as production became more stable. The lowest CVs for Goondiwindi, Moree, Narrabri and Warren were 40% (TF), 36% (TF), 29% (T5 and TF) and 30% (T5), respectively.

Somewhat by contrast, for the OSI simulations, the greatest median GM/ha was achieved by irrigating at 80% of the TF treatment for all study locations. This treatment also had the lowest CVs across all study locations (Figure 4.1). The median GMs/ha under this treatment were Goondiwindi $6112, Moree $5858, Narrabri $5624 and Warren $5227; the average irrigation water used was 3.87, 5.26, 4.67and 4.67 ML/ha, respectively. The 80% of TF treatment, when compared with the TF treatment, reduced irrigation applications by 1.18, 1.36, 1.29 and 0.88 ML/ha of water, respectively. As the amount of irrigation water used increased with the reduction of DI practices, the CVs of GMs/ha tended to decrease. The lowest CVs for Goondiwindi, Moree, Narrabri and Warren were 23% (80% of TF), 22% (80% of TF), 25% (80% of TF) and 15% (80% of TF), respectively. For each location, more water was used than for the full treatment under FI, but gross margins were also substantially higher.

For SDI, the greatest median GM/ha was achieved by irrigating at 80% of TF treatment at four locations. This treatment also had the lowest CV across all study locations (Figure 4.1). The median GMs/ha under this treatment were Goondiwindi $5649, Moree $5539, Narrabri $5129 and Warren $4749; the average irrigation water used for 80% of TF treatment was 4.57, 5.55, 5.07 and 4.39 ML, respectively. The 80% of TF treatment, compared with the TF treatment, reduced irrigation applications by1.28, 1.57, 0.59 and 1.27 ML/ha of water, respectively. As the amount of irrigation water increased, the CVs of GM/ha tended to decrease. The lowest CVs for Goondiwindi, Moree, Narrabri and Warren were 23% (80% of TF), 32% (80% of TF), 36% (80% of TF) and 23% (80% of TF), respectively. This irrigation system simulation (80% of TF) required the highest per ha application of water but GMs/ha were lower than for OSI at 80% of TF.

4.3.2. The effects of deficit irrigation practices in term of gross margin per ML

For the FI system, the greatest median GM/ML was achieved with T1 treatment at Goondiwindi and Warren, and with T4 treatment at Moree and Narrabri (Figure 4.2). The median GMs under these treatments at Goondiwindi, Moree, Narrabri and Warren were $1556, $767, $1141 and $927/ML, respectively, which demonstrated highly variable results. The T1and T4 treatments compared with the TF treatment, reduced irrigation applications by 2.67, 1.25, 1.93 and 2.5 ML/ha of water for Goondiwindi, Moree, Narrabri and Warren, respectively. The lowest CVs for Goondiwindi, Moree, Narrabri and Warren were 55% (T5) and 51% (T4), 40% (T4) and 43% (TF), respectively.

For the OSI system, the greatest median GM/ML was achieved with 20% of TF treatment at each study location (Figure 4.2). The lowest CVs occurred for the TF treatment at all study locations. The greatest median GMs/ML under this irrigation treatment were Goondiwindi $2307, Moree $1023, Narrabri $1396 and Warren $865/ML. The 20% of TF treatment compared with the TF treatment, reduced irrigation applications by 4.96,5.41,4.85 and 4.58 ML/ha of water, respectively. The lowest CVs for Goondiwindi, Moree, Narrabri and Warren were 40% (TF), 27% (TF), 41% (80%TF) and 25% (TF), respectively.

For the SDI system, the greatest median GM/ML was achieved with 80% of TF treatment at Goondiwindi and Warren, and with 60% of TF treatment at Moree and Narrabri (Figure 4.2). The lowest CVs at three of the four locations were achieved with the TF treatment. The greatest median GMs/ML under this treatment were Goondiwindi $850, Moree $707, Narrabri $896 and Warren $683/ML. Compared with the TF treatment, using the 80% of TF treatment at Goondiwindi and Warren reduced irrigation applications by 1.28 and 1.27 ML/ha of irrigation water, respectively, while at Moree and Narrabri the 60% of TF treatment reduced irrigation applications by 2.97 and 2.39 ML/ha of irrigation water, respectively. The lowest CVs for Goondiwindi, Moree, Narrabri and Warren were at 30% (TF), 28% (TF), 42% (80% of TF) and 22% (TF), respectively.

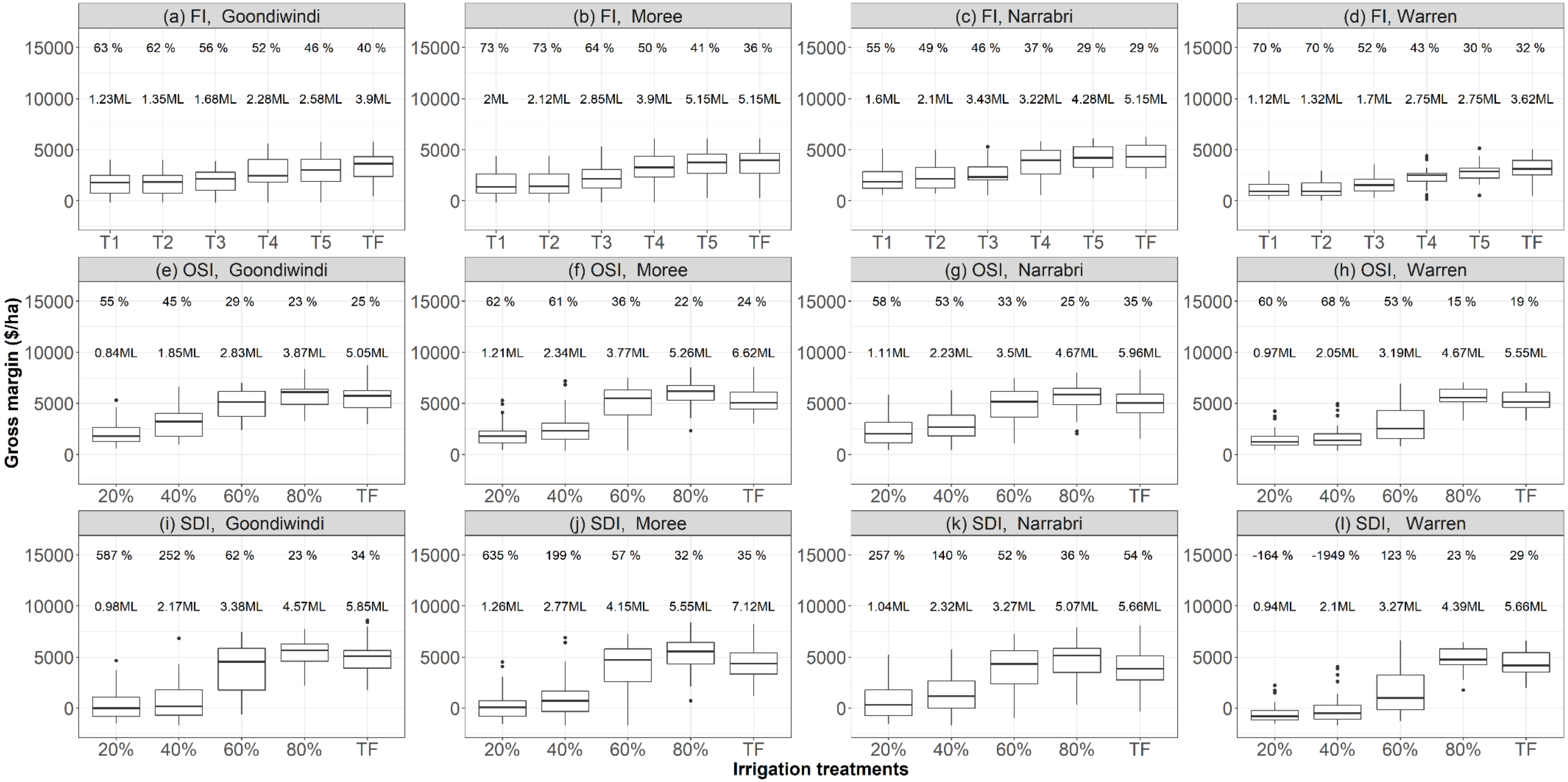

Figure 4.1: Gross margin (GM: $/ha) in response to irrigation treatments (ML/ha) for the furrow irrigation (FI), overhead sprinkler irrigation (OSI), and subsurface drip irrigation (SDI) systems for Goondiwindi, Moree, Narrabri, and Warren (1977/2017). Under the FI system, the treatments of irrigation events were '1 out of 4' (T1), '1 out of 3' (T2), '1 out of 2' (T3), '2 out of 3' (T4), '3 out of 4' (T5) irrigation events, and (TF) full irrigation treatment. The treatments of OSI and SDI included 20%, 40%, 60%, 80% of TF and TF treatment. The percentages at the top of the plots represented the coefficient of variation (CV) of the GM values and the box plots represented water applied as irrigation for each treatment.

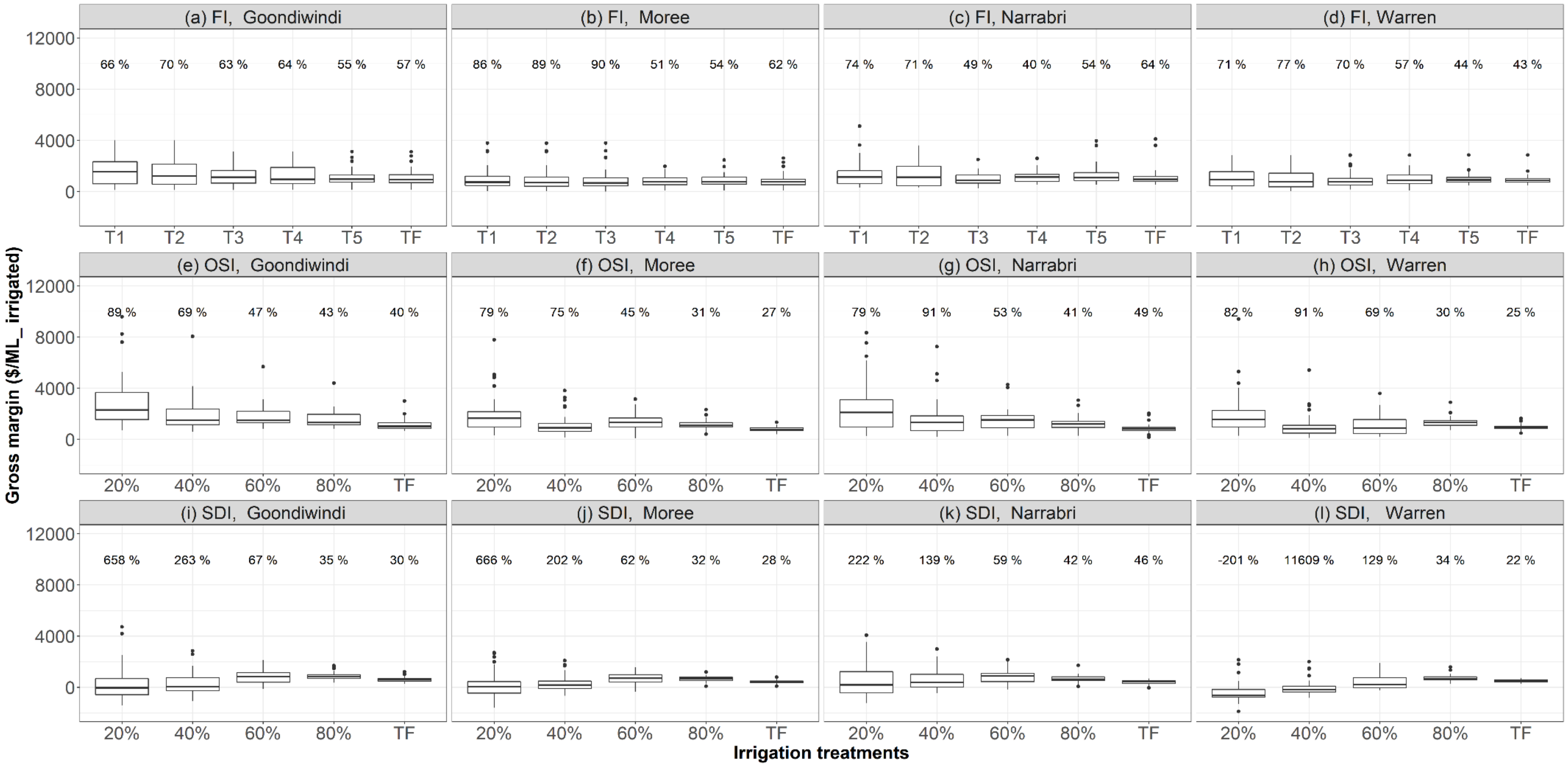

Figure 4.2: Gross margin (GM: $/ML irrigated)) in response to irrigation treatments for the furrow irrigation (FI), overhead sprinkler irrigation (OSI) and subsurface drip irrigation (SDI) systems for Goondiwindi, Moree, Narrabri, and Warren. Under the FI system, the treatments of irrigation events were ‘1 out of 4’ (T1), ‘1 out of 3’ (T2), ‘1 out of 2’ (T3), ‘2 out of 3’ (T4), ‘3 out of 4’ (T5) irrigation events, and (TF) full irrigation treatment. The treatments of OSI and SDI included 20%, 40%, 60%, 80% of TF and TF treatment. The percentages at the top of the plots represented the coefficient of variation (CV) of the GM values.

4.3.3. Sensitivity analysis of economic inputs under deficit irrigation practices

For FI, the TF treatment showed the greatest sensitivity to cotton (lint and seed) prices for all locations. A 10% change in cotton prices varied GM/ha differently across locations Goondiwindi ($625/ha), Moree ($678/ha), Narrabri ($706/ha) and Warren ($561/ha) (Table 4.2). Labour and water prices ranked as the second and third most important inputs in terms of GM/ha sensitivity for the FI system across all locations. The DI showed the greatest sensitivity to variation in labour costs between locations. The highest sensitivities were observed for TF treatment at Goondiwindi ($14/ha), T4 and TF at Moree ($18/ha), T5 at Narrabri ($16/ha) and T4 at Warren ($14/ha). The treatments at each location showing the greatest variations in GM/ha for varying water delivery were, TF treatment at Goondiwindi ($8/ha), T4 and TF treatments at Moree $10/ha, T5 treatment at Narrabri ($9/ha) and T4 treatment at Warren ($8/ha). Under the FI systems, GM/ha was more than 40 times more sensitive to variations in the cotton prices on the income side than it was to labour prices. Gross margins were more than 60 times more sensitive to cotton prices than to water prices. The financial outcome was sensitive to market forces, so it would be financially prudent for farmers to use their least costly resource, water, more economically at the risk of reduced crop yield.

For OSI, the greatest sensitivity in GM/ha to cotton price variations was shown by the 80% of TF treatment at Goondiwindi, Moree and Warren, and the 60% of TF treatment at Narrabri. Under these treatments, the average variation in GM/ha at Goondiwindi was $929/ha, Moree $959/ha, Narrabri $802/ha and at Warren $861/ha (Table 4.2). Labour price ranked as the second most important input in terms of GM sensitivity for the OSI system across all locations. The treatments showed the greatest sensitivity to variations in labour costs between locations. The highest sensitivities were for the 80% of TF treatment at Goondiwindi ($19/ha), TF treatment at Moree ($44/ha), 60% of TF treatment at Narrabri ($21/ha), and the 80% of TF and TF treatments at Warren ($26/ha). Cost of water delivery ranked as the least significant input assessed in terms of GM/ha sensitivity for the OSI system and this was consistent for all study locations, indicating that water was inexpensive. The treatments at each location showing the greatest variations in GM/ha for varying water prices were, 80% of TF treatment at Goondiwindi ($11/ha), TF treatment at Moree ($25/ha), 60% of TF treatment at Narrabri ($12/ha), and 80% of TF and TF application at Warren ($15/ha). Under the OSI system, GM/ha was more than 30 times more sensitive to variations in the cotton prices than it was to labour prices. Gross margins were more than 50 times more sensitive to cotton prices than to water prices.

For SDI, the 80% of TF treatment showed the greatest sensitivity to cotton price variations at Goondiwindi, Moree and Warren, and the 60% of TF application at Narrabri. Under these treatments, the average variation in GM/ha at Goondiwindi was $906/ha, Moree $931/ha, Narrabri $742/ha and Warren $828/ha (Table 4.2). Labour price ranked as the second most important input in terms of GM/ha sensitivity for the SDI system across all locations. The treatments showed that the sensitivity to variations in labour costs differed between locations. The highest sensitivities were shown for the TF treatment at Goondiwindi ($29/ha), TF at Moree ($44/ha), 60% of TF at Narrabri ($21/ha), and 80% of TF and TF at Warren ($31/ha). Cost of water delivery ranked as the least significant input assessed in terms of GM/ha sensitivity for the SDI system for all study locations. The treatments at each location showing the greatest variations in GM for varying water prices were the TF treatment at Goondiwindi ($17/ha), the TF treatment at Moree ($25/ha), the 60% of TF treatment at Narrabri ($12/ha), and the 80% of TF at Warren ($17/ha). Under the SDI system, GM/ha was more than 27 times more sensitive to variations in the cotton prices than it was to labour price. Gross margins were more than 47 times more sensitive to cotton prices than to water prices.

Table 4.2: Results of absolute values of GM sensitivity (2017 $AUD prices) for DI practices under the furrow irrigation (FI), overhead sprinkler irrigation (OSI), and subsurface drip irrigation (SDI) systems for Goondiwindi, Moree, Narrabri and Warren. Parameters values of cotton lint and seed, labour and water prices (cost of water delivery) varied at ± 10% ($/ha).

Systems	**Parameters**	**Goondiwindi**						**Moree**						**Narrabri**						**Warren**					
FI	**DI practices**	T1	T2	T3	T4	T5	TF	T1	T2	T3	T4	T5	TF	T1	T2	T3	T4	T5	TF	T1	T2	T3	T4	T5	TF
	Cotton lint and seed prices	361	373	425	469	531	625	332	340	440	592	651	678	371	428	452	652	695	706	261	261	346	489	505	561
	Labour price	4	5	9	11	11	14	9	9	12	18	17	18	4	9	11	10	16	14	4	4	7	14	7	12
	Water price	2	3	5	6	6	8	5	5	7	10	9	10	2	5	6	6	9	8	2	2	4	8	4	7
OSI	**DI practices**		20%	40%	60%	80%	TF		20%	40%	60%	80%	TF		20%	40%	60%	80%	TF		20%	40%	60%	80%	TF
	Cotton lint and seed prices		345	531	763	929	872		350	316	850	959	875		373	466	802	594	661		573	316	471	861	826
	Labour price		2	6	6	19	16		6	11	25	31	44		6	9	21	10	10		10	11	16	26	26
	Water price		1	3	4	11	9		3	6	14	18	25		3	5	12	5	6		5	6	9	15	15
SDI	**Cotton lint and seed prices**		174	217	731	906	869		185	291	792	931	834		214	327	742	489	580		453	130	334	828	768
	Labour price		5	11	13	25	29		6	13	25	31	44		6	9	21	19	17		8	8	16	31	26
	Water price		3	6	7	14	17		3	7	14	18	25		3	5	12	11	10		5	5	9	17	15

4.3.4. Durbin Watson test for autocorrelation in rainfall between sample years

The null hypothesis of autocorrelation between annual rainfalls was rejected for the four study locations for the period 1977 to 2017, with all DW values being between 1.54 and 2.45 (Table 4.3) for Goondiwindi, Moree and Warren with a 5% level of significance. Thus, it was able to accept that there were no autocorrelations with annual rainfall across any study location. As there is no autocorrelation in rainfall between years, it could randomly select rainfall years with the associated cotton production and GMs.

Table 4.3: Durbin Watson test results for in-crop rainfall with 41 years (1977/2017) across all study locations: Goondiwindi, Moree, Narrabri, and Warren. The DW test was used with 5% of significance and K = 1.

Locations	**Durbin Watson test (DW) for annual rainfall between Oct and Apr**
Goondiwindi	1.90
Moree	2.00
Narrabri	2.00
Warren	1.70

4.3.5. The effects of deficit irrigation practices on gross margin for a 10-year time horizon

The variability of average GMs ($/ha/year) as measured by CV, decreased at a diminishing rate with respect to increasing time horizons for all DI treatments and all irrigation systems (Figures 4.3, 4.4 and 4.5). For all three irrigation systems, across all locations, the average of median GMs was constant for each treatment for time horizons from one- to ten-years. In all cases, the greatest variability (the highest CV) occurred with a single year of GM and decreased at a diminishing rate within increased time horizons. The relatively small change in CVs occurring between the nine- and ten-year time horizons indicated that going beyond the ten-year time horizon would add little to the analysis for growers choosing a DI practice. Therefore, the following analysis considered the economic impact of compounding annual returns over a 10-year time horizon for all locations, irrigation systems and DI practices.

4.3.6. The probable economic returns (net present value) for ten-years from the adoption of deficit irrigation practices

For a ten-year period, the FI system using the TF treatment demonstrated first-order stochastic dominance (being the best option) over DI options at two study locations, Goondiwindi and Warren (Figure 4.6). At Moree and Narrabri, both T5 and TF treatments resulted in the highest NPV. Both T5 and TF treatments had stochastic dominance over T1-T4 treatments at Moree and Narrabri. The median (P=0.5) NPVs for 10 years at Goondiwindi, Moree, Narrabri, and Warren were $26,482, $29,186, $33,249 and $24,671/ha, respectively. The best-case scenario (P=1.0) during the 10-year NPVs at Goondiwindi, Moree, Narrabri, and Warren were $34,640, $36,793, $41,559 and $31,108/ha, respectively. Under the TF treatment, the worst-case scenarios (P=0.0) for the 10-year NPVs at Goondiwindi, Moree, Narrabri, and Warren were $18,828, $19,816, $21,699 and $18,541/ha, respectively. At Moree and Narrabri, the probable NPVs were similar for both the T5 and the TF treatments under all scenarios. Therefore, when there is limited water the T5 treatment may be the optimal decision under the FI system.

For a ten-year period, the 80% of TF treatment with OSI demonstrated stochastic dominance over other DI options at all study locations (Figure 4. 6). First-order stochastic dominance (being the best option) resulted from the 80% of TF treatment at Moree, Narrabri and Warren. At Goondiwindi, depending on the second condition, either the 80% of TF or TF the treatments resulted in the highest NPV. The median (P=0.5) NPVs at Goondiwindi, Moree, Narrabri, and Warren for the TF treatment over 10 years were $43,920, $43,525, $41,164 and $40,868/ha, respectively. The best-case scenario (P=1.0) for the 10-year NPVs at Goondiwindi, Moree, Narrabri, and Warren were $50,520, $51,161, $48,024 and $45,515/ha, respectively. Under the 80% of TF, the worst-case scenario (P=0.0) for the 10-year NPVs at Goondiwindi, Moree, Narrabri and Warren were $34,032, $37,129, $36,296 and $32,441/ha, respectively. At Goondiwindi, there was no difference between the 80% of TF and the TF treatments in terms of NPV in the best years (P>0.5), while in the worst years (P<0.5) the 80% of TF treatment had a higher NPV than the TF treatment.

For a ten-year period, the 80% of TF treatment with SDI demonstrated stochastic dominance over other DI options at all study locations (Figure 4.6). First-order stochastic dominance (being the best option) resulted from the 80% of the TF treatment at Goondiwindi, Moree and Narrabri. At Warren, either the 80% of TF or the TF treatments resulted in the highest NPV. Both 80% of TF and TF treatments had stochastic dominance over the 60% of TF treatment at Goondiwindi. The median (P=0.5) NPVs with the TF treatment over 10 years at Goondiwindi, Moree, Narrabri, and Warren were $29,965, $30,920, $27,775 and $25,175/ha, respectively. The best case scenario (P=1.0) for the 10-year NPVs at Goondiwindi, Moree, Narrabri, and

Warren were $36,301, $28,365, $30,830 and $26,103/ha, respectively. Under the 80% of TF, the worst-case scenario (P=0.0) for the 10-year NPVs at Goondiwindi, Moree, Narrabri, and Warren were $23,761, $24,819, $21,968 and $20,872/ha, respectively. At Warren, there were similar results for the 80% of TF and the TF treatments in terms of NPV in the worst years ($P<0.5$), while in the best years ($P>0.5$) the TF treatment had a higher NPV than the 80% of TF treatment.

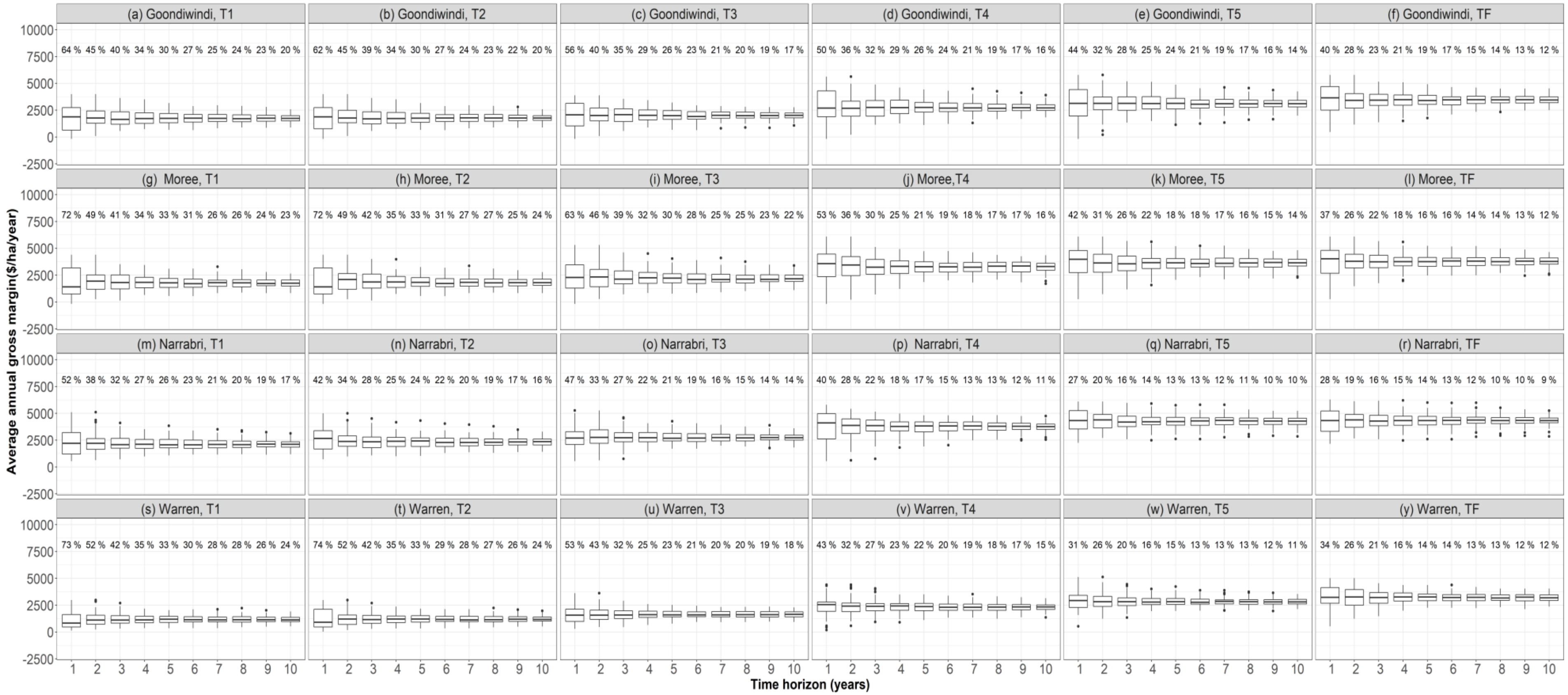

Figure 4.3: Average annual gross margin (AAGM; $/ha/year) for time horizons from one year to ten years for different levels of DI practices under the furrow irrigation (FI) system for Goondiwindi, Moree, Narrabri and Warren. For FI, the treatments of irrigation events were '1 out of 4' (T1), '1 out of 3' (T2), '1 out of 2' (T3), '2 out of 3 ' (T4), '3 out of 4' (T5) irrigation events, and (TF) treatment full irrigation. The percentages at the top of the plots represented the coefficient of variation (CV) of the AAGM values.

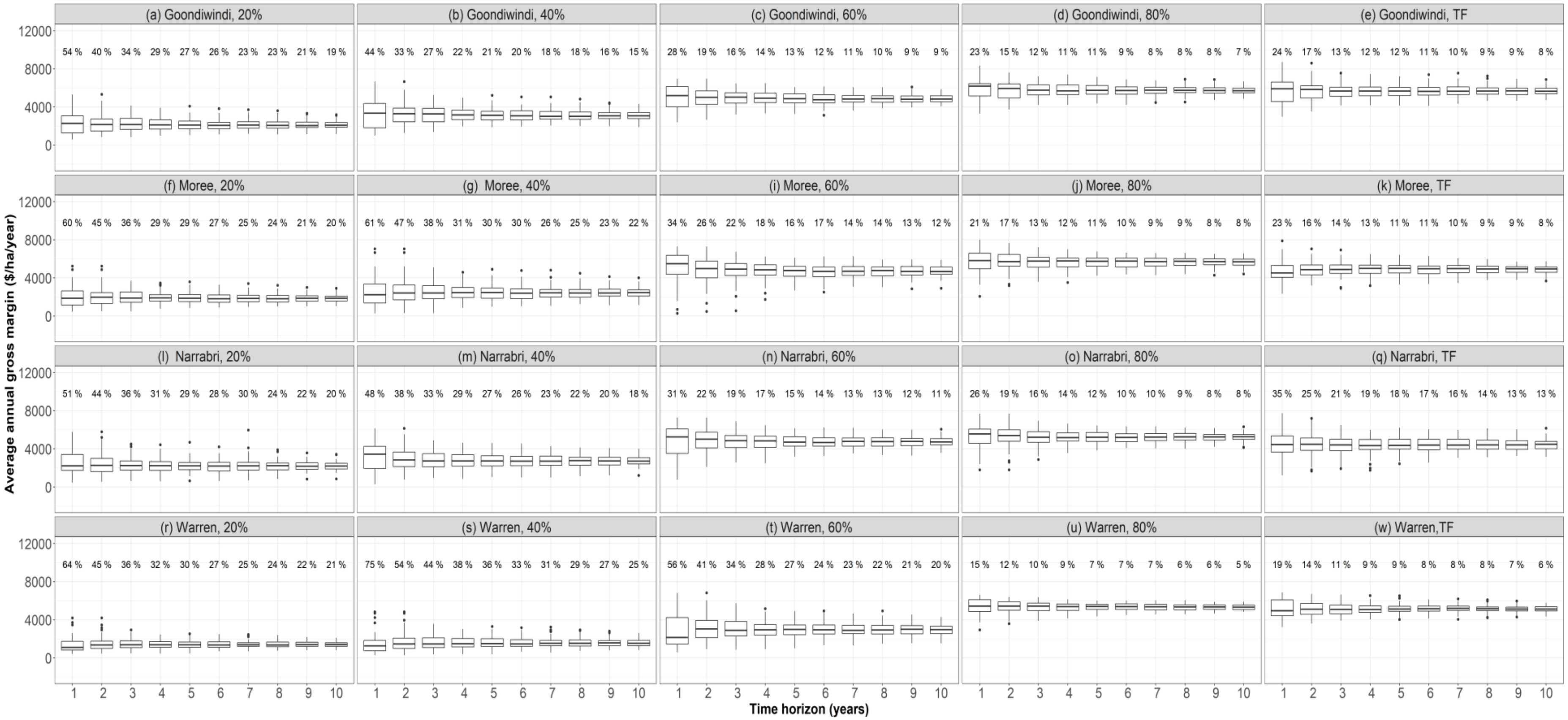

Figure 4.4*:* Average annual gross margin (AAGM; $/ha/year) for time horizons from one year to ten years for different levels of DI practices under the overhead sprinkler irrigation (OSI) system for Goondiwindi, Moree, Narrabri and Warren. For OSI, the treatments of irrigation events were 20%, 40%, 60%, 80% of TF treatment and TF treatment as full irrigation. The percentages at the top of the plots represented the coefficient of variation (CV) of the AAGM values.

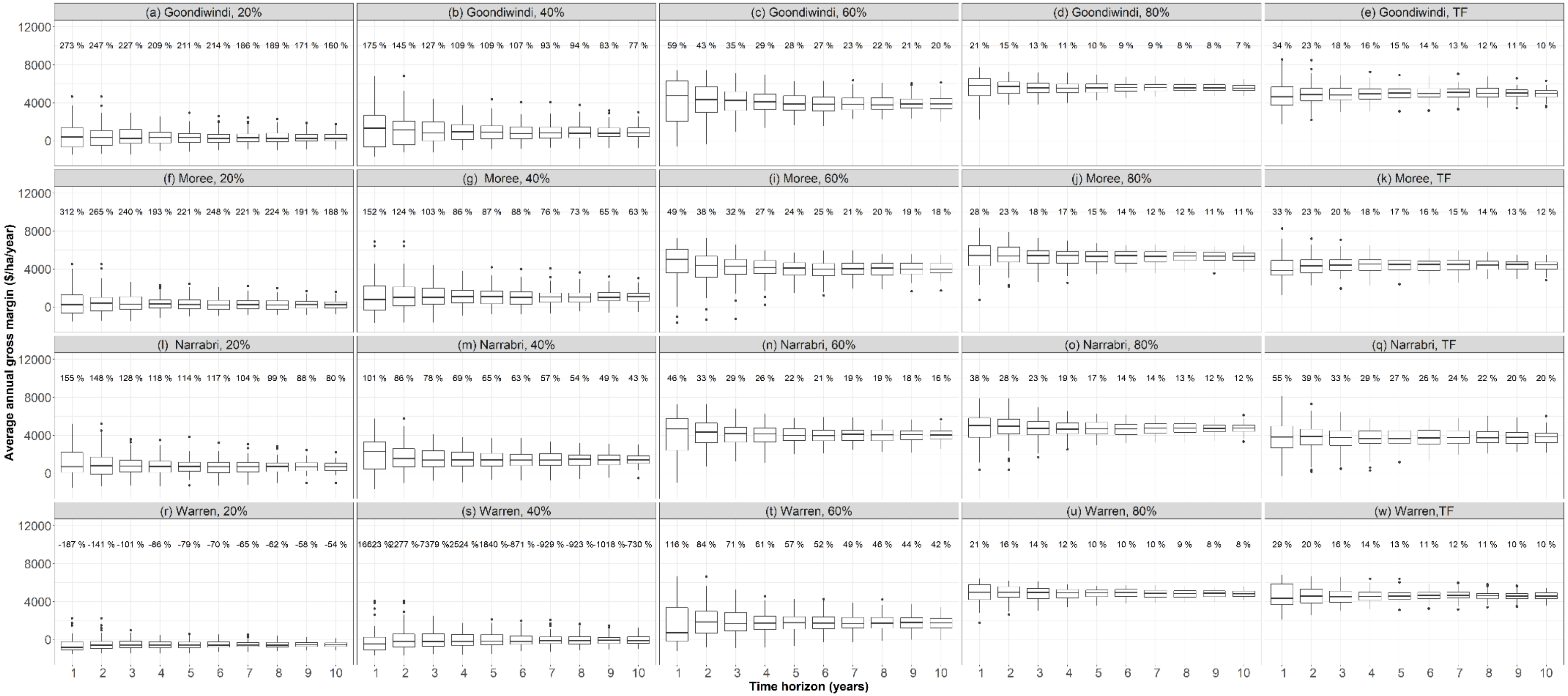

Figure 4.5: Average annual gross margin (AAGM; $/ha/year) for time horizons from one year to ten years for different levels of DI practices under the subsurface drip irrigation (SDI) system for Goondiwindi, Moree, Narrabri and Warren. For SDI, the treatments of irrigation events were 20%, 40%, 60%, 80% of TF treatment and TF treatment as full irrigation. The percentages at the top of the plots represented the coefficient of variation (CV) of the AAGM values.

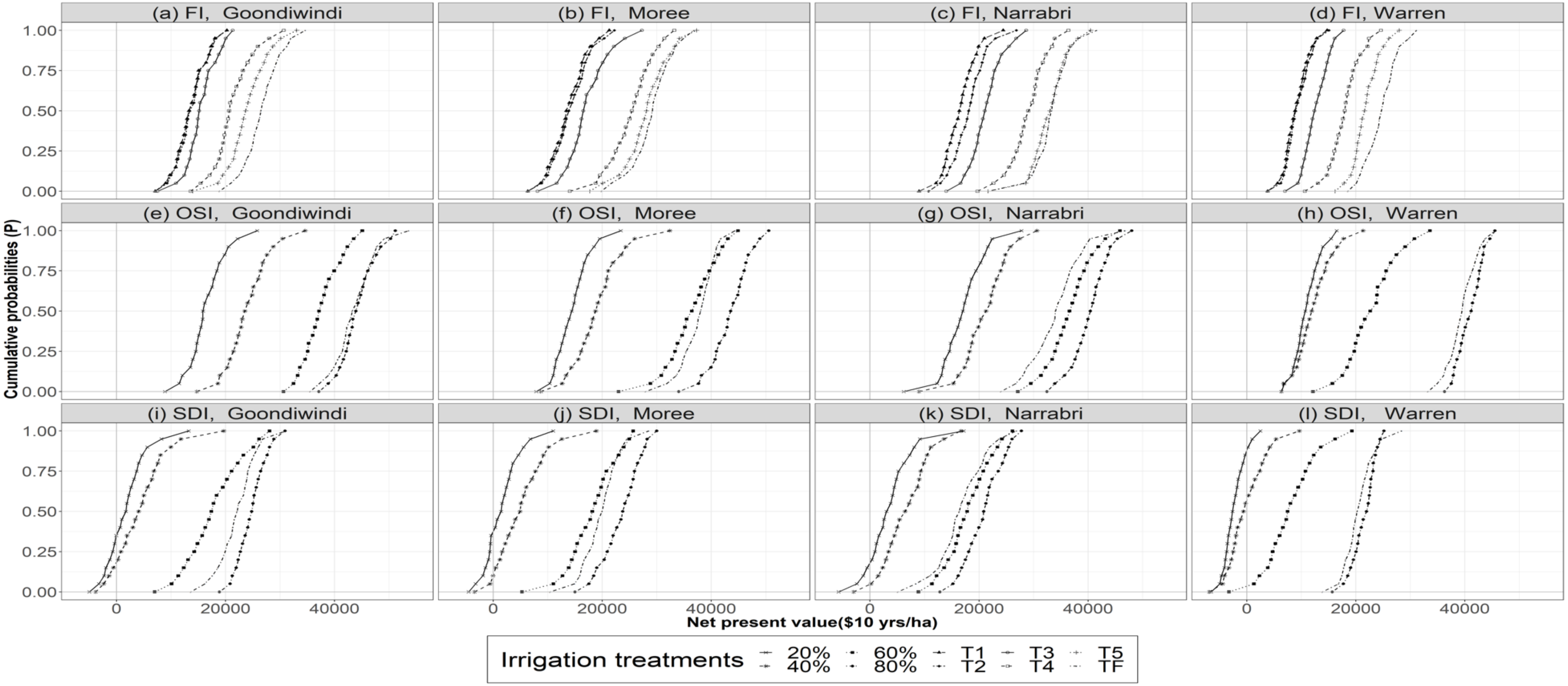

Figure 4.6: Probability of net present value (NPV) using cumulative distributions functions for a ten years period of discounted GMs, for three irrigation systems (furrow irrigation (FI), overhead sprinkler irrigation (OSI), and subsurface drip irrigation (SDI)) for Goondiwindi, Moree, Narrabri, and Warren during cotton growing seasons (1977/2017). FI treatments of irrigation events were '1 out of 4' (T1), '1 out of 3' (T2), '1 out of 2' (T3), '2 out of 3' (T4), '3 out of 4' (T5) irrigation and (TF) full irrigation treatments. The treatments of OSI and SDI systems included 20%, 40%, 60% and 80% of TF treatment and TF treatment as full irrigation, with an interest rate of 6.7%, probabilities of NPVs.

4.4. Discussion

The key advantage of adopting DI is to achieve a possible improvement in net income over time (Ali et al. 2007; Wen et al. 2013). Conserving water can be an effective approach to maximising net income, particularly under the FI, OSI and SDI systems (English 1990; English and Nuss 1982; Kirda 2002). The adoption of and outcomes from DI may depend, however, on what irrigation system is being used. As with this study, a previous study suggested that outcomes from furrow irrigation may depend much more on soil conditions, land topography, slope, and water drainage (Zounemat-Kermani and Asadi 2018). Under the FI system, there was no gain to adopt DI GM/ha and 10-year NPVs at all study locations (Figures 4.1and 4.6). The reason why FI had a lower yield compared to other systems is salinity can be a large problem with salts tending to accumulate on the tops of ridges. The results also revealed that the TF treatment had the greatest GMs/ha and NPV over 10 years across all locations. Furthermore, at all locations when applying DI under FI, it may be suggested that the use of longer periods between irrigations with greater levels of deficit water stress results in reduced crop yields and lower economic return (Bartimote et al. 2017).

An investigation in using DI under the OSI system showed that there were benefits in terms of GM/ha and 10-year NPVs. Applying 80% of TF increased both GM/ha and NPVs on average by 13% and 9% respectively, compared with TF treatment for all study locations (Figures 4.1 and 4.6). Surprisingly, reducing the amount of irrigation water by 20%, as was achieved by the 80% of TF treatment, did not show a significant reduction in the cotton yield (Chapter 3) which led to a small increase in GM/ha as cost reductions outweighed any reduction in income. This may provide an opportunity in further research to investigate how much greater area can be irrigated with the saved water, thus increasing the total production and the enterprise level of GM. In addition, the benefits of using an 80% of TF treatment under the OSI system were: a 20% reduction of water applied per hectare compared with TF, increased yield, increased GM/ha and decreased production costs (Mushtaq et al. 2013). Other research has shown that the application of DI under the OSI system can save up to 30% of water (Smith et al. 2015).The use of DI has been shown both in the results and by other researches above, to have positive effects in term of GM/ha and NPVs under the OSI system. These results supported the hypothesis that, under the OSI system, the use of DI can maximise GM.

Yang et al. (2015) demonstrated that the application of DI under SDI, particularly in relation to cotton crops, is a useful approach to increasing WUE, reducing irrigation water use and improving income. The modelling showed that was revealed that there were benefits of using DI under the SDI system regarding GM/ha and 10-year NPVs. Compared with the TF treatment, applying 80% of TF had increased both GM/ha and NPVs on average by 21% and 17% respectively, for all study locations (Figures 4.1 and 4.6). This investigation determined if there were cost and/or water savings that could be obtained without incurring adverse impacts when water was limited regarding the economics of DI for cotton crops within the MDB.

This study showed that there were benefits of using DI under all irrigation systems and study locations in terms of GMs/ML (Figure 4.2). For example, the greatest GMs/ML irrigated was for the T1 treatment under the FI system at Goondiwindi and Warren, whilst the most effective T4 treatment was at Moree and Narrabri. These treatments

(T1 and T4) under limited water availability can achieve a higher return per ML. However, crop yields decreased proportionately less than the decrease in water used. DI treatments, which had positive benefits in terms of GM/ML $_{irrigated}$ for all irrigation systems across all study locations, is an approach that should interest cotton growers in the MDB. The DI is a viable strategy when the cost of water irrigation is increased (Hargreaves and Samani 1984; Rodrigues and Pereira 2009).

Making a comparison between systems and locations, the FI system had the lower GMs/ha compared with OSI and SDI systems across all study locations (Figure 4.1) because this system had a lower yield and that led to a lower GM/ha and GM/ML compared with other systems. This finding was supported by Rajak et al. (2006) who showed that FI systems had lower yields and lower GM/ha than did SDI systems. For FI, if water is limited, cotton growers are better to use the restrictive T1 treatment, which will give a GM/ML return of $1098/ML (Figure 4.2) while for a non-limited water scenario, growers are financially better off using a TF treatment as it achieves higher median GM/ha. As more irrigation water is applied, the median GM/ML $_{irrigated}$ decreased for all treatments (Figure 4.2). DI with an SDI system had the lowest average of median GM/ML with higher water use compared to the other systems across all study locations (Figure 4.2). The results showed that the best system to maximise GM/ha and GM/ML with least water used, was the OSI system. Geerts and Raes (2009) reported that DI can play an important role in water management strategies for maximising economic returns for growers while improving sustainability by saving water, rather than for maximising yield per ML. Mushtaq et al. (2013) found that the

OSI system demonstrated the greatest water savings compared with the SDI and FI systems.

There was little difference in the range of median GMs ha/year for the time horizon (y1 to y10) after the first two years, and the CV continued to decrease as the time horizon increased (Figures 4.3, 4.4 and 4.5). A period of 10 years was sufficient for short-term decisions regarding which DI to adopt when using their current irrigation system and considering the average/expected GM over this timeframe. Overall, the findings from both agronomic (biophysical), research as previously presented in Chapter three and the economic analyses presented here demonstrated the benefits of DI for both OSI and SDI systems at all study locations within the MDB with focusing on short-term decisions. The next chapter looks at long-term capital investment decisions over 20 years. At the enterprise scale, each irrigation system is evaluated for its ability to use DI as a way to increase the area irrigated while maintaining cotton production. The whole of farm economics is assessed in terms of the costs and benefits of the different irrigation systems with varying levels of DI strategies applied.

4.5. Conclusion

Economic and risk analyses were used for short-term economic analysis of DI practices for irrigation systems across four locations in the MDB. The modelling showed that there were benefits in using DI in terms of GMs and NPVs for the OSI and SDI systems. For FI, there was no benefit from using DI in term of GM's or NPVs. Based on this economic and risk analyses, it was concluded that using DI had the potential to maximise the economic returns and minimise risk of cotton farming systems with limited water under SDI and OSI systems. These results suggested that it might be possible for cotton growers to grow the same amount of crop with less water (20% less than full irrigation) yet still to maximise GMs for these systems. Growers can maximise returns (GMs/ha) for each of the OSI and SDI systems by adopting a DI regime of applying 80% of TF for that system. A comparison of the overall productivity and profitability of the systems cannot be made without an analysis of infrastructure costs. This is investigated in the next chapter.

Chapter 5. Long term bio-economic and risk analyses of the deficit irrigation strategy for Australian cotton farming industry on an enterprise scale

Abstract

A scarcity of resources, including decreasing water availability, is challenging for Australian cotton farming systems. The adoption of deficit irrigation (DI) practices could allow a given amount of irrigation water to be used more efficiently over a larger area and thereby increase total production and on-farm profits. This may however depend on the type of irrigation system in use and the location. Bio-economic and risk modelling was used to investigate long-term capital investment in three irrigation systems in combination with different levels of DI, to maximise the profitability of cotton enterprises. The irrigation systems were furrow irrigation (FI), overhead sprinkler irrigation (OSI) and subsurface drip irrigation (SDI) and there were four study sites in the Murray-Darling Basin (MDB), Australia (Goondiwindi, Moree, Narrabri, and Warren). The analyses were based on modelling a 1000 ha cotton enterprise in each location for a 20-year time period to evaluate net benefits, payback period, equivalent annual annuity (EAA), and annual cash flows (ACFs). The findings showed that a significant reduction in water application, down to as little as 40% of what is considered treatment full (TF) irrigation, could maximise yields and EAAs. Results were reasonably consistent across the locations, but there were differences in outcomes by irrigation systems, with OSI allowing for the greatest reduction in water

applied. Therefore, utilising DI under the OSI system has the potential to increase the area irrigated, and to maximise the net benefits of the cotton farm at the enterprise scale.

5.1. Introduction

In Australia, the Murray-Darling Basin (MDB) is a key source of agricultural gross domestic production (GDP) at A$3-5bn per annum (Connor et al. 2009; Qureshi et al. 2018; Qureshi et al. 2009). Particularly, cotton production contributes significantly to the MDB GDP (Qureshi et al. 2018). Australian cotton is grown under both irrigation and rainfall-only (dryland) (Godfrey et al. 2019). Although dryland systems produce substantially lower yield than irrigated systems, they incur significant capital and operational expenses (Anwar and Darbyshire 2017; Godfrey et al. 2019). The high costs of an irrigated system could expose farmers to greater downside risks, such as loss of yield during water shortages (Godfrey et al. 2019; Rao et al. 2016). The majority of Australian cotton farms (83%) within the MDB are at least partly irrigated (Williams et al. 2018). , with the use of three irrigation methods; furrow irrigation (FI), overhead sprinkler irrigation (OSI), and subsurface drip irrigation (SDI) (McCarthy 2010; Pratley 2003). More than 80% of Australian cotton growers use the FI system (Williams et al. 2018) because of it has simple mechanical requirements and relatively low capital infrastructure and production costs (Mazarei et al. 2020; Uddin et al. 2018). By contract, OSI and SDI, require comparatively more infrastructure, installation work and advanced pumping and technical knowledge to implement and operate (Reynolds et al. 2020; Wang et al. 2020).Yet, other systems may be economically superior over time. The water resources of the basin are currently in high and varied demand (e.g. farming, environmental uses, domestic and industrial) which, along with droughts and climate change result in both short and long term reductions in the availability of irrigation water (Azad and Ancev 2016; Roth 2014; Stiller and Wilson 2014; Wheeler et al. 2020). For Australian irrigated cotton growers, this presents challenges in relation to increasing total cotton productivity and farm profits (Spivey et al. 2018).

One of the most important variables in the irrigation system, that affects the final yield is the amount of water applied per unit area. The optimum area that can be irrigated by a given amount of water becomes a crucial question for grower. When irrigation water is limited or costly, it becomes economically desirable to switch to more efficient irrigation methods (Hargreaves and Samani 1984). Understanding the economic aspects of the issues relating to water use efficiency is essential to maximise farm profitability (Qureshi et al. 2018). This can be done better with the use of DI that aims to increase economic return per unit of water applied (Cammarano et al. 2012; English 1990). A substantial amount of research (Cammarano et al. 2012; Luo et al. 2017; Peake et al. 2016; Qureshi and Whitten 2014; Qureshi et al. 2014; Rodrigues and Pereira 2009) has been conducted at the field scale, and suggested that the adoption of DI is one among a wide range of strategies that maintains yields, improves WUE and maximises gross margins (GMs).

Chapter three and four addressed the possibility of improving various measures of cotton production efficiency by using DI under OSI and SDI systems across four locations within the MDB. Both chapters adopted biophysical modelling and economic and risk analyses. The findings of Chapter three showed that the use of DI improved

WUE and marginal water use efficiency (MWUE) while maintaining lint yields comparable to TF practice. However, for FI systems, DI at any rate resulted in lower lint yields and WUE. The outcome of the economic and risk analyses presented in Chapter 4 revealed that the adoption of DI at 80% of TF for OSI or SDI systems resulted in improvements in GM/ha and GM/ML. The use of DI becomes more economically attractive as the cost of irrigation increases (Rodrigues and Pereira 2009). The economic gain obtained by utilizing DI can be invested in expanding the total productive area (Masasi et al. 2019). The use of DI has also been shown to have economic benefits when key resources other than water, for example, increase energy and labour costs (Mebrahtu 2017).

Some studies (Baio et al. 2017; Bosch et al. 1992; Enciso et al. 2005; O'Brien et al. 1998; Spivey et al. 2018) have evaluated the economics of investment (i.e., fixed costs) in irrigation systems. However, these studies did not consider the effect of DI adoption on an enterprise scale. From the literature review, this study is the first attempt to evaluate DI effects on farm economics on such a scale. Specifically, this chapter presents an economic evaluation that includes the capital costs and benefits of DI under three irrigation systems at the enterprise scale to identify the optimum arrangement of irrigated and dryland production. The adoption of DI practices was evaluated to assess how the limited water can be used over a larger area with increasing total enterprise cotton production and profits. This economic, financial and risk analyses consider net benefits, payback period, equivalent annual annuity (EAA), and annual cash flows (ACF) for the farming enterprise.

This study used Monte Carlo simulation method as discussed in Chapter four. This approach is a useful for capital budgeting tool that allows the growers to reflect the uncertainty associated with various components (e.g., net benefits, payback period, EAA, and ACF). Therefore, the output from these components consists of distributions of net cash flows, which can be used for decision-making and risk management. On this ground, this study considered capital costs and their impact on longer term net returns based on DI strategies with the three different systems within the MDB. The randomisation of potential seasons when looking ahead was a good extra feature used in terms of long-term decisions based on economic impacts. This research provides some clear guidance for growers into financial decisions around irrigation – at least for the conditions considered – that was not otherwise available in this form.

5.2. Materials and methods

5.2.1. Study locations and irrigation systems

There were four locations within the MDB (Goondiwindi, Moree, Narrabri, and Warren). The characteristics of the soils, including the plant available water capacity (PAWC) typical for each location, were obtained from the APSoil (APSIM) database (Dalgliesh et al. 2006), and are presented in Table 5.1.

Table 5.1: Location, soil type, APSoil identifier, average annual rainfall during the 41year period of the simulation study (1977/2017) and plant available water capacity (PAWC) in the surface 1200 mm of soil at each study location in the MDB.

Location	**State**	**Lat./Long.**	**Soil type**	**APSoil number**	**Average annual rainfall (mm)**	**PAWC (mm)**
Goondiwindi	Qld.	28°27'2.40"S, 150°9'35.27"E	Grey Vertisol	219	614	253
Moree	NSW	31°47'24.40"S, 147°44'1.40"E,	Grey Vertisol	870	594	372
Narrabri	NSW	30°19'1.18"S, 149°48'51.10"E	Grey Vertisol	124	652	279
Warren	NSW	31°47'25"S, 147°44'17"E	Medium clay Vertisol	705	487	234

5.2.2. Bio-economic modelling

Bio-economic modelling, which combines biophysical and economic modelling, was used in this study. There is a dynamic interaction between the biophysical APSIM model presented in Chapter three with the economic analysis for a small scale and short term economic analyses presented in Chapters four and this Chapter. The outcome of chapter 3 informed the worked conducted in chapter 4 where the optimum DI and irrigation system with highest WUE was compared with other treatment scenarios in terms of economic feasibility. There is a lack of comprehensive bio-economic studies for the long-term use of DI that include consideration of capital investment in different systems with DI. Therefore, this Chapter focuses on the economic assessment of DI adoption from long term perspectives. Once the optimum irrigation system was identified, the economic analyses were expanded for an enterprise scale with longer period of 20 years using Monti Carlo simulation used to expand the sample size as explained in Section 4.2.3, Chapter four. It is important to note here that conducting capital budgeting analysis (net benefits) requires field data for large area (1000 ha and for long period of time). Since such data were not available in the studied locations, the generated data by Monte Carlo simulation were used.

The biophysical modelling was undertaken using the cotton model within the APSIM version 7.9, modelling framework (Holzworth et al. 2014; Keating et al. 2003). Daily weather data from 1977 to 2017 for each location were obtained from the SILO Patched Point Dataset (Jeffrey et al. 2001) https://www.longpaddock.qld.gov.au/silo/. These data provided 41-years of data to develop crop yield estimates in the APSIM model for each irrigation system, each DI practice (including dry-land) and location.

The economic analysis was based on a 1000 ha enterprise, for a 20-year period. The sample size of yields from each system, DI practice and location can be expanded using a Monte Carlo random selection process from the 41- years of climate data (1977-2017). The Monte Carlo method provides approximate solutions to a group of mathematical problems by conducting statistical sampling trials (van Griensven et al. 2006). This study used Monte Carlo simulations through the random selection from known probabilistic distributions (Heard et al. 2013; Kvalheim et al. 2019; Luo et al.

2017). This approach was used to expand the sample size of net benefits values in order to generate NPV over time, EAA, and payback period calculations.

The management rules and assumptions used for these simulations are summarised in Table 5.2. The cotton cultivar used was Sicot 71BRF (Conaty et al. 2018; Nguyen et al. 2018) for both irrigated and dryland systems across all study locations. The sowing depth was 65 mm (DAF 2018a) for irrigated simulations and 50 mm for dryland simulations. To ensure that nitrogen was not a limiting factor for crop growth, nitrogen fertiliser as urea was applied at planting (100 N kg/ha), with 50 N kg/ha top dressings on 15 December and on 25 January (CSD 2008; Hulugalle et al. 2016). For dryland simulations, 250 kg/ha urea N was applied at sowing with no further fertiliser applications during the crop growth (Cotton Australia 2019). Irrigated and dryland simulations both used a solid planting configuration. For dryland crops, a sowing window was used to allow flexible sowing options based on rainfall events (with the sowing trigger set at 30 mm rain over three days and sow sowing needing to be completed by the end of the window). Dryland crops were sown every year regardless of conditions to allow results to be combined with data from the irrigated simulations.

Table 5.2: Crop agronomic management used to run the APSIM cotton model for both irrigated and dryland simulations across four locations: Goondiwindi, Moree, Narrabri and Warren within the MDB over the period from 1977 to 2017.

Parameters	**Irrigation system**				**References**	**Dry land system**				**References**
Locations	Goondiwindi	Moree	Narrabri	Warren		Goondiwindi	Moree	Narrabri	Warren	
Sowing window start date and sowing window end date	October 23 October 23	October 15 October 15	October 11 October 11	October 13 October 13	(Luo et al. 2015b; Zhang et al. 2016b)	1 October - 30 November	1 October – 30 November	1 October – 30 November	1 October – 30 November	(Anwar and Darbyshire 2017)
Plants/m^2 established	9.5,	9	10.5	10	(DAF 2018a)	8	8	8	8	(Cotton Australia 2019)
Sowing depth	65 mm	65 mm	65 mm	65 mm	(DAF 2018a)	50 mm	50 mm	50 mm	50 mm	(DAF 2018a)

The maximum water available for each irrigation system and DI practice was based on the findings presented in the previous chapters. This study also used the same approaches as in the previous chapters, which detailed DI treatments and irrigation trigger points for FI, OSI and SDI systems at 100 mm, 50 mm and 20 mm, respectively (Chapter 3). The cotton production area was set at 1000 ha, including irrigated and dryland cotton production at each location. The total available irrigation water for the enterprise was set at 2500 ML/year , as per Eq. 5.1 Due to the infrastructure, the area irrigated each year was also fixed. The area irrigated was determined by the water required for a field scale, for the 75-percentile range of total water applied for each irrigation system and for each DI treatment. From the previous chapter, we took the 75-percentile of (TF) at Goondiwindi, Moree and Warren which was 5ML/ha, while at Narrabri the 75-percentile of TF was 6 ML/ha. For consistency, we allocated 2500 ML for simulated farms at each study location dividing this by 5 ML/ha, which resulted in 500 ha being established for FI for the TF treatment. The remainder of the 1000 ha enterprise was allocated as dryland cotton production. Lint yields from both the irrigated and the dryland areas of cotton production enterprise were summed, and the total divided by 1000 ha to give average lint yields per hectare for the enterprise.

5.1 Water available = 5 ML/ha * 500 ha = 2500 ML

5.2.3. An economic evaluation of enterprise level net benefits with deficit irrigation practices

The annual profit (π) production function of the enterprise used in the analysis was:

5.2 $$\pi_{ijkt} = (y_{ijkm}P - \mathrm{VC}_{ijkm})A_{ijk} + (y_{D,km}P - \mathrm{VC}_{km})(1000 - A_{ijk}) - \mathrm{FC}_{ijkt}$$

$$given\ A_{ijk} = \frac{2500\ ML}{\mathrm{ML/ha}(y_{ijk}, 75\ percentile)}$$

where the irrigation systems are denoted by the subscript *i* = 1, 2, 3 representing FI, OSI and SDI, the DI practice used for all years is represented by *j*, the location of the enterprise is represented by *k*, and the year of production is represented by *t* (*t*= 0,1,2,…*T*). The randomly selected annual cotton production yield (*y*) for both cotton lint and seed yields (kg/ha) is represented by *m* (*m* = 1,2,3 …41) from the yield sample set. The same random sample year (*m*) is used for both the irrigated and the dryland production systems in year *t*. The price of cotton lint and seed yields from a tonne of cotton yield (t/ha) is represented by *P*. Dryland yield production is represented by Y_D. The variable costs per hectare for irrigated and dryland production are represented by *VC*. The area dedicated to irrigation is represented by *A*, given the irrigated water required (ML/ha) for irrigation system (*i*), DI practice(*j*), and location (*k*) to achieve a 75 percentile cotton yield (t/ha). The dryland (non-irrigated area) is the remainder of the 1000 ha within the cotton production enterprise. All input variable costs were collected from (https://agmargins.net.au/). Fixed costs, including loan repayements for the irrigation systems and the enterprise overheads are represented by FC_{ijkt}.

Capital investment costs for each system and DI practice comprise costs that are independent of the area irrigated (e.g., pumping requirements for 2500 ML/year) and capital costs that increase as the total irrigated area increases (e.g., area laser levelled). A list of irrigation capital infrastructure costs and the expected working life for each irrigation system were based on 500 ha and 1000 ha being irrigated (see Table 5.3).

The capital costs of the irrigation systems required for the analysis were obtained by direct communication (telephone/Zoom interviews and emails) with industry experts. The personnel interviewed included two irrigation researchers at USQ (Joe Foley and Malcolm Gillies, pers. comm., Dec., 2019 and Jan., 2020), the Principal Development Extension Officer, Queensland Department of Agriculture and Fisheries (Graham Harris, pers. comm., Dec., 2019 and Jan.,2020) and an irrigation system consultant (Jim Purcell, pers. comm.,Mar., 2020). The figures of the cost data obtained were ground-truthed with three industry suppliers located in Toowoomba, Qld. who service the irrigation industry in the study area. In reality, irrigation water is often sourced from district irrigation channels, abutting rivers or on-property irrigation bores; each with different fixed and variable costs. For this analysis a river supply for irrigated water was assumed. Due to the soil types of study areas, irrigated land preparation includes surface drainage works. Runoff due to rainfall falling on already wet ground, or FI irrigation runoff requires that fields have tail drains and that the farm has a series of levees and culverts to harvest the water and return it to storage. The costs of these additional surface works are included for all three irrigation systems (see Table 5.3).

Table 5.3:Enterprise for 500 and 1000 ha enterprise of cotton production, with fixed production costs for furrow irrigation (FI), overhead sprinkler irrigation (OSI), and subsurface drip irrigation (SDI) systems for Goondiwindi, Moree, Narrabri and Warren. Baseline values are in $AUD.

FI capital items	**Qty**	**Unit/attachment**	**Unit cost ($)**	**Total cost ($) for 500 ha**	**1000 ha**	**Life**
Discing and harrowing	1	Operation/ha	150	75,000	150,000	20
Survey (setting out and checking)	1	Operation/enterprise	30,000	30,000	30,000	20
Laser levelling initial set up	1	Operation/ha	650	325,000	650,000	20
Gypsum	1	Operation/ha	350	175,000	350,000	10
Cultivation	1	Operation/ha	30	15,000	30,000	10
Head ditch of FI	1	Setup/ha	100	50,000	100,000	20
Tail drain of FI	1	Setup/ha	100	50,000	100,000	20
Maintenance (Desilting of head and tail drain)	1	Item/ha	50	25,000	50,000	1
Bedformer	1	Item/enterprise	28,000	28,000	28,000	20
Rotobuck 4 metre boxscraper	1	Item/enterprise	20,000	20,000	20,000	20
Syphon	9600	Item/ha	4	38,400	76,800	10
Syphon replacement (maintenance)	480	Item/ha	4	1920	3840	1
Levees	1	Setup/ha	220 (for 500 ha)	110,000		20
			165(for 1000ha)		165,000	20
Culverts	1	Setup/ha	1700 (for 500 ha)	850,000		20
			1275 (for 1000 ha)		1,275,000	20
Bore and river pump	1	Setup/enterprise		1,500,000	1,500,000	20
Tail water drain	1	Setup/ha		385,000	385,000	20
Annual maintenance (levees, culverts, bore/river pump and tail water drain)			4%	113,800	133,000	1

			Total cost ($) for			
OSI capital items	**Qty**	**Unit/attachment**	**Unit cost ($)**	**500 ha**	**1000 ha**	**Life**
Discing and harrowing	1	Operation/ha	150	75,000	150,000	20
Survey (setting out and checking)	1	Operation/enterprise	18,000	18,000	18,000	20
Laser levelling initial set up	1	Operation/ha	325	195,000	390,000	20
Gypsum	1	Operation/ha	350	175,000	350,000	10
Cultivation	1	Operation/ha	20	10,000	20,000	10
Lateral mover suppled and installed	3	Setup/enterprise	450,500	1,351,500	1,351,500	20
Pump (generator 53Kva)	3	Item/enterprise	50,000	150,000	150,000	20
Maintenance of lateral mover, pump 2% of capital cost per year		Items/enterprise		30,863	31,697	1
Levees	1	Setup/ha	220 (for 500 ha)	110,000		20
			165(for 1000 ha)		165,000	20
Culverts	1	Setup/ha	1700 (for 500 ha)	850,000		20
			1275 (for 1000ha)		1,275,000	20
Bore and river pump	1	Setup/enterprise		1,500,000	1,500,000	20
Tail water drain	1	Setup/ha		385,000	385,000	20
Annual maintenance (levees, culverts, bore/river pump and tail water drain)			4%	113,800	133,000	1

SDI capital items	Qty	Unit/attachment	Unit cost ($)	Total cost ($) for 500 ha	1000 ha	Life
Discing and harrowing	1	Operation/ha	150	75,000	150,000	10
Survey (setting out and checking)	1	Operation/enterprise	18,000	18,000	18,000	10
Laser levelling initial set up	1	Setup/ha		195,000	390,000	10
Gypsum	1	Operation/ha	350	175,000	350,000	10
Cultivation	1	Operation/ha	20	10,000	20,000	10
Installation	1	Items/enterprise	3000	1,500,000	3,000,000	10
Diesel pumps screen filters and control system	1	Items/enterprise	3750	1,875,000	1,875,000	10
Drip line	1	Items/enterprise	3000	1,500,000	3,000,000	10
PVC main, PVC submains and infield valves	1	Items/enterprise	2250	1,125,000	2,250,000	10
Maintenance of PVC main, PVC submains, pumps, filters and drip line (4%)	1	Items/enterprise		180,000	360,000	1
Levees	1	Setup/ha	220 (for 500 ha)	110,000		20
			165 (for 1000 ha)		165,000	20
Culverts	1	Setup/ha	1700 (for 500 ha)	850,000		20
			1275 (for 1000ha)		1,275,000	20
Bore and river pump	1	Setup/enterprise		1,500,000	1,500,000	20
Tail water drain	1	Setup/ha		385,000	385,000	20
Annual maintenance (levees, culverts, bore/river pump and tail water drain)			4%	113,800	133,000	1

Cotton enterprises at all locations had an additional annual overhead cost of $75,500 added to total fixed costs (FC_{ijkt}). This was to cover consultant and contractor fees ($5000), fuel and oil for farm equipment ($5000), power and gas ($1000), office and administration ($5000), insurance ($2500), permanent labour hire ($50,000), repairs and maintenance ($2000) of equipment and, council rates ($5000).

To allow the costs to be estimated on a per hectare basis, the total costs for irrigating the full 1000 ha were calculated, as were the total costs for irrigating 500 ha, or half the area of the enterprise, for each irrigation system. Using a linear regression, the initial investment costs were estimated with respect to the total area irrigated for each irrigation system (see Figure 5.1). This initial infrastructure is expected to have a life-span of 20- years for FI and OSI systems. The SDI has two phases, first purchase and installation with the cost spread for 20-years, then at 10 years the drip lines are replaced with ground preparation included (discing and harrowing, gypsum application and cultivation). This investment for FI and OSI systems requires a principal-interest loan for 20-years at 7% p.a. adding loan repayment costs to the enterprises annual fixed costs (FC). For the SDI system, the same approach was used for a loan of 20 years plus an additional loan at year 11 for the second 10-year period. For the SDI, the pumps and main lines are expected to last 20-years and requires a 20 years -loan; however, the drip line is expected to last only 10-years and requires a loan to fund replacement at year 11 (see Table 5.3). Other annual maintenance items such as the replacement of syphons were also added to the annual fixed costs (FC_{ijkt}). This study used the payment function (PMT) in Excel 2016 to calculate the annual loan repayments.

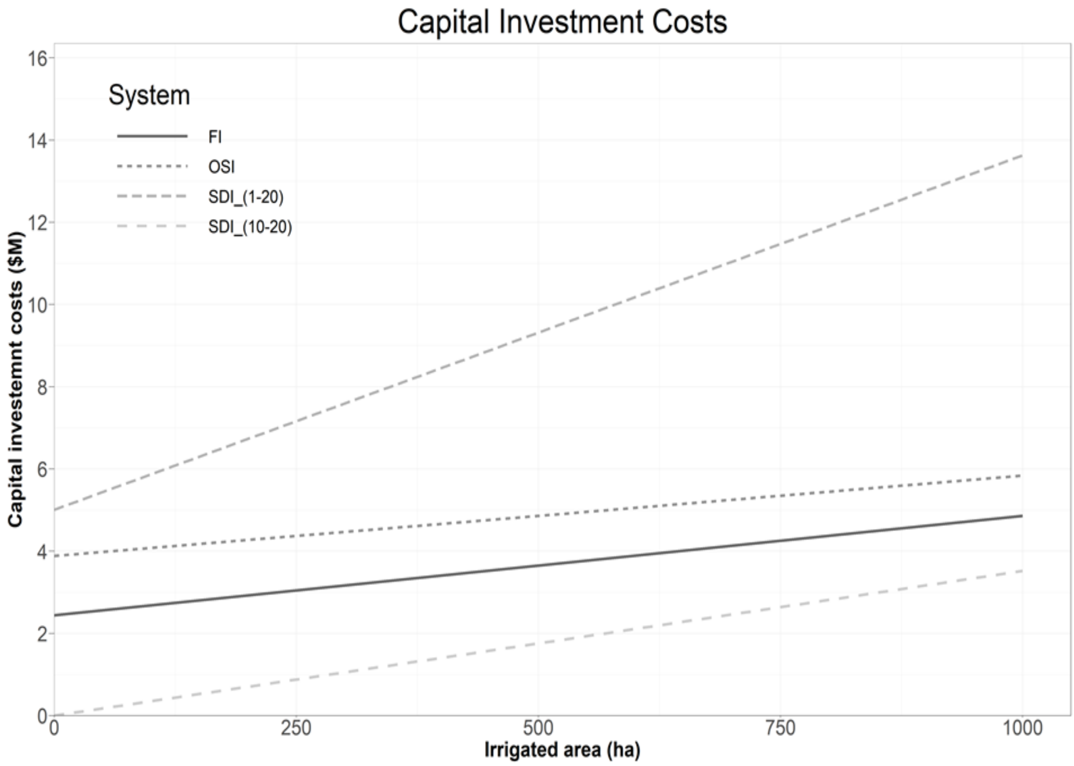

Figure 5.1: Capital investment cost values for three irrigation systems. The value at zero ha represents the capital investment cost which are independent of irrigation system size and the slope of the regression lines indicate the change in capital investment costs with respect to the change in irrigated area. These were established by calculating the costs for irrigating 500 ha and 1000 ha for cotton production for the 20-year investment horizon, while the slope of the regression line for increasing the irrigation area represents the dependent costs. Furrow irrigation (FI), overhead sprinkler irrigation (OSI), and subsurface drip irrigation (SDI) systems are presented. The OSI and FI systems have life expectancy in excess of 20-years. The SDI has two phases of 10-years each.

5.2.4. Payback period

The payback period approach is defined as the time required to recover the initial investment in a project (Crespo et al. 2019; Pendergast et al. 2014). By accumulating the annual net cash inflows until the initial investment was recovered, we determined the period needed for growers to recover the costs under each scenario.

5.2.5 Net present value

The net present value (NPV) is used in capital budgeting and investment planning to analyse the profitability of a projected investment. The NPV (Eq.5.3) is the sum of the present values of future incomes (benefits) and outgoings (costs), also referred to as discounted cash flows, over a period of time (Berk et al. 2015; Gaspars-Wieloch 2019). The impacts on cash flows for 20 years (T = 20) of each level of DI for each of the three irrigation systems were assessed. A benefit of using NPV is that it gives a single value that is easy to compare with other investment options. A limitation of NPV is that it is not able to compare assets with different life expectation. This was why all the analyses were based on a 20-year time horizon to overcome this limitation. A discount rate (r) of 6.7% pa was used for the NPV for the enterprise used in the analysis (Scott et al. 2013):

$$5.3 \quad \text{NPV}_{\boldsymbol{ijkn}} = \sum_{t=1}^{T} \frac{\pi_{ijkt}}{(1+r)t}$$

where n represents the number of iterations (n = 1,2,3 …N) for N = 100; and (π) represents the annual profit (Eq. 5.2) for each irrigation system (i), DI practice (j), and location (*K*). (*t*) represents the random sample of the annual profit for the time horizon (*T* = 20-years).

5.2.6 Equivalent annual annuity

The equivalent annual annuity (EAA) approach is used in capital budgeting to compare projects with different life periods and is a measure used to determine the financial efficiency of projects (Manuschevich and Beier 2016; Paulo and Tomé 2017). The EAA approach (Eq.5.4) was used in this study to take NPV for each system and convert them into an EAA. This EAA approach used average values per ha for 20-years. The EAA was calculated using the formulae of Paulo and Tomé (2017).

5.4. $\mathrm{EAA}_{ijkw} = \frac{\mathrm{NPV}_{ijkw}}{(1+r)-T} rA$

where EAA_{ijkm} represents equivalent annual annuity as dollars per ha for each system with each DI practice and location, NPV (Eq.5.3), *A* represents total area used, *r* represents the discount rate and *T* represents the investment time horizon of 20-years. All economic analyses were undertaken by using Microsoft Excel 2016. All figures were created using R (R Core Team 2019; version 3.3.5) with the ggplot2 package (Wickham 2016).

5.3 Results

5.3.1 Effects of deficit irrigation practices on cotton enterprise lint yields

For FI, the greatest median annual lint yields (irrigated and dryland production) per hectare for an enterprise were achieved with T5 at Goondiwindi, Narrabri and Warren, and TF at Moree; 1.7, 1.8, 2.0 and 1.5, t/ha, respectively (see Figure 5.1 and Table 5.4). For these strategies, the average water allocations used were 2.6, 4.3, 3.4 and 2.8 ML/ha, for Goondiwindi, Moree, Narrabri and Warren, respectively, with the proportion of the total land used for irrigation being 76%, 42%, 58% and 77%, respectively. The rest of the total land area of 1000 ha per enterprise was utilised for dryland cotton production.

For OSI, the highest annual lint yield values were produced at Narrabri. The greatest median annual lint yields for OSI were produced by the 40% of TF strategy; 2.6, 2.9, 2.7 and 2.5 t/ha, respectively for all locations. Under this strategy, the average water allocations used were 1.9, 2.3, 2.2 and 2.1 ML/ha, respectively, with the proportion of the total land used for irrigation being 100%, 96%, 96% and 100% at Goondiwindi, Moree, Narrabri and Warren respectively. The OSI system can produce the greatest annual lint yield of the three systems (see Table 5.4).

For SDI, the greatest median annual lint yields were produced by the 40% of TF strategy across all study locations; 2.5, 2.5, 2.4 and 2.0 t/ha, respectively. For this strategy, the average water allocations used were 2.2, 2.8, 2.3 and 2.1 ML/ha for

Goondiwindi, Moree, Narrabri and Warren, with the proportion of the total land used for irrigation being 81%, 64%, 69% and 81%, respectively.

5.3.2 Effects of deficit irrigation practices on the payback period

With FI, in half of the sequences, the initial investment costs would be paid back in two to three years at Moree and within three years at Goondiwindi and Narrabri using the T4, T5 or TF irrigation strategies (see Figure 5.2 and Table 5.4). At Warren, the T5 and TF strategies would pay off the system in 50% of cases in three to four years. The T4, T5 and TF strategies would be certain to pay off the initial investment costs in under eight years at Goondiwindi, Moree and Narrabri, with only the T5 and TF strategies guaranteed to pay off the investment costs at Warren in under 10 years. At Narrabri, the T3 strategy would also achieve payback within the 10 years. Failure to pay back the investment costs within a 10-year period is most likely at Warren with the T1 and T2 strategies having a 100% and 98% probability of non-recovery of initial investment cost. The T1 and T2 strategies at Goondiwindi and Moree and the T3 strategy at Warren all have about a 50% probability of failing to recover costs in the 10-year window.

With OSI, half the time the initial investment costs would be paid back in two years at all locations by using the 40% of TF strategy. Initial investment costs would be certain to be paid off within three years at Moree and Narrabri under this strategy, while at Goondiwindi and Warren. Failure to pay back the investment costs within a 10-year period is most likely at Goondiwindi and Warren with the 20% of TF strategy having a 25% and 70% probability of non-recovery of initial investment, respectively.

With SDI, half the time the initial investment costs would be paid back in two to three years at Moree and within three years at Goondiwindi, Moree and Narrabri using the 40% and 60% of TF irrigation strategies. At Warren the strategies would pay off the system in 50% of cases in three to four years, while 40% and 60% of TF strategies would be certain to pay off the initial investment costs in under seven and eight years at Goondiwindi and Moree. At Narrabri, the 40% and 60% of TF strategy would also achieve payback within the 10 years. At Warren, only 60% of TF was guaranteed to pay off the initial investment within +9 years, while with the other strategies there is chance of non-recovery of initial investment costs within the 10- year window. Failure to pay back the investment costs within a 10-year period is most likely at Goondiwindi, Moree, Narrabri and Warren with the 20% of TF strategy having a 98%, 80%, 98% and 100% probability of non-recovery, respectively.

5.3.3 Effects of deficit irrigation practices on equivalent annual annuity

Under the FI system, the greatest median EAA per hectare for 20-years was achieved with the TF strategy at Goondiwindi and Moree, and the T5 strategy at Narrabri and Warren (see Figure 5.4 and Table 5.4). At Warren, T1 and T2 strategies had negative EAA because of low lint yields from the irrigated area. The lowest CVs of EAA for Goondiwindi, Moree, Narrabri, and Warren were 24% (TF), 18% (T5), 15% (T5) and 18% (T5), respectively. Across all locations, the highest EAA values were at Narrabri under the FI system. The highest lint yields led to the highest EAA, while the lowest value of EAA was at Warren compared to other locations under the FI system.

Under the OSI system, the greatest median EAA was achieved with the 40% of TF strategy at all locations. The 20% of TF strategy at Warren resulted in negative EAAs. The lowest CVs of EAA for Goondiwindi, Moree, Narrabri and Warren were 11% (60% of TF), 10% (40% of TF), 11% (60% of TF) and 18% (60% of TF), respectively. Therefore, the greatest median EAA values were achieved under the OSI system when compared with the other two systems.

Under the SDI system, the greatest median EAAs were achieved with the 40% of TF strategy at Goondiwindi and Moree, and the 60% of TF strategy at Narrabri and Warren. The 20% of TF strategy resulted in the high probability of a negative EAA at all locations. The lowest CVs of EAA for Goondiwindi, Moree, Narrabri and Warren were 23% (40% of TF), 19% (40% of TF), 16% (60% of TF) and 41% (60% of TF), respectively.

5.3.4 Effects of deficit irrigation practices on annual cash flow at the enterprise scale

For a 20- year time horizon, the FI system had a positive ACF for most strategies across all locations (see Figure 5.5). The highest ACF, as indicated by first-order stochastic dominance, resulted from the T5 strategy at Warren, and from both the TF and T5 the strategies at Goondiwindi, Moree and Narrabri. Under these strategies and the best-case scenario (P=1.0) the 20-year ACFs at Goondiwindi, Moree, Narrabri, and

Warren were $3919/ha, $3657/ha, $3966/ha and $3142/ha, respectively. The medians (P=0.5) of the 20-years ACF at Goondiwindi, Moree, Narrabri, and Warren with the T5 and TF strategies were $1554/ha, $1991/ha, $1846/ha and $851/ha, respectively. In the worst-case scenario (P=0.0) the 20-year ACFs at Goondiwindi, Moree, Narrabri, and Warren were $-971/ha, $-673/ha, $80/ha and $-1274/ha, respectively. At Warren, the T1 and T2 strategies had negative ACF for all scenarios (P= 0.0, 0.5 & 1.0). For all strategies, the worst case scenario (P= 0.0) had negative ACF across all locations. Compared to other locations, Warren has low rainfall and lower soil PAWC which resulted in greater yield sensitivity to lower irrigation rates.

The OSI system had positive ACFs for most strategies across all locations. The highest ACF, as indicated by first-order stochastic dominance, resulted from the 40% of TF strategy at Moree and Warren, and the 60% of TF strategy at Goondiwindi and Narrabri. Under these strategies, in the best-case scenario (P=1.0) the 20-year ACFs at Goondiwindi, Moree, Narrabri, and Warren were $6211/ha, $5933/ha, $5856/ha and $5309/ha, respectively. The median (P=0.5) ACF for 20 years at Goondiwindi, Moree, Narrabri, and Warren were $3477/ha, 3906/ha, $3655/ha and $2954/ha, respectively. In the worst-case scenario (P=0.0) the 20-year ACFs at Goondiwindi, Moree, Narrabri, and Warren were $-52/ha, $-22/ha, $-96/ha and $27/ha, respectively. Under the 20% of TF strategy, Warren had negative ACF for the scenarios (P= 0.5 & 0.0).

Under the SDI system, most strategies had positive ACFs for all locations. The highest ACF, as indicated by first-order stochastic dominance, resulted from the 40% of TF strategy at Goondiwindi and Moree, and the 60% of TF strategy at Narrabri, and 40% of TF or 60% of TF strategies at Warren. Under these strategies, in the best-case scenario (P=1.0) the 20-year ACFs at Goondiwindi, Moree, Narrabri, and Warren were \$4691/ha, \$4380/ha, \$4988/ha and \$3898/ha, respectively. The median (P=0.5) ACFs within 20-years at Goondiwindi, Moree, Narrabri, and Warren under the 40% of TF and 60% of TF strategies were \$2183/ha, \$1857/ha, \$2642/ha and \$1596/ha, respectively. In the worst-case scenario (P=0.0) the 20-year ACFs at Goondiwindi, Moree, Narrabri, and Warren were \$-223/ha, \$-312/ha, \$-1079/ha and \$-205/ha, respectively. The 20% of TF strategy was clearly worse than other strategies at (P= 0.0 & 0.5) for all locations under the SDI system, with all locations having negative ACFs.

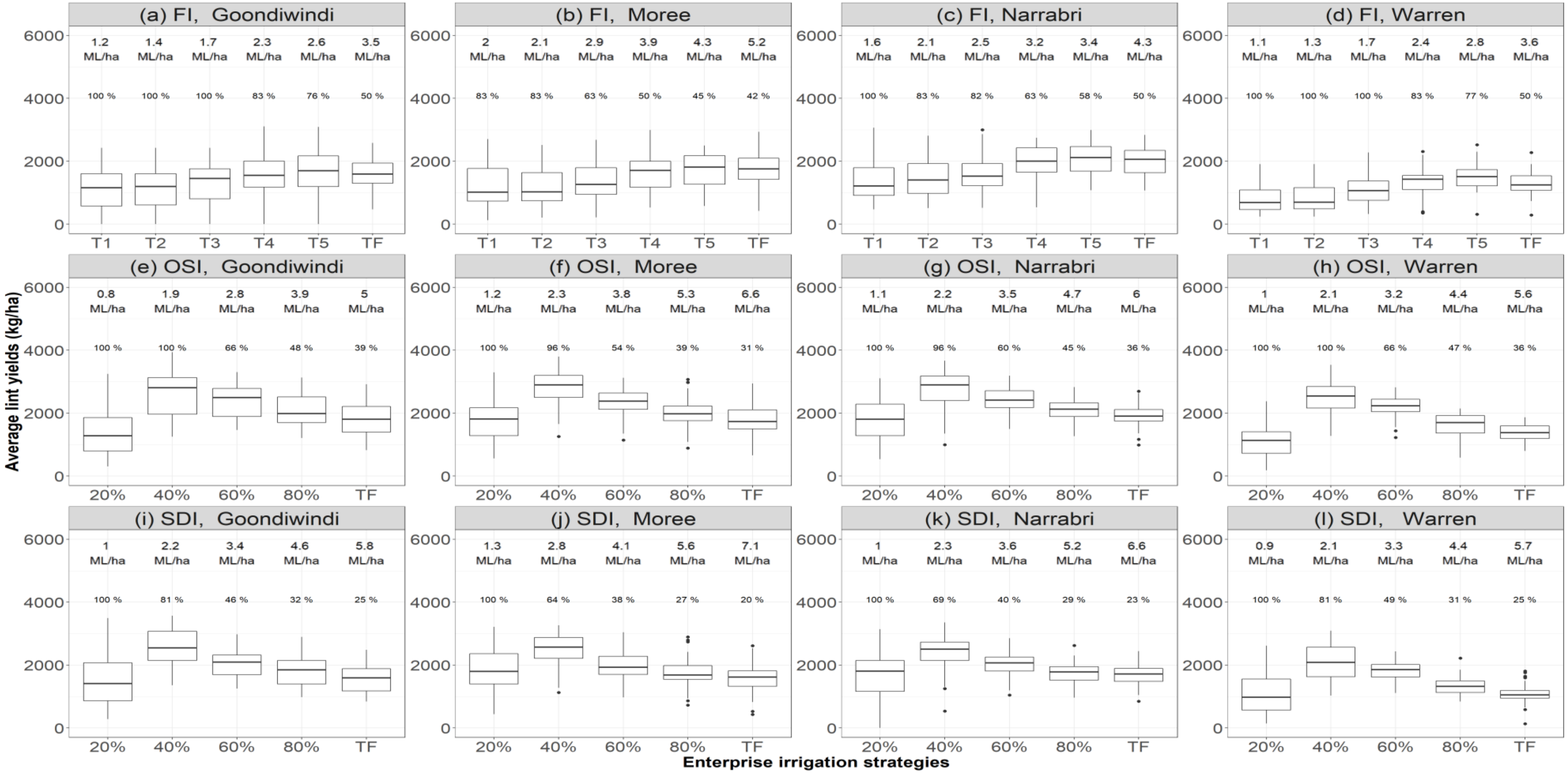

Figure 5.2: Annual lint yield (kg/ha) for an enterprise of 1000 ha combining irrigated and dry land production. Furrow irrigation (FI), overhead sprinkler irrigation (OSI), and subsurface drip irrigation (SDI) systems are presented for Goondiwindi, Moree, Narrabri, and Warren. The enterprise irrigation strategies for the FI system were '1 out of 4' (T1), '1 out of 3' (T2), '1 out of 2' (T3), '2 out of 3' (T4), '3 out of 4' (T5) irrigation and the (TF) strategy which was full irrigation. The enterprise irrigation strategies of OSI and SDI systems were 20%, 40%, 60% and 80% of TF and TF applications. Average water allocation (ML) for an enterprise is presented for each system, strategy and location. The percentages at the top of the plots represent the proportion of irrigated area per enterprise.

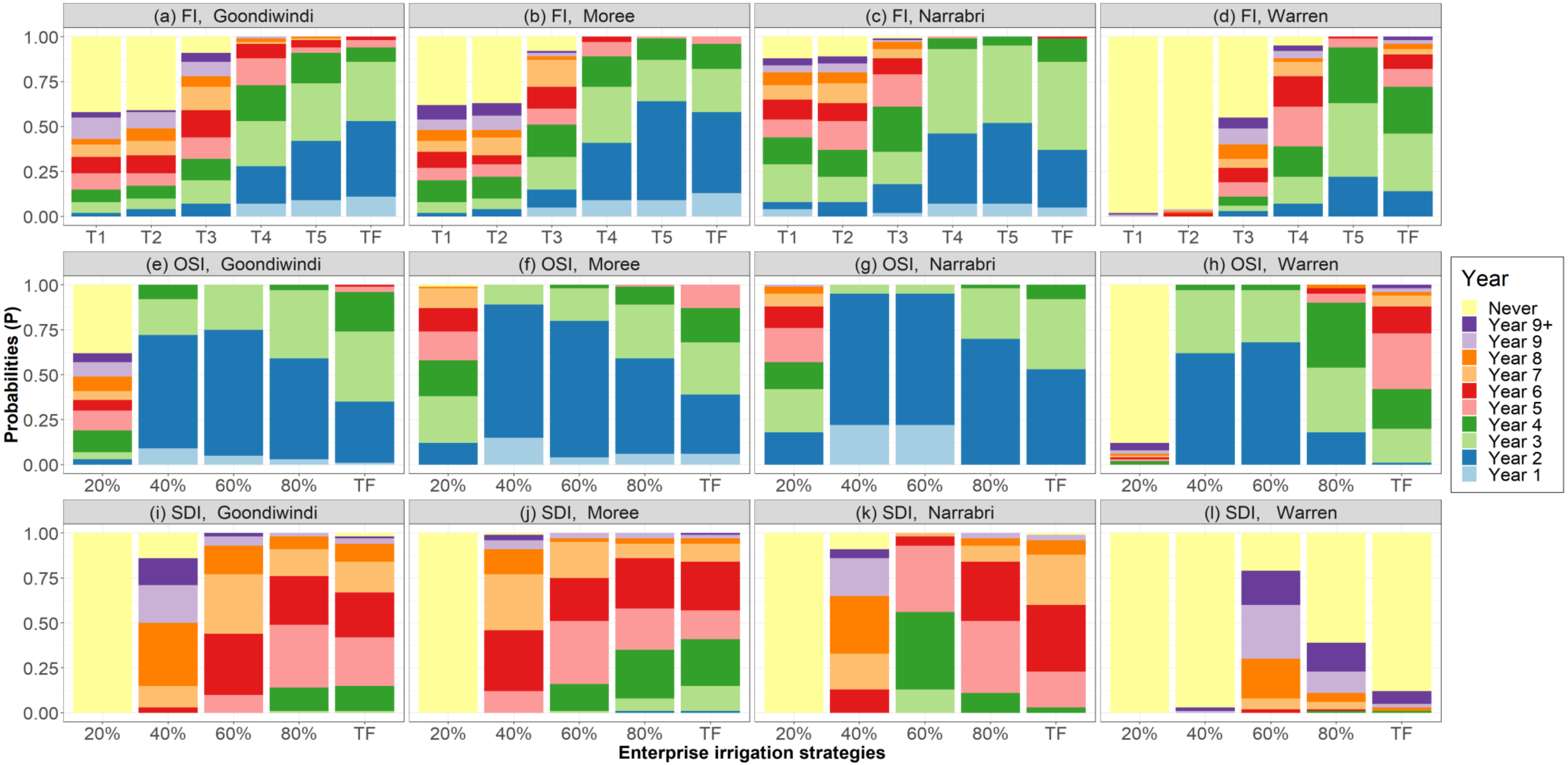

Figure 5.3: Probability of payback period of initial capital costs for 1000 ha for a 20 year period. Furrow irrigation (FI), overhead sprinkler irrigation (OSI), and subsurface drip irrigation (SDI) systems are presented for Goondiwindi, Moree, Narrabri, and Warren. Never means that it was not within the 20-year time horizon. The enterprise irrigation strategies for the FI system were '1 out of 4' (T1), '1 out of 3' (T2), '1 out of 2' (T3), '2 out of 3' (T4), '3 out of 4' (T5) irrigation and the (TF), strategy which was full irrigation. The enterprise irrigation strategies of OSI and SDI systems were 20%, 40%, 60% and 80% of TF and TF applications.

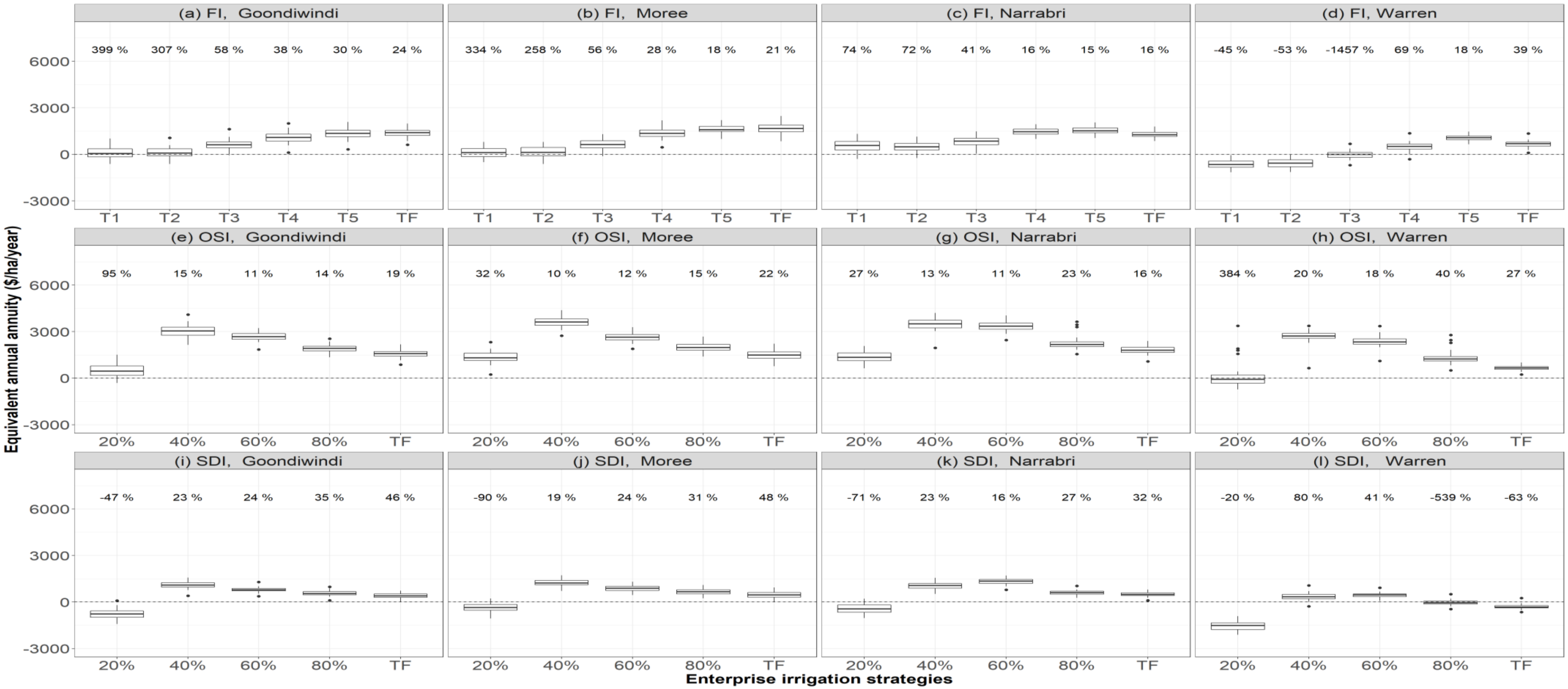

Figure 5.4: Equivalent annual annuity (EAA: $/ha/year) for 1000 ha for a 20-year period with discounted NPV using a rate of 6.7% pa. Furrow irrigation (FI), overhead sprinkler irrigation (OSI), and subsurface drip irrigation (SDI) systems are presented for Goondiwindi, Moree, Narrabri, and Warren. The enterprise irrigation strategies for the FI system were ‘1 out of 4’ (T1), ‘1 out of 3’ (T2), ‘1 out of 2’ (T3), ‘2 out of 3’ (T4), ‘3 out of 4’ (T5) irrigation and the (TF) strategy, which was full irrigation. The enterprise irrigation strategies of OSI and SDI systems were 20%, 40%, 60% and 80% of TF and TF applications.

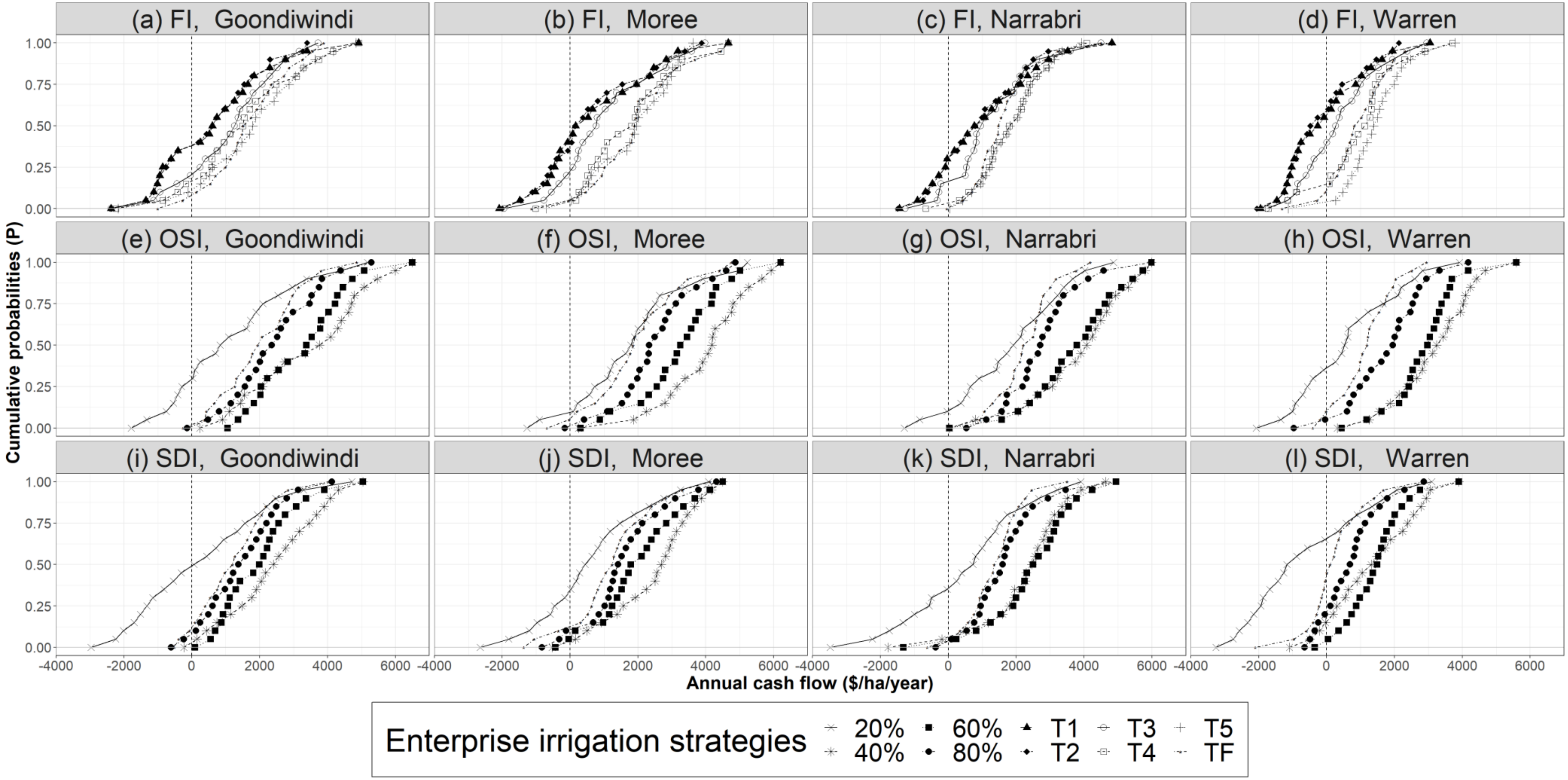

Figure 5.5:Cumulative probability of annual cash flow (ACF; $/ha/year) without discounting. Furrow irrigation (FI), overhead sprinkler irrigation (OSI), and subsurface drip irrigation (SDI) systems are presented for Goondiwindi, Moree, Narrabri, and Warren. The enterprise irrigation strategies for the FI system were '1 out of 4' (T1), '1 out of 3' (T2), '1 out of 2' (T3), '2 out of 3' (T4), '3 out of 4' (T5) irrigation and the (TF) strategy, which was full irrigation. The enterprise irrigation strategies of OSI and SDI systems were 20%, 40%, 60% and 80% of TF and TF applications.

Table 5.4: Summary of the best performing DI practices which give the greatest median values for the annual lint yield, total irrigated land (ha), the payback period (PP) and equivalent annual annuity (EAA). Furrow irrigation (FI), overhead sprinkler irrigation (OSI), and subsurface drip irrigation (SDI) systems are presented for Goondiwindi, Moree, Narrabri, and Warren.

System/ Irrigation practices	**FI**				**OSI**				**SDI**			
location	Goondiwindi	Moree	Narrabri	Warren	Goondiwindi	Moree	Narrabri	Warren	Goondiwindi	Moree	Narrabri	Warren
Annual lint yield at enterprise (Kg/ha)	1679 (T5)	1767 (TF)	2042 (T5)	1508 (T5)	2608 (40%)	2860 (40%)	2747 (40%)	2476 (40%)	2541 (40%)	2478 (40%)	2389 (40%)	2061 (40%)
Total irrigated land(ha)	76% (T5)	42% (TF)	58% (T5)	77% (T5)	100% (40%)	96% (40%)	96% (40%)	100% (40%)	81% (40%)	64% (40%)	69% (40%)	81% (40%)
PP (year)	6 (T5)	5 (T5)	4 (T5)	5 (T5)	3 (60%)	4 (40%)	3 (40%)	3 (60%)	7 (60%)	6 (60%)	5 (60%)	9 + (60%)
EAA($/ha)	1367 (TF)	1666 (TF)	1537 (T5)	1072 (T5)	3051 (40%)	3607 (40%)	3456 (40%)	2671 (40%)	1091 (40%)	1233 (60%)	1038 (60%)	346 (60%)

5.4 Discussion

Our analysis of long-term investment decisions showed that in most cases (location and system), a farmer with both dryland and irrigated cotton could reduce water applications below, increase the proportion of irrigated cotton and realise a net economic gain. In particular, under the OSI system, the 40% of TF strategy could achieve the highest annual lint yields and EAA (see Figures 5.2, and 5.3 and Table 5.4). With more than 95% of the cotton enterprise area irrigated under this strategy, at all locations the median yields were between 2476 and 2860 kg/ha, generating a median EAA between $2671 and $3607/ha. Under this strategy, between 93 and 100% of years generated a positive ACF for all study locations. Across all study locations, this strategy also presented the best opportunity to produce a positive ACF (see Figures 5.3, and 5.5 and Table 5.4). Under this strategy, 50% of the time the payback period was between two and three years across all locations.

The OSI system has been shown to be the most efficient system (Smith et al. 2015). It is an effective way to apply limited irrigation water per unit area while maintaining yield. Spivey et al. (2018) undertook a financial evaluation of an OSI system, but without the use of DI, and found that the OSI was a better system than rainfed in terms of cash flow and payback period for cotton production modelled for North Carolina in the United States. The current analysis has expanded on their research by incorporating DI practices to show the implications for irrigation capital investments and increasing the proportion of land irrigated within an enterprise. The findings showed that with the implementation of DI practices the benefits of an OSI system are further improved. By applying less water per unit area, the irrigated area can be increased, maximising yields and improving net profits for the field scale (Darouich et al. 2014; Sorensen et al. 2011).

Although both the OSI and the SDI systems had similar yields (see Figure 5.2), the OSI system resulted in better EAA, with the whole area irrigated and shorter payback periods due to the lower initial capital investment. The initial costs of installing an OSI system, at $5800/ha for 1000 ha, are up to 62% less expensive than a for SDI system. SDI also required additional capital investment in the 10th year.

The OSI system is superior to the FI system in that it can better control irrigation application volumes and timings, and hence it has greater opportunities to irrigate a larger area (McCarthy 2010). Better yields lead to higher EAA and shorter payback periods, which can cover the initial investment cost of the OSI system within three years. These results are consistent with the findings of Spivey et al. (2018). The lower yields of the FI system in addition to the higher initial investment costs for an SDI system (Reynolds et al. 2020) led to these systems having lower profitability and longer timeframes to recover initial investment costs than the OSI system. It can be concluded that the use of DI under OSI should be considered when assessing the long-term investment decisions of profit maximisation of a cotton enterprise.

The OSI system does, however, have a higher (+33%) initial capital investment compared to the FI system. The FI system is the most common irrigation system used in Australian cotton production (Roth 2014; Williams et al. 2018), with 83% of cotton growers within the MDB using the FI system. This may be because the FI system has the lowest initial capital costs at $3892/ha and is technologically the simplest to operate. The modelling showed however that the FI system generally produced lower annual lint yields compared to the OSI and the SDI systems (Figure 5.2 and Table 5.4) and was best at relatively high levels of irrigation in most locations. At Goondiwindi, Narrabri and Warren the FI system using the T5 strategy resulted in the greatest annual yields. This was achieved when the irrigated area ranged between 45% and 77% of the total available area, and when the rest of the area was under dryland production.

Our modelling of the SDI system showed that the 40% of TF strategy was the best practice across all study locations in terms of annual lint yields (see Figure 5.2 and Table 5.4). On average, 73% of the total land area was irrigated. Even though the SDI system produced the highest yields, it had lower EAA and longer payback periods due to the high upfront costs (Figures 5.2, 5.3, and 5.4 and Table 5.4). With an estimated total installation cost for an SDI system being $13628/ha, and with a short life expectancy of 10 years, the SDI system presents problems for recovering the initial investment costs, even when it returns the highest average yields/ha. One notable finding from this analysis is that if severe water restrictions are encountered, less than 40% of a TF strategy is possible to apply through an SDI system, but then the costs of the system will become a burden that a farming enterprise will not be able to recover through improved production.

The SDI system required even higher capital investment than the OSI system. With lower fixed costs, including lower borrowing costs, SDI may become economically more viable than OSI systems. The high initial cost increases the risk of not recovering the initial investment costs compared to other systems (Wilde et al. 2009). The SDI system did have superior WUE and MWUE (see Chapter 3). Results from field trials, by Enciso et al. (2005) in Western Texas in the United States over three seasons, suggested that using SDI achieved greatest cotton yields and net returns under the TF strategy. However, our results found that the use of DI increased annual lint yields but lowered EAA, due to costs, such as river pump construction, levees, and culverts. Enciso et al. (2005) did not account for these infrastructure investment costs in their analysis.

Overall, if the grower is making short- term decisions when the irrigation water is at adequate availability per unit area, the best option may be to use the 80% of TF strategy to achieve higher productivity and to maximise profitability (see Chapters 3 and 4). Agronomic and economic modelling showed that, when making short -term decisions and treating overhead costs as sunk costs, the 80% of TF strategy for the OSI and SDI systems maintained yields and produced the greatest GMs and the greatest NPV over ten years. If the grower is making long term decisions when the irrigation water is not at adequate availability at the enterprise scale, the results of this chapter showed that when considering the initial capital costs and benefits of irrigating more area at the enterprise scale for a 20-year time horizon, the economic benefits of using DI for OSI systems were greater than for the SDI. Based on this study, under an OSI system, the 40% of TF strategy allows growers to irrigate the whole of their production area and to maximise profitability. Using SDI systems with 40% of TF strategy had benefits in terms of lint yields but was not beneficial in terms of EAA. The SDI system has high initial investment costs for 20-years and requires an additional capital investment in the 10th year.

Currently, high initial investment costs and high operating costs pose a significant barrier to the adoption of SDI systems. To assess the impacts that lower initial investment costs of the SDI system would have on profitability, an analysis was undertaken. We modelled a 50% reduction of selected installation costs (including diesel pumps, screen filters, control systems, drip lines, PVC mains, PVC submains and infield valves), which came to $6814/ha. This analysis found that the profitability of the SDI system improved significantly. This indicates that if technology improvements can reduce the costs of the SDI system infrastructure and the costs of pumping water at the pressure that this system requires, then SDI systems have the potential to become an economically feasible proposition

Future work, in terms of long-term decision making, requires taking into account the impact of DI the effects of the different irrigation systems on various environmental aspects such as soil health and runoff, and other factors that have been covered in Chapter 2. Therefore, it would be beneficial to take into account the environmental effects in the further development of the model in the future. In addition, exploring the application of DI for SDI and OSI with advanced irrigation scheduling (on-field monitoring and automation) for tackling seasonal water scarcity can be another potential topic for future work.

5.5 Conclusion

Economic and risk evaluations, based on modelling of the capital costs and benefits of incorporating DI under the FI, OSI and SDI systems at the enterprise scale (1000 ha), were presented in this chapter. We found that the OSI system is superior to the FI and SDI systems in terms of enterprise profitability. Applying the 40% of the TF strategy under the OSI system allowed the irrigation of the whole production area. This strategy maximised the annual lint yield and EAA at all studied locations. It also achieved the shortest payback period which was within three years. The approach used in this study to analyse long-term irrigation investment decisions for a 20-year period can be applied when adapting to limited irrigation water conditions or when prices in water markets are increased for either small- or large-scale farming systems.

Chapter 6. General implications, conclusions and recommendations

This study explored the productivity and economic impacts of DI on Australian cotton production under three irrigation systems. Previous studies have focused on the agronomic and economic benefits of irrigation for cotton production (Cammarano et al. 2012; Luo et al. 2017), and recommended that further research about the economic implications of irrigation decisions, and also identified the need for detailed of investigations on the economic impacts of adopting new technologies (strategies) the for effective use of irrigation water in the cotton industry. Economic investment comparisons for cotton production have been undertaken by a number of authors (Baio et al. 2017; Bosch et al. 1992; Enciso et al. 2005; O'Brien et al. 1998; Spivey et al. 2018) but these have not focused on investigating DI practices and their effects on whole farm profitability or long-term investment decisions. The literature review revealed that there is a paucity of research pertaining to the impacts of different DI practices on Australian cotton production systems, suggesting a need for investigating the potential impacts of DI on enterprise profitability, especially at both the field and the enterprise scales. Other research has compared the efficiencies of different irrigation systems for cotton production (Raine and Foley 2002), but did not yet include DI as a variable in those comparisons.

For this study, the APSIM cotton model was used to evaluate biophysical responses at the crop level (Chapter three). Many researchers (Attia et al. 2016; Cammarano et al. 2012; Farahani et al. 2009; Ma et al. 2013; Modala et al. 2015; Tsakmakis et al. 2018; Xin et al. 2016) have used a variety of cotton models including DSSAT, AquaCrop, CROPWAT and Cotton2K for studies of cotton irrigation strategies, although none has focused on comparing the three main cotton irrigation systems: furrow irrigation (FI), overhead sprinkler irrigation (OSI) and subsurface drip irrigation (SDI). For this study, the model was configured, and its outputs were validated for predicting cotton yields and crop water use across four locations in the Murray-Darling Basin (MDB). This phase of the research considered crop yields, yield variability, water use efficiency (WUE) and marginal water use efficiency (MWUE). The DI practices were shown to improve lint yield (kg/ha), WUE (kg/mm) and MWUE (kg/mm) when using OSI or SDI irrigation systems, but this was not the case with FI. These results were supported by Darouich et al. (2014) and Chai et al. (2016b) that showed that using DI can improve WUE and maintain yields of cotton production; however, irrigation system type may matter have an effect . The reason why FI had a lower yield compared to the OSI and SDI systems was salinity can be a significant problem, with salts tending to accumulate on the tops of ridges. This study showed that, across 41 years, mean lint yields peaked under the OSI and SDI systems when 80% of the full irrigation treatment (80% of TF) was applied, while WUE and MWUE were maximised between 60% and 80% of TF application, depending upon the study location. When this analysis of WUE and MWUE is considered, both gave consistent patterns of response to DI practices, with the marginal responses to the application of irrigation water providing a more consistent and robust result compared to the WUE. If this modelling is translated to the farm, it will aid growers to generate the best returns from money spent on water purchases; from that perspective, they could use 40% of TF treatment for the SDI system and between 60% to 80% of TF for the OSI system. Thus, this analysis could assist growers with OSI and SDI systems in making water application decisions.

In Chapter four, the variable costs of operating the irrigation systems were considered in conjunction with the income derived from the crop yield to calculate gross margins per hectare (GM/ha) and per megalitre of irrigated water (GM/ML), as well as 10-year net present values (NPV) to compare the performance of each system and each DI strategy. The results suggested that, in terms of short-term decisions, when using either the OSI or the SDI irrigation system, applying 80% of TF treatment maximised economic returns. Adopting DI could therefor provide an opportunity for increasing net income (Ali et al. 2007; Cammarano et al. 2012). It was, however, shown that, under FI, no economic benefits were achieved with the application of any DI treatment. The utilisation of DI with OSI or SDI led to maximising GMs and NPVs while reducing water use on a per unit area basis. Under the OSI and SDI systems, GM/ha and NPV were higher than the FI system. With reduced applications of water, the OSI and SDI systems were able to achieve higher GM/ML returns than the FI systems. The results show that GMs/ML were maximised at lower applications of water than is required to maximise yield and GMs/ha. Based on these findings it can be concluded that growers could increase their income by using DI with an OSI or a SDI system by reducing production costs while improving yield potential. When water becomes expensive or supply is restricted, using DI with OSI or SDI systems will provide growers with the ability to maintain farm profitability when making short term decisions about irrigation management when using current irrigation infrastructure.

To understand better the benefits of DI when investing in different irrigation system, an assessment of the costs and benefits of the irrigation systems for the farming enterprise as a whole is required. Decision making for long-term infrastructure needs to be examined over an extended time period (Chapter five). Previous studies (Baio et al. 2017; Bosch et al. 1992; Enciso et al. 2005; O'Brien et al. 1998; Spivey et al. 2018) have undertaken an economic evaluation only of one or two systems in terms of cash flow and other economic analyses without considering DI practices and without examining the enterprise scale. Total cotton production from the enterprise could be optimised for a given volume of irrigation water by combining irrigated and dryland production, while the costs of the required irrigation system will be offset against the value of the increased production. This will address the research gap for the long-term economic evaluation of infrastructure investment decisions. This research looked into the economic consequences for each of the major cotton irrigation systems used in the Australian industry when adopting DI. In Chapter Five, for long term decision making, the analyses were based on modelling a 1000 ha cotton enterprise with 2500 ML/year of irrigation water over a 20-year time horizon to evaluate net benefits, payback period, equivalent annual annuity (EAA), and annual cash flows (ACF). The most significant findings of this analysis were that under the OSI system, 40% of TF strategy was the best practice to achieve the highest combined yield and the highest EAA. Under this strategy, the OSI system also achieved the shortest payback period, with initial capital costs recovered within three years for all study locations An economic evaluation of full irrigation for cotton irrigation systems was carried out in North Carolina in the United States by Spivey et al. (2018). They found that the OSI system was superior in terms of cash flow, payback period, and NPV. Therefore, both the results of this study and previous studies found that the use of an OSI system could help growers to maximise their enterprise profitability and to minimise their risk. In addition, the OSI system had better WUE and MWUE compared to the FI system. Overall, EAA and ACF were greatest under the OSI system compared to the FI and SDI systems. When growers are making long-term decisions, it is better to use 40% of TF strategy under the OSI system to increase irrigated land, with a minimised payback period and maximise farm profitability.

When long-term making decisions are being made about irrigation systems, this study showed that the greatest benefits were offered by the OSI system when compared to the SDI and FI systems, considering yields, water use and capital costs. The analysis suggested that OSI systems, while more expensive than FI systems, can be installed and used profitably for both small and large areas. The analysis also demonstrated the economic benefits that can be gained by using DI with this system. The SDI system demonstrated good potential from the point of view of superior yields, but was disadvantaged by very high installation costs, especially for large areas. If technological advances can overcome the problems of installing large scale SDI systems, and if the associated costs of the equipment and installation can be reduced by around 50%, then SDI systems will become relatively more feasible and profitable for cotton farming enterprises. For the FI system, initial costs were lower than other systems, but the lower yields meant that FI always fell below the other systems in terms of total cotton production and long-term profitability. In addition, the FI system was shown to have the lowest WUE and MWUE of the three systems. The overwhelming dominance of FI within the cotton industry highlighted that economic and production considerations are not the only factors that growers consider when making long-term irrigation infrastructure investment decisions. Overall, this thesis has evaluated the economic benefits of analysing risk in relation to both short-term and long-term decisions about incorporating the use of DI practices on Australian cotton crops. As DI practices under OSI systems have been demonstrated to achieve the highest GMs, NPV, EAA, and ACF, and the lowest payback period, compared to the SDI and FI systems, it is recommended that using DI practices under OSI system be promoted.

This thesis provides significant research that is globally relevant by employing biophysical, economic and risk modelling to investigate the impacts of DI practices under three irrigation systems and their implications for short and long-term decision making. This study also addresses the research gap represented by the lack of information related to the optimum level of DI for maximising the net benefits of the cotton industry at the field and enterprise scales. This thesis provides also a comprehensive analysis of the economics of short- and long-term decision-making, involving irrigation system selection and choice of DI strategy for cotton farming enterprises in areas impacted by restricted water allocations. The proposed multi approach of APSIM and economic analysis was proved to an efficient tool for predicting crop productivity under uncertain water availability and consequently help in decision making for further advancement in agronomy research in general and cotton production in particular. The outcomes of this study will be of interest to growers, scientists and policy makers in expanding and increasing the utilisation of DI practices within the cotton industry across Australia and other cropping systems globally. At the same time, there are also some the limitations of this study, so the next logical steps in this area of bio-economic research, as guided by the findings of this thesis, should include the following:

1. Applying the methodology of this research to consider the economics and benefits of applying DI under different irrigation systems to cotton production in other regions.
2. Using the approaches established in this research to assess and compare at an enterprise scale the benefits of new irrigation systems or modifications to existing irrigation systems. An example of this is installation and/or operating performance which could alter the economics of SDI systems, which are currently suitable for limited scale (<100 ha) installations, to be feasible at a larger scale.
3. Undertaking controlled field trials over time.

Conducting further research about DI practices under the three irrigation systems that takes into consideration physically measured environmental consequences such as soil health and runoff.

4. Assessing, at the enterprise scale, more complex farming systems that might include the full or partial irrigation of multiple crops, either in parallel or in rotation, using the same irrigation system, thereby spreading the initial investment costs over a more diverse income stream.
5. Utilizing the output of APSIM model to investigate the feasibility of DI application in different environments and field conditions.

The proposed multi approach of APSIM and economic analysis was proved to be an efficient tool for predicting crop productivity under uncertain water availability and consequently help in decision making for further advancement in agronomy research in general and cotton production in particular. In summary, this research aimed impact DI practices under three irrigation systems and to optimise the decision-making for short and long periods for both industries and growers. Outputs from this research, particularly the water risk framework provide a sound theoretical basis for the assessment both the field and enterprise scales on-farm water risk.

References

ABARES (2018) Australian commodity statistics. Australian Bureau of Agricultural and Resource Economics and Science, Canberra

Abbas G et al. (2020) Applications of Crop Modeling in Cotton Production. In: Cotton Production and Uses. Springer, pp 429-445

Abdel-Gadir A, Dougherty M, Fulton J, Curtis L, Tyson T, Harkins H, Norris B (2012) Effect of different deficit-irrigation capabilities on cotton yield in the tennessee valley Irrigat Drainage Sys Eng 1:277-285

Abdi H (2010) Coefficient of Variation Encyclopedia of research design 1:169-171

ABS (2012) Water use on Australian farms - 2010-2011. Australian Bureau Statistics, Australia

ABS (2016) Water Use on Australian Farms 2014- 2015.

Abuarab M, Mostafa E, Ibrahim M (2013) Effect of air injection under subsurface drip irrigation on yield and water use efficiency of corn in a sandy clay loam soil Journal of advanced research 4:493-499

Adamson D, Mallawaarachchi T, Quiggin JC (2007) Water use and salinity in the Murray–Darling Basin: A state-contingent model Aust J Agric Resour Econ 51:263-281

Adeyemi O, Grove I, Peets S, Norton T (2017) Advanced monitoring and management systems for improving sustainability in precision irrigation Sustainability 9:353

Al-Ghobari HM, Mohammad FS, El Marazky MSA (2015) Assessment of smart irrigation controllers under subsurface and drip-irrigation systems for tomato yield in arid regions Crop and Pasture Science 66:1086-1095

Alghory A, Yazar A (2019) Evaluation of crop water stress index and leaf water potential for deficit irrigation management of sprinkler-irrigated wheat Irrigation Science 37:61-77

Ali MH, Hoque MR, Hassan AA, Khair A (2007) Effects of deficit irrigation on yield, water productivity, and economic returns of wheat Agric Water Manage 92:151-161

Amparo Martinez-Gimeno M, Provenzano G, Bonet L, Intrigliolo DS, Badal E, Ballestrer C Assessing the performance of surface and subsurface drip systems on irrigation water use efficiency of citrus orchards in Spain. In: EGU General Assembly Conference Abstracts, 2017. p 415

An-Vo D-A, Mushtaq S, Reardon-Smith K, Kouadio L, Attard S, Cobon D, Stone R (2019) Value of seasonal forecasting for sugarcane farm irrigation planning European journal of agronomy 104:37-48

Antille DL (2018) Evaluation of Fertigation Applied to Furrow and Overhead Irrigated Cotton Grown in a Black Vertosol in Southern Queensland, Australia Appl Eng Agric 34:197-211 doi:https://doi.org/10.13031/aea.12519

Anwar MR, Darbyshire R Effect of climate variability on Australian dryland cotton yield. In: " Doing More with Less", Proceedings of the 18th Australian Agronomy Conference 2017, Ballarat, Victoria, Australia, 24-28 September 2017, 2017. Australian Society of Agronomy Inc, pp 1-4

Aparicio J, Tenza-Abril AJ, Borg M, Galea J, Candela L (2019) Agricultural irrigation of vine crops from desalinated and brackish groundwater under an economic perspective. A case study in Siġġiewi, Malta Sci Total Environ 650:734-740

Attia A, Rajan N, Nair SS, DeLaune PB, Xue Q, Ibrahim AMH, Hays DB (2016) Modeling cotton lint yield and water use efficiency responses to irrigation scheduling using cotton2k Agron J 108:1614-1623 doi:10.2134/agronj2015.0437

Aujla M, Thind H, Buttar G (2008) Cotton yield and water use efficiency at various levels of water and N through drip irrigation under two methods of planting Agric Water Manage 71:167-179

Ayars J, Phene C, Hutmacher R, Davis K, Schoneman R, Vail S, Mead R (1999) Subsurface drip irrigation of row crops: a review of 15 years of research at the Water Management Research Laboratory Agric Water Manage 42:1-27

Azad M, Ancev T (2016) Economics of salinity effects from irrigated cotton: An efficiency analysis Water Economics and Policy 2:24

Baio FH, Silva SP, Camolese HS, Neves DC (2017) Financial analysis of the investment in precision agriculture techniques on cotton crop Engenharia Agrícola 37:838-847

Barbosa BD, Colombo A, De Souza JG, Baptista VS, Araújo A (2018) Energy efficiency of a center pivot irrigation system Engenharia Agrícola 38:284-292

Bartimote T, Quigley R, Bennett JM, Hall J, Brodrick R, Tan DK (2017) A comparative study of conventional and controlled traffic in irrigated cotton: II. Economic and physiological analysis Soil and Tillage Research 168:133-142

Basal H, Dagdelen N, Unay A, Yilmaz E (2009) Effects of deficit drip irrigation ratios on cotton (Gossypium hirsutum L.) yield and fibre quality Journal of Agronomy and Crop Science 195:19-29

Bell JM, Schwartz RM, McInnes KJ, Howell TA, Morgan CS (2018) Deficit irrigation effects on yield and yield components of grain sorghum Agric Water Manage 203:289-296

Berk J, DeMarzo P, Stangeland D (2015) Corporate Finance (3rd Canadian ed.). Toronto: Pearson Canada,

Bhattarai SP, Midmore DJ, Pendergast L (2008) Yield, water-use efficiencies and root distribution of soybean, chickpea and pumpkin under different subsurface drip irrigation depths and oxygation treatments in vertisols Irrigation science 26:439

Bosch DJ, Powell NL, Wright FS (1992) An economic comparison of subsurface microirrigation with center pivot sprinkler irrigation J Prod Agric 5:431-437

Braunack M (2013) Cotton farming systems in Australia: factors contributing to changed yield and fibre quality Crop and Pasture Science 64:834-844

Brouwer C, Prins K, Kay M, Heibloem M (1988) Irrigation water management: irrigation methods. Training manual. The International Institute for Land Reclamation and Improvement, Wageningen, Netherlands

Brown P Flood vs. pivot irrigation for forage crops: what are the advantages and disadvantages? In: Proceedings, California Alfalfa & Forage Symposium and Western Seed Conference, San Diego, CA, 2008.

Burton M (2010) Irrigation management principles and practices. In. CABI North American Office, Cambridge MA, pp x, 375 p

Cammarano D, Payero J, Basso B, Wilkens P, Grace PR (2012) Agronomic and economic evaluation of irrigation strategies on cotton lint yield in Australia Crop and Pasture Science 63:647-655

Camp CR (1998) Subsurface drip irrigation: a review American Society of Agricultural Engineers 41:1353

Camp CR, Lamm FR, Evans RG, Phene CJ Subsurface drip irrigation-past, present, and future. In: National irrigation symposium. Proceedings of the 4th Decennial Symposium, Phoenix, Arizona, USA, November 14-16, 2000., 2000. American Society of Agricultural Engineers, pp 363-372

Capra A, Consoli S, Scicolone B (2008) Deficit irrigation: Theory and practice Agricultural Irrigation Research Progress:53-82

Capra A, Consoli S, Scicolone B Economic analysis of citrus orchards under deficit irrigation in South Italy. In: XXVIII International Horticultural Congress on Science and Horticulture for People (IHC2010): International Symposium on 922, 2010. pp 209-215

Carberry PS et al. (2009) Re-inventing model-based decision support with Australian dryland farmers. 3. Relevance of APSIM to commercial crops Crop and pasture science 60:1044-1056

Chai Q, Gan Y, Zhao C, Xu H-L, Waskom RM, Niu Y, Siddique KH (2016a) Regulated deficit irrigation for crop production under drought stress. A review Agronomy for Sustainable Development 36:3

Chai Q, Gan Y, Zhao C, Xu HL, Waskom RM, Niu Y, Siddique KHM (2016b) Regulated deficit irrigation for crop production under drought stress. A review Agronomy for Sustainable Development 36 doi:10.1007/s13593-015-0338-6

Chapagain AK, Hoekstra AY, Savenije H, Gautam R (2006) The water footprint of cotton consumption: An assessment of the impact of worldwide consumption of cotton products on the water resources in the cotton producing countries Ecol Econ 60:186-203

Chauhan Y, Solomon K, Rodriguez D (2013) Characterization of north-eastern Australian environments using APSIM for increasing rainfed maize production Field Crops Res 144:245-255

Colaizzi PD, Evett SR, Howell TA (2004) Irrigation methods and capacities for cotton in the Northern High Plains. Paper presented at the High Plains Groundwater Resources: Challenges and Opportunities, Conf. Proc., Lubbock, TX,

Çolak YB, Yazar A, Gönen E, Eroğlu EÇ (2018) Yield and quality response of surface and subsurface drip-irrigated eggplant and comparison of net returns Agric Water Manage 206:165-175

Conaty WC (2011) Temperature-time thresholds for irrigation scheduling in drip and deficit furrow irrigated cotton.

Conaty WC, Johnston DB, Thompson AJE, Liu S, Stiller WN, Constable GA (2018) Use of a managed stress environment in breeding cotton for a variable rainfall environment Field Crops Res 221:265-276 doi:https://doi.org/10.1016/j.fcr.2017.10.012

Connor J, Schwabe K, King D, Kaczan D, Kirby M (2009) Impacts of climate change on lower Murray irrigation Aust J Agric Resour Econ 53:437-456

Coria G, Penizzotto F, Pringles R (2019) Economic analysis of photovoltaic projects: The Argentinian renewable generation policy for residential sectors Renewable energy 133:1167-1177

Cortignani R, Severini S (2009) Modeling farm-level adoption of deficit irrigation using Positive Mathematical Programming Agric Water Manage 96:1785-1791 doi:http://dx.doi.org/10.1016/j.agwat.2009.07.016

Cotton Australia (2019) Australian cotton production manual:2019. Cotton Austalia, Austalia

CRDC (2012) WATERpak – a guide for irrigation management in cotton and grain farming systems, Third edition edn. Cotton Research and Development Corporation, NSW, Australia

Crespo CM, Rodríguez Díaz JA, García Morillo J, McNabola A (2019) Pump-as-Turbine Selection Methodology for Energy Recovery in Irrigation Networks: Minimising the Payback Period Water 11:149

CSD (2008) Cotton & wheat gross margin analysis. Cotton seed distributiors, Australia

CSD (2017) Cotton Seed Distributors, Variety Trial Results (2009-2015) http://www.csd.net.au/resources. Accessed 5/11/2017

Cusicanqui J, Dillen K, Geerts S, Raes D, Mathijs E, García M (2013) Economic assessment at farm level of the implementation of deficit irrigation for quinoa production in the Southern Bolivian Altiplano Spanish journal of agricultural research:894-907

DAF (2010) Varieties and planting. Queensland Government,Department of Agriculture and Fisheries. https://www.daf.qld.gov.au/business-priorities/plants/field-crops-and-pastures/broadacre-field-crops/cotton/growing/varieties-and-planting. Accessed 18 July 2018

DAF (2015) Cotton industry overview. Department of Agriculture and Fisheries, Queensland Government https://www.daf.qld.gov.au/plants/field-crops-and-pastures/broadacre-field-crops/cotton. Accessed 12 June 2017

DAF (2018a) Cotton production Department of Agriculture and Fisheries https://www.daf.qld.gov.au/business-priorities/plants/field-crops-and-pastures/broadacre-field-crops/cotton/growing. Accessed 13/06/2018 2018

DAF (2018b) Sub-surface drip irrigation (SDI) - Advantages and limitations. Queensland Government, Department of Agriculture and Fisheres. https://www.daf.qld.gov.au/business-priorities/plants/field-crops-and-pastures/broadacre-field-crops/managing-water-resources/sub-surface-drip-irrigation/advantages-and-limitations. Accessed 21 July 2018

Dağdelen N, Başal H, Yılmaz E, Gürbüz T, Akçay S (2009) Different drip irrigation regimes affect cotton yield, water use efficiency and fiber quality in western Turkey Agric Water Manage 96:111-120 doi:10.1016/j.agwat.2008.07.003

Dalgliesh N, Wockner G, Peake A Delivering soil water information to growers and consultants. In: Proceedings of the 13th Australian Agronomy Conference, 2006. Australian Society of Agronomy Perth, Western Australia, pp 10-14

Darouich HM, Pedras CMG, Gonçalves JM, Pereira LS (2014) Drip vs. surface irrigation: A comparison focussing on water saving and economic returns using multicriteria analysis applied to cotton Biosys Eng 122:74-90 doi:http://dx.doi.org/10.1016/j.biosystemseng.2014.03.010

De Pascale S, Dalla Costa L, Vallone S, Barbieri G, Maggio A (2011) Increasing water use efficiency in vegetable crop production: from plant to irrigation systems efficiency HortTechnology 21:301-308

DEEDI (2011) Centre Pivot/Lateral Move Irrigation Gueensland Government, Brisbane

Del Amor M, Francisco dA (2007) Response of tomato plants to defcit irrigation under surface or subsurface drip irrigation Journal of Applied Horticulture 9:97-100

Deng X-P, Shan L, Zhang H, Turner NC (2006) Improving agricultural water use efficiency in arid and semiarid areas of China Agric Water Manage 80:23-40

DeTar WR (2008) Yield and growth characteristics for cotton under various irrigation regimes on sandy soil Agric Water Manage 95:69-76 doi:10.1016/j.agwat.2007.08.009

Devasirvatham V (2008) Improved lettuce establishment by subsurface drip irrigation. P.h.D, University of Western Sydney, Australia

Domínguez A, de Juan JA, Tarjuelo JM, Martínez RS, Martínez-Romero A (2012) Determination of optimal regulated deficit irrigation strategies for maize in a semi-arid environment Agric Water Manage 110:67-77 doi:https://doi.org/10.1016/j.agwat.2012.04.002

Du T, Kang S, Zhang J, Li F (2008) Water use and yield responses of cotton to alternate partial root-zone drip irrigation in the arid area of north-west China Irrigation Science 26:147-159 doi:10.1007/s00271-007-0081-0

Dukes MD, Perry C (2006) Uniformity testing of variable-rate center pivot irrigation control systems Precision Agriculture 7:205

Enciso J, Jifon J, Anciso J, Ribera L (2015) Productivity of onions using subsurface drip irrigation versus furrow irrigation systems with an internet based irrigation scheduling program International Journal of Agronomy 2015:6

Enciso J, Unruh BL, Colaizzi PD, Multer WL (2003) Cotton response to subsurface drip irrigation frequency under deficit irrigation Appl Eng Agric 19:555

Enciso JM, Colaizzi PD, Multer WL (2005) Economic analysis of subsurface drip irrigation lateral spacing and installation depth for cotton Trans ASAE 48:197-204

English M (1990) Deficit irrigation. I: Analytical framework Journal of irrigation and drainage engineering 116:399-412

English MJ, Nuss GS (1982) Designing for deficit irrigation Journal of the Irrigation and Drainage Division 108:91-106

Esfandiari M, Maheshwari B (1997) Application of the optimization method for estimating infiltration characteristics in furrow irrigation and its comparison with other methods Agric Water Manage 34:169-185

Eskandari S, Christopher N, Oliver G, Backhouse D, Haling RE (2017) Mycorrhizal Symbioses of Cotton Grown on Sodic Soils: A Review from an Australian Perspective Pedosphere 27:1015-1026

Eskandari S, Guppy CN, Knox OG, Backhouse D, Haling RE (2018) Understanding the impact of soil sodicity on mycorrhizal symbiosis: Some facts and gaps identified from cotton systems Applied Soil Ecology 126:199-201

Evans R, Stevens W, Iversen W Development of site-specific irrigation research under linear move systems. In: Proceedings 26th Annual Intl. Irrigation. Technical Conference, Irrigation. Assoc., Falls Church, VA. Presented November, 2006. pp 6-8

Evans RG, Sadler EJ (2008) Methods and technologies to improve efficiency of water use Water Resour Res 44 doi:10.1029/2007WR006200

Expósito A, Berbel J (2017) Sustainability implications of deficit irrigation in a mature water economy: A case study in southern Spain Sustainability 9:1144

FAO (2002) Deficit Irrigation Practices, 22 edn. Food And Agriculture Organization Of The United Nations, Rome

Farahani HJ, Izzi G, Oweis TY (2009) Parameterization and evaluation of the AquaCrop model for full and deficit irrigated cotton Agron J 101:469-476

Farquhar G, Richards R (1984) Isotopic composition of plant carbon correlates with water-use efficiency of wheat genotypes Funct Plant Biol 11:539-552

Fereres E, Soriano MA (2006) Deficit irrigation for reducing agricultural water use J Exp Bot 58:147-159

Fereres E, Soriano MA (2007) Deficit irrigation for reducing agricultural water use J Exp Bot 58:147-159 doi:10.1093/jxb/erl165

Foley JP, Raine SR (2001) Centre pivot and lateral move machines in the Australian cotton industry. National Centre for Engineering in Agriculture Publication 1000176/1 University of Southern Queensland: Toowoomba

Foley JP, Raine SR (2002) Overhead irrigation in the Australian cotton industry

Foley JP, Wigginton D, Eberhard J (2006) Optimizing overhead irrigation systems. Paper presented at the In Proceedings of the 13th Australian Cotton Conference (ACGRA 2006), Australian Cotton Growers Research Association.,

Frahan BH et al. (2007) Positive Mathematical Programming for Agricultural and Environmental Policy Analysis: Review and Practice. In: Weintraub A, Romero C, Bjørndal T, Epstein R, Miranda J (eds) Handbook Of Operations Research In Natural Resources. Springer US, Boston, MA, pp 129-154. doi:10.1007/978-0-387-71815-6_8

García-Vila M, Fereres E, Mateos L, Orgaz F, Steduto P (2009) Deficit irrigation optimization of cotton with AquaCrop Agron J 101:477-487

Gaspars-Wieloch H (2019) Project net present value estimation under uncertainty Central Europ J Operations Res 27:179-197

Geerts S, Raes D (2009) Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas Agric Water Manage 96:1275-1284 doi:10.1016/j.agwat.2009.04.009

Ghasemi A, Zahediasl S (2012) Normality tests for statistical analysis: a guide for non-statisticians International journal of endocrinology and metabolism 10:486

Godfrey S, Anwar M, Nordblom T Financial risk profiles for dryland cotton by APSIM-Ozcot and@ Risk®. In: 19th Australian Agronomy Conference, 2019.

Golzardi F, Baghdadi A, Afshar RK (2017) Alternate furrow irrigation affects yield and water-use efficiency of maize under deficit irrigation Crop and Pasture Science 68:726-734

Grabham MK (2012) Performance evaluation and improvement of bankless channel surface irrigation systems. University of Southern Queensland

Grimes D, Yamada H (1982) Relation of Cotton Growth and Yield to Minimum Leaf Water Potential 1 Crop Sci 22:134-139

Gude VG (2016) Desalination and sustainability – An appraisal and current perspective Water Res 89:87-106 doi:http://dx.doi.org/10.1016/j.watres.2015.11.012

Guinn G, Mauney J (1984) Fruiting of Cotton. I. Effects of Moisture Status on Flowering 1 Agron J 76:90-94

Gwydir irrigation system trials: 2009-14 (2016) vol 37. Berekua Pty. Ltd, Brisbane

Hargreaves GH, Samani ZA (1984) Economic considerations of deficit irrigation Journal of irrigation and Drainage engineering 110:343-358

Harris G, Shaw A (2007) Sprinkler irrigation: Profitable or not? the Australian Cottongrower,

Heard J, Malcolm B, Jackson T, Tocker J, Grabham P, White A (2013) Whole farm analysis versus activity gross margin analysis: a sheep farm example Australian Farm Business Management Journal 10:16-29

Hearn A (1994) OZCOT: A simulation model for cotton crop management Agricultural Systems 44:257-299

Heeren DM, Trooien TP, Werner HD, Klocke NL (2011) Development of deficit irrigation strategies for corn using a yield ratio model Appl Eng Agric 27:605-614

Heermann DF, Hein PR (1968) Performance characteristics of self-propelled center-pivot sprinkler irrigation system American Society of Agricultural Engineers 11:11-15

Holzworth DP et al. (2014) APSIM – Evolution towards a new generation of agricultural systems simulation Environ Model Software 62:327-350 doi:http://dx.doi.org/10.1016/j.envsoft.2014.07.009

Howell TA (2001) Enhancing water use efficiency in irrigated agriculture Agron J 93:281-289

Howell TA, Evett SR, Tolk JA, Schneider AD (2004) Evapotranspiration of full-, deficit-irrigated, and dryland cotton on the Northern Texas High Plains Journal of irrigation and drainage engineering 130:277-285

Howell TA, Yazar A, Schneider AD, Dusek DA, Copeland KS (1995) Yield and water use efficiency of corn in response to LEPA irrigation American Society of Agricultural Engineers 38:1737-1747

Huang Y, Chen L, Fu B, Huang Z, Gong J (2005) The wheat yields and water-use efficiency in the Loess Plateau: straw mulch and irrigation effects Agric Water Manage 72:209-222

Hulugalle NR, McCorkell B, Heimoana VF, Finlay LA (2016) Soil properties under cotton-corn rotations in Australian cotton farms Journal of Cotton Science 20:294-298

Hutmacher R (2001) Subsurface drip and furrow irrigation comparison with alfalfa in the Imperial Valley. In: Proc. 2001 California Alfalfa & Forage Symposium, Modesto, CA, 2001. Citeseer, pp 11-13

Ibragimov N, Evett SR, Esanbekov Y, Kamilov BS, Mirzaev L, Lamers JP (2007) Water use efficiency of irrigated cotton in Uzbekistan under drip and furrow irrigation Agric Water Manage 90:112-120

Irmak S, Djaman K, Rudnick DR (2016) Effect of full and limited irrigation amount and frequency on subsurface drip-irrigated maize evapotranspiration, yield, water use efficiency and yield response factors Irrigation science 34:271-286

Jacques D, Fox G, White P (2018) Farm level economic analysis of subsurface drip irrigation in Ontario corn production Agric Water Manage 203:333-343

Jeffrey SJ, Carter JO, Moodie KB, Beswick AR (2001) Using spatial interpolation to construct a comprehensive archive of Australian climate data Environ Model Software 16:309-330

Jha AK et al. (2016) Impact of irrigation method on water use efficiency and productivity of fodder crops in Nepal Climate 4:4

Jones et al. (2017) Brief history of agricultural systems modeling Agricultural systems 155:240-254

Jones HG (2004) Irrigation scheduling: advantages and pitfalls of plant-based methods J Exp Bot 55:2427-2436

Jones JW et al. (2003) The DSSAT cropping system model European journal of agronomy 18:235-265

Kalfountzos D, Alexiou I, Kotsopoulos S, Zavakos G, Vyrlas P (2007) Effect of subsurface drip irrigation on cotton plantations Water Resour Manage 21:1341-1351

Kaman H, Çetin M, Kirda C (2008) Soil salinity in a drip and furrow irrigated cotton field under influence of different deficit irrigation techniques

Karam F, Lahoud R, Masaad R, Daccache A, Mounzer O, Rouphael Y (2006) Water use and lint yield response of drip irrigated cotton to the length of irrigation season Agric Water Manage 85:287-295

Kaur P, Bhagria T, Mutti NK, Rinwa A, Mahajan G, Chauhan BS (2019) cotton Production in Australia. Cotton Production. Wiley Online Library,

Keating BA et al. (2003) An overview of APSIM, a model designed for farming systems simulation European journal of agronomy 18:267-288

Kifle M, Gebretsadikan T (2016) Yield and water use efficiency of furrow irrigated potato under regulated deficit irrigation, Atsibi-Wemberta, North Ethiopia Agric Water Manage 170:133-139

Kirby M, Bark R, Connor J, Qureshi ME, Keyworth S (2014) Sustainable irrigation: How did irrigated agriculture in Australia's Murray–Darling Basin adapt in the Millennium Drought? Agric Water Manage 145:154-162

Kirby M, Connor JD, Bark RH, Qureshi ME, Keyworth SW (2012) The economic impact of water reductions during the Millennium Drought in the Murray-Darling Basin.

Kirda C (2002) Deficit irrigation scheduling based on plant growth stages showing water stress tolerance Food and Agricultural Organization of the United Nations, Deficit Irrigation Practices, Water Reports 22

Kirda C, Moutonnet P, Hera C, Nielsen D (2002) Deficit Irrigation Practices vol 22. FAO, Rome, Italy

Kodur S, Robinson JB (2014) Modelling deep drainage rates of irrigation strategies under cropping sequence in subhumid, subtropical Australia Irrigation and Drainage 63:365-372 doi:10.1002/ird.1813

Koech R, Smith R, Gillies M (2014) A real-time optimisation system for automation of furrow irrigation Irrigation science 32:319-327

Koech R, Smith R, Gillies MH (2010) Furrow irrigation in the Australian cotton industry: alternative water delivery systems and their potential for automation. National Centre for Engineering in Agriculture University of Southern Queensland, Toowoomba,

Kvalheim OM, Grung B, Rajalahti T (2019) Number of components and prediction error in partial least squares regression determined by Monte Carlo resampling strategies Chemometrics Intellig Lab Syst 188:79-86

Lamm FR (2016) Cotton, tomato, corn, and onion production with subsurface drip irrigation: A review American Society of Agricultural and Biological Engineers 59:263-278

Lamm FR (2012) Subsurface Drip Irrigation: Status of the Technology in 2010 American Society of Agricultural and Biological Engineers 55:483 doi:https://doi.org/10.13031/2013.41387

Lamm FR, Rogers DH, Alam M, O'Brien DM, Trooien TP Summary of twenty years of Kansas SDI research. In: Proc. 2009 Irrigation Association Technical Conference, 2009.

Laurenson S, Cichota R, Reese P, Breneger S (2018) Irrigation runoff from a rolling landscape with slowly permeable subsoils in New Zealand Irrigation Science 36:121-131

Linker R, Ioslovich I, Sylaios G, Plauborg F, Battilani A (2016) Optimal model-based deficit irrigation scheduling using AquaCrop: A simulation study with cotton, potato and tomato Agric Water Manage 163:236-243 doi:http://dx.doi.org/10.1016/j.agwat.2015.09.011

Liu H et al. (2017) Responses of yield, water use efficiency and quality of short-season cotton to irrigation management: interactive effects of irrigation methods and deficit irrigation Irrigation Science 35:125-139 doi:10.1007/s00271-016-0526-4

Loka D (2012) Effect of water-deficit stress on cotton during reproductive development. University of Arkansas,

Lorite IJ, Mateos L, Orgaz F, Fereres E (2007) Assessing deficit irrigation strategies at the level of an irrigation district Agric Water Manage 91:51-60

Lowien Z, Gall L (2016) Grower Led Irrigation System Comparison in The Gwydir Valley, CRDC1606 Technical Research Report 30th June 2016. NSW

Lowien Z, Gall L (2106) Grower Led Irrigation System Comparison in The Gwydir Valley. Gwydir Valley Irrigations Association Inc, NSW

Luo Q, Bange M, Braunack M, Johnston D (2016) Effectiveness of agronomic practices in dealing with climate change impacts in the Australian cotton industry — A simulation study Agricultural Systems 147:1-9 doi:10.1016/j.agsy.2016.05.006

Luo Q, Bange M, Johnston D, Braunack M (2015a) Cotton production in a changing climate. Paper presented at the Australian Society of Agronomy Inc, Diverse and Sustainable Landscapes, 17th Australian Agronomy Conference, 20-24 September 2015, Hobart, Australia,

Luo Q, Bange M, Johnston D, Braunack M Cotton production in a changing climate. In: Building Productive, Diverse and Sustainable Landscapes, 17th Australian Agronomy Conference, 20-24 September 2015, Hobart, Australia. Conference Proceedings, 2015b. Australian Society of Agronomy Inc, pp 155-158

Luo Q, Behrendt K, Bange M (2017) Economics and risk of adaptation options in the Australian cotton industry Agricultural Systems 150:46-53 doi:http://dx.doi.org/10.1016/j.agsy.2016.09.014

Luo Z, Wang E, Fillery IP, Macdonald LM, Huth NI, Baldock J (2014) Modelling soil carbon and nitrogen dynamics using measurable and conceptual soil organic matter pools in APSIM Agric Ecosyst Environ 186:94-104

Ma Y, Lei T, Zhang X, Chen Y (2013) Volume replacement method for direct measurement of soil moisture and bulk density Transactions of the Chinese Society of Agricultural Engineering 29:86-93

Maas S (2013) Australian cotton production manual 2013. Cotton Research and Development Corporation, Australia

Mangalassery S, Rejani R, Singh V, Adiga JD, Kalaivanan D, Rupa TR, Philip PS (2019) Impact of different irrigation regimes under varied planting density on growth, yield and economic return of cashew (Anacardium occidentale L.) Irrigation Science 37:483-494

Manuschevich D, Beier CM (2016) Simulating land use changes under alternative policy scenarios for conservation of native forests in south-central Chile Land Use Policy 51:350-362

Maraseni TN (2012a) Climate change, water security and the need for integrated policy development: the case of on-farm infrastructure investment in the Australian irrigation sector Environmental research letters 7:034006 doi:10.1088/1748-9326/7/3/034006

Maraseni TN (2012b) Including the costs of water and greenhouse gas emissions in a reassessment of the profitability of irrigation Agric Water Manage 103:25-32 doi:10.1016/j.agwat.2011.10.014

Martínez-Gimeno M, Bonet L, Provenzano G, Badal E, Intrigliolo D, Ballester C (2018) Assessment of yield and water productivity of clementine trees under surface and subsurface drip irrigation Agric Water Manage 206:209-216

Martínez J, Reca J (2014) Water use efficiency of surface drip irrigation versus an alternative subsurface drip irrigation method Journal of Irrigation and Drainage Engineering 140:1-9

Masasi B, Taghvaeian S, Boman R, Datta S (2019) Impacts of Irrigation Termination Date on Cotton Yield and Irrigation Requirement Agriculture 9:39

Mateos L, Berengena J, Orgaz F, Diz J, Fereres E (1991) A comparison between drip and furrow irrigation in cotton at two levels of water supply Agric Water Manage 19:313-324

Mazarei R, Mohammadi AS, Naseri AA, Ebrahimian H, Izadpanah Z (2020) Optimization of furrow irrigation performance of sugarcane fields based on inflow and geometric parameters using WinSRFR in Southwest of Iran Agric Water Manage 228:105899 doi:https://doi.org/10.1016/j.agwat.2019.105899

McCarthy A (2010) Improved irrigation of cotton via real-time, adaptive control of large mobile irrigation machines. P.h.D, University of Southern Queensland

McCarthy AC, Hancock NH, Raine SR (2010) VARIwise: A general-purpose adaptive control simulation framework for spatially and temporally varied irrigation at sub-field scale Comput Electron Agric 70:117-128 doi:http://dx.doi.org/10.1016/j.compag.2009.09.011

McCown RL, Hammer GL, Hargreaves JG, Holzworth DP, Freebairn DM (1996) APSIM: a novel software system for model development, model testing and simulation in agricultural systems research Agricultural systems 50:255-271

McCown RL, Hochman Z, Carberry PS (2002) Probing the enigma of the decision support system for farmers: learning from experience and from theory

McGuire PJ, Holden JR, McDougall A (1998) Irrigation Systems Irrigation of Sugarcane Manual; Holden, JR, McGuire, PJ, Eds:13-23

McHugh A, Bhattarai S, Lotz G, Midmore DJ (2008) Effects of subsurface drip irrigation rates and furrow irrigation for cotton grown on a vertisol on off-site movement of sediments, nutrients and pesticides Agronomy for Sustainable Development 28:507-519

Mebrahtu Y (2017) Response of onion to deficit irrigation under different furrow irrigation water management techniques in Raya valley, northern Ethiopia. P.h.D, Hawassa University

Meng Z, Duan A, Wang X, Gao Y, Shen X (2016) Effect of Regulated Deficit Irrigation on Growth Relation of Root and Shoot in Cotton Nongye Jixie Xuebao/Transactions of the Chinese Society for Agricultural Machinery 47:99-104 doi:10.6041/j.issn.1000-1298.2016.04.014

Misuraca P (2014) The Effectiveness of a Costs and Benefits Analysis in Making Federal Government Decisions: A Literature Review The MITRE Corporation

Modala NR (2015) Evaluation of the CSM-CROPGRO-Cotton Model for the Texas Rolling Plains Region and Simulation of Deficit Irrigation Strategies for Increasing Water Use Efficiency 58 doi:10.13031/trans.58.10833

Monsanto, CSD, CottonInfo (2016) Introduction to irrigated cotton production: Southern new south wales and northern victoria 2015/16. Australia

Montgomery J, Wigginton D (2008) Evaluating furrow irrigation performance: Results from the 2006-07 season Surface Irrigation Cotton CRC Team Bulletin

Muhammad D, Raza I, Ahmad S, Afzal M, Mian M (2010) Efficiency of drip vs furrow irrigation system with variable plant density on cotton under southern Punjab climatic conditions J Sci Agri 63:226-231

Mulu A, Alamirew T (2012) Deficit irrigation application using center pivot sprinkler irrigation for onion production International Journal of Basic & Applied Sciences:148-159

Murthy K (2002) Arguing a case for Cobb-Douglas production function

Mushtaq S, Maraseni T, Reardon-Smith K (2013) Climate change and water security: estimating the greenhouse gas costs of achieving water security through investments in modern irrigation technology Agricultural systems 117:78-89

Narayanamoorthy A (2005) Economics of drip irrigation in sugarcane cultivation: Case study of a farmer from Tamil Nadu Indian J Agric Econ 60:236-248

Narayanan K, Seid MM (2015) Effect of Deficit Irrigation on Maize under Conventional, Fixed and Alternate Furrow Irrigation Systems at Melkassa, Ethiopia International Journal of Engineering Research & Technology 4:119-126

Nguyen LT, Osanai Y, Anderson IC, Bange MP, Braunack M, Tissue DT, Singh BK (2018) Impacts of waterlogging on soil nitrification and ammonia-oxidizing communities in farming system Plant Soil 426:299-311

O’Brien DM, Lamm FR, Stone LR, Rogers DH (2001) Corn yields and profitability for low–capacity irrigation systems Appl Eng Agric 17:315

O’Brien DM, Rogers DH, Lamm FR, Clark GA (1998) An economic comparison of subsurface drip and center pivot sprinkler irrigation systems Appl Eng Agric 14:391-398

Odhiambo W, Nyangito H, Nzuma J (2003) Measuring and analysing agricultural productivity in Kenya: A review of approaches. Kenya Institute for Public Policy Research and Analysis,

Omary M, Camp CR, Sadler EJ (1997) Center pivot irrigation system modification to provide variable water application depths Appl Eng Agric 13:235-239

Pabuayon IL, Singh S, Lewis KL, Ritchie GL (2019) Water Extraction and Productivity of Cotton, Sorghum, and Sesame under Deficit Irrigation Crop Sci 59:1692-1700

Pahlow M, Krol MS, Hoekstra AY (2015) Assessment of measures to reduce the water Footprint of cotton farming in india Value of water research report series 68:1-14

Pathak T, Fraisse C, Jones J, Messina C, Hoogenboom G (2007) Use of global sensitivity analysis for CROPGRO cotton model development Transactions of the ASABE 50:2295-2302

Paulo JA, Tomé M (2017) Using the SUBER model for assessing the impact of cork debarking rotation on equivalent annual annuity in Portuguese stands 2017 26 doi:10.5424/fs/2017261-09931

Payero J, Khalilian A (2017) Comparison of Irrigated and Dryland Crop Production in SC Clemson University Extension Publications 7:2019

Peake AS, Carberry PS, Raine SR, Gett V, Smith RJ (2016) An alternative approach to whole-farm deficit irrigation analysis: Evaluating the risk-efficiency of wheat irrigation strategies in sub-tropical Australia Agricultural Water Management 169:61-76

Pendergast L, Bhattarai SP, Midmore DJ (2014) Benefits of oxygation of subsurface drip-irrigation water for cotton in a Vertosol Crop and Pasture Science 64:1171-1181

Pereira LS (1999) Higher performance through combined improvements in irrigation methods and scheduling: a discussion Agric Water Manage 40:153-169

Perry C, Barnes E, Munk D, Fisher K, Bauer P (2012) Cotton Irrigation Management for Humid Regions.

Pitman MG, Läuchli A (2002) Global impact of salinity and agricultural ecosystems. In: Salinity: environment-plants-molecules. Springer, pp 3-20

Power B, Rodriguez D, DeVoil P, Harris G, Payero J (2011) A multi-field bio-economic model of irrigated grain–cotton farming systems Field Crops Res 124:171-179

Pratley JE (2003) Principles of field crop production. vol Accessed from https://nla.gov.au/nla.cat-vn876330. Oxford University Press, South Melbourne, Victoria, Australia ; New York

Quiggin JC (2001) Environmental economics and the Murray–Darling river system Aust J Agric Resour Econ 45:67-94

Quigley T (2017) Growing Cotton Under Sprinkler Irrigation. Cotton Research and Development Corporation, NSW

Qureshi ME, Ahmad MD, Whitten SM, Reeson A, Kirby M (2018) Impact of climate variability including drought on the residual value of irrigation water across the Murray–Darling Basin, Australia Water Economics and Policy 4:1550020

Qureshi ME, Grafton RQ, Kirby M, Hanjra MA (2011) Understanding irrigation water use efficiency at different scales for better policy reform: a case study of the Murray-Darling Basin, Australia Water Policy 13:1-17

Qureshi ME, Shi T, Qureshi SE, Proctor W (2009) Removing barriers to facilitate efficient water markets in the Murray-Darling Basin of Australia Agric Water Manage 96:1641-1651

Qureshi ME, Whitten SM (2014) Regional impact of climate variability and adaptation options in the southern Murray–Darling Basin, Australia Water Resources and Economics 5:67-84 doi:https://doi.org/10.1016/j.wre.2013.12.002

Qureshi ME, Whitten SM, Franklin B (2013a) Impacts of climate variability on the irrigation sector in the southern Murray-Darling Basin, Australia Water Resources and Economics 4:52-68

Qureshi ME, Whitten SM, Franklin B (2013b) Impacts of climate variability on the irrigation sector in the southern Murray-Darling Basin, Australia Water Resources and Economics 4:52-68 doi:https://doi.org/10.1016/j.wre.2013.12.001

Qureshi ME, Whitten SM, Kirby M (2014) A multi-period positive mathematical programming approach for assessing economic impact of drought in the Murray–Darling Basin, Australia Econ Modelling 39:293-304

R Core Team v (2019) R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria

Raine SR (2008) Scheduling technologies to improve irrigated water use efficiency a focus on centre pivots and lateral moves Proceedings of the Combinable Crops 2008:27-31

Raine SR, Foley JP (2001) Application systems for cotton irrigation—are you asking the right questions and getting the answers right. In: Growing opportunities. Irrigation 2001 National Conference, 2001. pp 11-12

Raine SR, Foley JP (2002) Comparing systems for cotton irrigation The Australian Cottongrower 23:30-35

Raine SR, Foley JP, Henkel CR (2000) Drip irrigation in the Australian cotton Industry: A scoping study. University of Southern Queensland. National Centre for Engineering in Agriculture, Toowoomba

Rajak D, Manjunatha MV, Rajkumar GR, Hebbara M, Minhas PS (2006) Comparative effects of drip and furrow irrigation on the yield and water productivity of cotton (Gossypium hirsutum L.) in a saline and waterlogged vertisol Agric Water Manage 83:30-36 doi:http://dx.doi.org/10.1016/j.agwat.2005.11.005

Rao SS, Tanwar SPS, Regar PL (2016) Effect of deficit irrigation, phosphorous inoculation and cycocel spray on root growth, seed cotton yield and water productivity of drip irrigated cotton in arid environment Agric Water Manage 169:14-25 doi:http://dx.doi.org/10.1016/j.agwat.2016.02.008

Reba M, Teague T, Vories E (2014) A retrospective review of cotton irrigation on a production farm in the Mid-South Journal of Cotton Science 18:137-144

Reddy KS, Ricart S, Maruthi V, Pankaj PK, Krishna TS, Reddy AA (2020) Economic Assessment of Water Harvesting plus Supplemental Irrigation for Improving Water Productivity of a Pulse–Cotton Based Integrated Farming System in Telangana, India Irrigation and Drainage 69:25-37

Redfern R (2015) Australian Cotton Production Manual 2015. The Australian cotton industry,

Reynolds S, Guerrero B, Golden B, Amosson S, Marek T, Bell JM (2020) Economic feasibility of conversion to mobile drip irrigation in the Central Ogallala region Irrigation Science:1-7

Richards QD, Bange MP, Johnston SB (2008) HydroLOGIC: An irrigation management system for Australian cotton Agricultural Systems 98:40-49 doi:http://dx.doi.org/10.1016/j.agsy.2008.03.009

Robertson MJ, Rebetzke GJ, Norton RM (2015) Assessing the place and role of crop simulation modelling in Australia Crop and Pasture Science 66:877-893

Rodrigues GC, Paredes P, Gonçalves JM, Alves I, Pereira LS (2013) Comparing sprinkler and drip irrigation systems for full and deficit irrigated maize using multicriteria analysis and simulation modelling: Ranking for water saving vs. farm economic returns Agric Water Manage 126:85-96

Rodrigues GC, Pereira LS (2009) Assessing economic impacts of deficit irrigation as related to water productivity and water costs Biosys Eng 103:536-551

Rodrigues P, Machado T, Pereira L, Teixeira J, El Amami H, Zairi A (2003) Feasibility of deficit irrigation with center-pivot to cope with limited water supplies in Alentejo, Portugal. In: Tools for Drought Mitigation in Mediterranean Regions. Springer, pp 203-222

Roth G (2010) Economic, environmental and social sustainability indicators of the Australian cotton industry. Cotton Research and Development Corporation, NSW, Australia

Roth G (2014) Australian grown cotton: sustainability report 2014.

Roth G, Harris G, Gillies M, Montgomery J, Wigginton D (2013) Water-use efficiency and productivity trends in Australian irrigated cotton: a review Crop and Pasture Science 64:1033-1048 doi:http://dx.doi.org/10.1071/CP13315

Sammis TW (1980) Comparison of Sprinkler, Trickle, Subsurface, and Furrow Irrigation Methods for Row Crops 1 Agron J 72:701-704

Sampathkumar T, Pandian BJ, Rangaswamy MV, Manickasundaram P, Jeyakumar P (2013) Influence of deficit irrigation on growth, yield and yield parameters of cotton–maize cropping sequence Agric Water Manage 130:90-102 doi:http://dx.doi.org/10.1016/j.agwat.2013.08.018

Saunders M, Lewis P, Thornhill A (2009) Research methods for business students. Fourth edition edn. Pearson education, British

Schmidt JE, Peterson C, Wang D, Scow KM, Gaudin AC (2018) Agroecosystem tradeoffs associated with conversion to subsurface drip irrigation in organic systems Agric Water Manage 202:1-8

Schneider D, Howell TA (1998) Comparison of SDI, LEPA, and spray irrigation efficiency. 1998

Scott JF, Cacho OJ, Scott JM (2013) Economic risk analysis of different livestock management systems Animal Production Science 53:788-795 doi:http://dx.doi.org/10.1071/AN11249

Seidl C, Wheeler SA, Zuo A (2020) High turbidity: Water valuation and accounting in the Murray-Darling Basin Agric Water Manage 230:105929

Shehata AA-A (2009) Comparison among different irrigation systems for deficit-irrigated corn in the Nile Valley Agricultural Engineering International: CIGR Journal 1:1-25

Shock C, Feibert E (2002) Deficit irrigation of potato Food and Agriculture Organization 22:47-55

SILO (2017) SILO climate data. https://legacy.longpaddock.qld.gov.au/silo/.

Smith P et al. (2015) A review of centre pivot and lateral move irrigation installations in the Australian cotton industry. New South Wales Department of Primary Industries, NSW, Australia

Snowden C, Ritchie G, Thompson T (2013) Water Use Efficiency and Irrigation Response of Cotton Cultivars on Subsurface Drip in West Texas

Snowden M (2012) Water use efficiency and irrigation response of cotton cultivars under sub-surface drip irrigation in West Texas.

Sorensen RB, Butts CL, Nuti RC (2011) Deep subsurface drip irrigation for cotton in the Southeast Journal of Cotton Science 15:233-242

Soth J, Grasser C, Salerno R (1999) The impact of cotton on fresh water resources and ecosystems: A preliminary analysis.

Spivey TA, Wilkerson GG, Buol GS, Edmisten KL, Barnes EM (2018) Use of CSM-CROPGRO-Cotton to Determine the Agronomic and Economic Value of Irrigation to Upland Cotton Production in North and South Carolina Transactions of the ASABE 61:1627-1638 doi:https://doi.org/10.13031/trans.12801

Stanhill G (1986) Water Use Efficiency Advances in Agronomy 39:53-85

Steduto P (1996) Water Use Efficiency Sustainability of Irrigated Agriculture 312:193-209

Stewart B, Steiner J (1990) Water-Use Efficiency Advances in Soil Science 13:151-173

Stiller WN, Wilson IW (2014) Australian Cotton Germplasm Resources vol 3. Intech, Australia doi:46794

Sui R, Thomasson JA, Ge Y (2012) Development of sensor systems for precision agriculture in cotton International Journal of Agricultural and Biological Engineering 5:1-14

Suleiman AA, Tojo Soler CM, Hoogenboom G (2007) Evaluation of FAO-56 crop coefficient procedures for deficit irrigation management of cotton in a humid climate Agric Water Manage 91:33-42 doi:10.1016/j.agwat.2007.03.006

Tarjuelo J, Montero J, Honrubia F, Ortiz J, Ortega J (1999) Analysis of uniformity of sprinkle irrigation in a semi-arid area Agric Water Manage 40:315-331

Tedeschi LO (2006) Assessment of the adequacy of mathematical models Agricultural systems 89:225-247

Temesgen T, Ayana M, Bedadi B (2018) Evaluating the Effects of Deficit Irrigation on Yield and Water Productivity of Furrow Irrigated Onion (Allium cepa L.) in Ambo, Western Ethiopia Irrigation & Drainage Systems Engineering 7:6-6 doi:10.4172/2168-9768.1000203

Thorburn PJ, Biggs JS, Collins K, Probert ME (2010) Using the APSIM model to estimate nitrous oxide emissions from diverse Australian sugarcane production systems Agric Ecosyst Environ 136:343-350 doi:http://dx.doi.org/10.1016/j.agee.2009.12.014

Thorp KR et al. (2014) Development and application of process-based simulation models for cotton production: A review of past, present, and future directions Journal of Cotton Science 18:10-47

Thorp KR, Hunsaker DJ, Bronson KF, Andrade-Sanchez P, Barnes EM (2017) Cotton Irrigation Scheduling Using a Crop Growth Model and FAO-56 Methods: Field and Simulation Studies Transactions of American Society of Agricultural and Biological Engineers 60:2023-2039 doi:https://doi.org/10.13031/trans.12323

Tsakmakis ID, Zoidou M, Gikas GD, Sylaios GK (2018) Impact of irrigation technologies and strategies on cotton water footprint using AquaCrop and CROPWAT models Environmental Processes 5:181-199

Turral H, Etchells T, Malano H, Wijedasa H, Taylor P, McMahon T, Austin N (2005) Water trading at the margin: The evolution of water markets in the Murray-Darling Basin Water Resour Res 41:1-8

Uddin J, Smith R, Gillies M, Moller P, Robson D (2018) Smart automated furrow irrigation of cotton Journal of Irrigation and Drainage Engineering 144:04018005

Ünlü M, Kanber R, Koç DL, Tekin S, Kapur B (2011) Effects of deficit irrigation on the yield and yield components of drip irrigated cotton in a mediterranean environment Agric Water Manage 98:597-605 doi:http://dx.doi.org/10.1016/j.agwat.2010.10.020

van Griensven Av, Meixner T, Grunwald S, Bishop T, Diluzio M, Srinivasan R (2006) A global sensitivity analysis tool for the parameters of multi-variable catchment models Journal of hydrology 324:10-23

Van Ittersum MK, Donatelli M (2003) Modelling cropping systems-highlights of the symposium and preface to the special issues European journal of agronomy 18:187-197

Walker WR (1989) Guidelines for designing and evaluating surface irrigation systems. vol 45. Irrigation and Drain, Rome, Italy

Wample R, Smithyman R (2002) Regulated deficit irrigation as a water management strategy in Vitis vinifera production. In: Food and Agricultural Organization of the United Nations (FAO) (ed.), Deficit Irrigation Practices. Rome, Italy, pp 89–100

Wang C, Nair SS (2013) The economics of deficit irrigation Nat Resour Model 26:331-364 doi:10.1111/nrm.12004

Wang J, Niu W, Li Y, Lv W (2018) Subsurface drip irrigation enhances soil nitrogen and phosphorus metabolism in tomato root zones and promotes tomato growth Applied Soil Ecology 124:240-251

Wang M, Wei J, Yuan J, Xu K A research for intelligent cotton picking robot based on machine vision. In: Information and Automation, 2008. ICIA 2008. International Conference on, 2008. IEEE, pp 800-803

Wang YP, Zhang LS, Mu Y, Liu WH, Guo FX, Chang TR (2020) Effect of a root-zone injection irrigation method on water productivity and apple production in a semi-arid region in North-Western China Irrigation and Drainage 69:74-85

Waterman A (2017) Take care of those on-farm storages. The Australian cottongrower, NSW

Wen Y (2017) Spatial Variation of Soil Moisture and its Effect on Lint Yield in a Deficit Irrigated Cotton Field bioRxiv:109025 doi:http://dx.doi.org/10.1101/109025

Wen Y, Rowland DL, Piccinni G, Cothren JT, Leskovar DI, Kemanian AR, Woodard JD (2013) Lint yield, lint quality, and economic returns of cotton production under traditional and regulated deficit irrigation schemes in southwest Texas Journal of Cotton Science 17:10-22

Wheeler SA, Xu Y, Zuo A (2020) Modelling the climate, water and socio-economic drivers of farmer exit in the Murray-Darling Basin Clim Change 158:551-574

White SC (2007) Partial rootzone drying and deficit irrigation in cotton for use under large mobile irrigation machines. PhD, University of Southern Queensland

Wickham H (2016) ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York

Wilde C, Johnson J, Bordovsky J (2009) Economic analysis of subsurface drip irrigation system uniformity Appl Eng Agric 25:357-361

Williams AJ et al. (2015) Australian Cotton Production Manual 2015. Autralia

Williams AJ, Mushtaq S, Kouadio L, Power B, Marcussen T, McRae D, Cockfield G (2018) An investigation of farm-scale adaptation options for cotton production in the face of future climate change and water allocation policies in southern Queensland, Australia Agric Water Manage 196:124-132 doi:https://doi.org/10.1016/j.agwat.2017.10.026

Willmott CJ, Matsuura K (2005) Advantages of the mean absolute error (MAE) over the root mean square error (RMSE) in assessing average model performance Clim Res 30:79-82

Xin Q, Hamid JF, Ahmad K, Edward MB (2016) Cotton Water Productivity and Growth Parameters in the Humid Southeast: Experimentation and Modeling 59 doi:10.13031/trans.59.11601

Yadav S, Godara A, Yadav V (2018) Impact of Bt Cotton Production Technology in Haryana Indian Research Journal of Extension Education 18:66-71

Yang C, Luo Y, Sun L, Wu N (2015) Effect of Deficit Irrigation on the Growth, Water Use Characteristics and Yield of Cotton in Arid Northwest China Pedosphere 25:910-924 doi:http://dx.doi.org/10.1016/S1002-0160(15)30071-0

Yang Y, Yang Y, Han S, Macadam I, Liu DL (2014) Prediction of cotton yield and water demand under climate change and future adaptation measures Agric Water Manage 144:42-53 doi:http://dx.doi.org/10.1016/j.agwat.2014.06.001

Zaccaria D, Carrillo-Cobo MT, Montazar A, Putnam DH, Bali K (2017) Assessing the Viability of Sub-Surface Drip Irrigation for Resource-Efficient Alfalfa Production in Central and Southern California Water 9:837

Zamora DS, Jose S, Jones JW, Cropper WP (2009) Modeling cotton production response to shading in a pecan alleycropping system using CROPGRO Agroforestry systems 76:423-435

Zhang D, Luo Z, Liu S, Li W, Dong H (2016a) Effects of deficit irrigation and plant density on the growth, yield and fiber quality of irrigated cotton Field Crops Research 197:1-9

Zhang D, Luo Z, Liu S, Li W, WeiTang H, Dong H (2016b) Effects of deficit irrigation and plant density on the growth, yield and fiber quality of irrigated cotton Field Crops Res 197:1-9 doi:10.1016/j.fcr.2016.06.003

Zhang F, Zhan J, Zhang Q, Yan H, Sun Z (2016c) Allocating agricultural production factors: A scenario-based modeling of wheat production in Shandong Province, China Physics and Chemistry of the Earth, Parts A/B/C 96:55-63 doi:https://doi.org/10.1016/j.pce.2016.06.002

Zhang J, Sui X, Li B, Su B, Li J, Zhou D (1998) An improved water-use efficiency for winter wheat grown under reduced irrigation Field Crops Res 59:91-98

Zhou S, Wang J, Liu J, Yang J, Xu Y, Li J (2012) Evapotranspiration of a drip-irrigated, film-mulched cotton field in northern Xinjiang, China Hydrological Processes 26:1169-1178

Zhu X, Chikangaise P, Shi W, Chen W-H, Yuan S (2018) Review of intelligent sprinkler irrigation technologies for automated sensor irrigation management International Journal of Agricultural and Biological Engineering 11:23-30

Zonta JH, Bezerra JR, Sofiatti V, Brandão ZN (2015) Yield of cotton cultivars under different irrigation depths in the Brazilian semi-arid region Revista Brasileira de Engenharia Agrícola e Ambiental 19:748-754

Zonta JH, Brandao ZN, Rodrigues JIDS, Sofiatti V (2017) Cotton response to water deficits at different growth stages Revista Caatinga 30:980-990

Zonta JH, Brandão ZN, Sofiatti V, Bezerra JRC, da Cunha Medeiros J (2016) Irrigation and nitrogen effects on seed cotton yield, water productivity and yield response factor in semi-arid environment Australian Journal of Crop Science 10:118

Zounemat-Kermani M, Asadi R (2018) Technical and economic evaluation of the deficit irrigation on yield of cotton. Paper presented at the 2018 IAAE Annual Conference :International Association for Applied Econometrics, Canada, June 26 - 29, 2018

Appendix

Table 1: Summary of cotton crop datasets used for the validation of the APSIM cotton: Years; locations; In crop rainfall; Establishment method; Number in incrop irrigation; Plant stand (P/m^2); Type of soil; APSIM soil number; PAWC, plant – available water content; Sowing Date; N fertiliser nitrogen applied (kg/ha); Days to defoliation concentration in QLD and NSW in Australia (CSD 2017).

Years	Locations	Incorp rainfall (mm)	Establishment method	Number of Incorp irrigation	Plant stand (P/m2)	AP soil number	PAWC (mm)	Sowing date	Fert. N (kg/ ha)	Days to defoliation	Observed values	Modelled values
2010	Boggabri	305	Pre -irrigated	3	9.8	122	278	5-Oct	160	177	2692.22	2692.22
	Bongeen	338	Rain moisture	0	3	1	290	23-Sep	0	189	3075.85	3075.85
	Bourke	261	Watered up	5	9.8	621-YP	190	14-Oct	200	164	12.28	2376.69
	Breeza	425	Pre- irrigated	2	10.5	119	207	16-Oct	157	175	830.82	830.82
	Chinchilla	414	Rain moisture	0	4	29	246	1-Nov	0	154	3075.85	1030.58
	Dalby	316	Pre- irrigated	4	4.5	27	285	9-Oct	220	187	2161.04	2072.51
	Emerald	473	Watered up	8	11	911	415	26-Sep	230	140	912.54	1877.29
	Goondiwindi	260	Watered up	5	10.8	219	253.5	9-Oct	253	165	1906.8	2308.59

	Griffith	233	Watered up	10	11	697	225	8-Oct	330	167	2610.5	2565.1
	Hillston	180	Watered up	8	11	696	148	2-Oct	250	179	2912.41	2828.42
	Macalister	300	Pre- irrigated	3	7.5	26	384	5-Nov	190	155	2145.15	1804.65
	Moree	321	Watered up	6	10	870	315	7-Oct	270	170	1164.51	2821.61
	Mungindi	410	Watered up	8	10.2	1280	302	8-Oct	170	161	2315.4	2206.44
	Narrabri	497.1	Watered up	7	14	124	357	9-Oct	280	169	2585.53	2901.06
	North Star	255	Rain moisture	0	3.5	236	293	25-Sep	0	171	2510.62	578.85
	Spring Ridge	351	Rain moisture	0	6	94	302	21-Oct	46	171	935.24	2433.44
	St George	592	Pre- irrigated	6	8.3	40	191	13-Oct	197	153	3023.64	1847.78
	Trangie	465	Watered up	7	9	684	254	29-Sep	225	171	2124.72	2192.82
	Warra	290	Rain moisture	0	8	19	209	11-Nov	45	129	2637.74	944.32
2011	Bellata	489	Rain moisture	0	6	83	276	31-Oct	0	185	456.27	755.91
	Boggabri	310	Rain moisture	6	9.5	122	278	8-Oct	170	153	2197.36	2113.37
	Bongeen	797.5	Rain moisture	0	8.5	1	290	26-Oct	40	190	331.42	335.96
	Bourke	501	Rain moisture	5	10	621-YP	190	22-Oct	243	158	2585.53	2472.03
	Breeza	447	Rain moisture	2	9.5	119	207	7-Oct	132	182	1965.82	2049.81

	Burdekin	757	Rain moisture	4	7	682	162	8-Jan	193	173	1518.63	1486.85
	Chinchilla	720	Rain moisture	0	8.5	29	246	28-Oct	40	186	978.37	867.14
	Clermont	455	Rain moisture	0	7.5	1261	358	14-Dec	30	145	715.05	1150.89
	Croppa Creek	733.7	Rain moisture	0	3	57	320	15-Nov	0	139	594.74	794.5
	Dalby	814	Rain moisture	2	10	27	285	29-Oct	260	194	2758.05	2497
	Dirranbandi	346	Rain moisture	6	8	155	105	29-Sep	259	161	2758.05	2497
	Goondiwindi	406	Rain moisture	6	7.5	219	253	14-Oct	250	212	2381.23	2476.57
	Griffith	440	Watered up	5	12	697	225	7-Oct	250	187	1806.92	1977.17
	Gurley	290	Rain moisture	0	7.5	57	320	7-Oct	0	172	715.05	910.27
	Hillston	512	Rain moisture	8	7	696	148	20-Sep	200	198	2585.53	2401.66
	Macalister	600	Rain moisture	2	10	26	384	28-Oct	220	183	1264.39	2117.91
	Moree	275	Rain moisture	6	9	870	315	6-Oct	207	172	2392.58	2689.95
	Mungindi	339	Watered up	7	6	1280	302	8-Oct	193	166	2394.85	2415.28
	Narrabri	713.3	Rain moisture	5	11	124	357	6-Oct	234	176	2079.32	2072.51
	North Star	362	Rain moisture	0	7.5	236	293	30-Oct	0	159	535.72	562.96
	St George	380	Rain moisture	8	10	40	191	28-Sep	297	168	2599.15	2689.95

	Walgett	357	Rain moisture	9	8	1017	339	21-Oct	180	182	2544.67	2744.43
	Warra	600	Rain moisture	0	9	19	209	28-Oct	45	155	839.9	955.67
	Warren	510	Rain moisture	7	12	705	234	11-Oct	160	169	2590.07	2576.45
2012	Bellata	728	Rain moisture	0	7.5	83	276	30-Oct	0	198	2590.07	2576.45
	Boggabri	500	Rain moisture	4	9.8	122	278	22-Oct	170	191	1221.26	1570.84
	Bongeen	190	Rain moisture	0	7.5	1	290	26-Oct	37	168	2333.56	2313.13
	Bourke	446	Watered up	5	9	621-YP	190	11-Oct	240	154	1520.9	1525.44
	Breeza	567	Rain moisture	1	8.9	119	207	11-Oct	151	193	2912.41	2487.92
	Burdekin	945	Rain moisture	5	6.5	682	162	3-Jan	135	171	2217.79	2360.8
	Chinchilla	405	Rain moisture	0	5	29	246	25-Oct	70	179	1132.73	1060.09
	Clermont	765	Rain moisture	0	7.5	1261	358	10-Dec	45	185	1082.79	1080.52
	Croppa Creek	780	Rain moisture	0	7.3	68	278	29-Oct	46	175	1159.97	1296.17
	Dalby	273	Rain moisture	4	7	27	285	2-Nov	120	184	1035.12	1293.9
	Dirranbandi	400	Rain moisture	5	10	155	105	19-Oct	320	169	2027.11	2004.41
	Emerald	430	Pre -irrigated	7	2.5	911	415	6-Oct	230	137	2599.15	2344.91
	Goondiwindi	680	Pre- irrigated	5	9.5	219	253	21-Oct	180	202	1554.95	1502.74

	Gurley	890	Rain moisture	0	6.5	57	320	24-Oct	0	178	2011.22	2022.57
	Hillston	500	Watered up	8	9	696	148	30-Sep	180	204	1327.95	1491.39
	Macalister	429	Rain moisture	3	11	26	384	23-Oct	190	179	2830.69	2519.7
	Moree	716	Rain moisture	5	9.5	870	315	13-Oct	270	172	2349.45	2494.73
	Mullaley	450	Rain moisture	0	8	1170	258	18-Oct	130	195	2692.22	2599.15
	Mungindi	580	Watered up	0	7. 5	1280	302	3-Nov	0	190	1421.02	1491.39
	Narrabri	750	Rain moisture	4	11	124	357	11-Oct	270	210	1091.87	2038.46
	North Star	600	Rain moisture	0	5	236	293	22-Sep	64	189	2801.18	2962.35
	St George	585	Pre -irrigated	6	11.4	40	191	24-Oct	307	147	1023.77	1253.04
	Walgett	395	Watered up	5	7.2	1017	339	14-Oct	210	168	2226.87	2231.41
	Warra	429	Rain moisture	0	8	19	209	9-Nov	160	144	3030.45	2887.44
	Warren	500	Rain moisture	3	9.5	705	234	13-Oct	250	169	1291.63	1298.44
2013	Boggabri	250	Watered up	6	9.8	122	278	15-Oct	170	182	2551.48	2633.2
	Bongeen	511	Rain moisture	0	6	1	290	22-Oct	92	178	2344.91	2049.81
	Bourke	30	Pre -irrigated	7	7.8	621-YP	190	2-Oct	240	157	2297.24	1307.52
	Breeza	389	Pre -irrigated	2	9.3	119	207	16-Oct	181	195	2163.31	1806.92

	Chinchilla	543	Rain moisture	0	7	29	246	21-Nov	45	183	971.56	991.99
	Dalby	362.9	Pre - irrigated	3	13	27	285	25-Oct	185	166	2145.15	2308.59
	Goondiwindi	306	Pre - irrigated	7	10.6	227	204	16-Oct	312	141	2369.88	2222.33
	Griffith	150	Watered up	8	6	697	225	5-Oct	275	195	2299.51	2440.25
	Hillston	80	Watered up	11	9	696	148	4-Oct	240	227	2923.76	2960.08
	Moree	338	Pre -watered	6	8.75	870	315	8-Oct	345	155	2217.79	1968.09
	Mungindi	212	Pre - irrigated	9	11.4	1280	302	9-Oct	250	156	2669.52	2737.62
	Narrabri	349	Watered up	7	10.3	124	357	12-Oct	275	164	2891.98	2281.35
	North Star	452	Rain moisture	0	4.9	236	236	18-Oct	10	193	1602.62	1409.67
	Spring ridge	432	Rain moisture	0	4.5	94	302	10-Oct	100	189	1825.08	1804.65
	St George	173	Pre- irrigated	8	11.2	40	191	8-Oct	300	147	2444.79	2417.55
	Walgett	34	Watered up	10	12.3	1017	339	18-Oct	200	179	3075.85	2517.43
	Warra	526	Rain moisture	0	6.5	19	209	25-Oct	160	148	1175.86	1275.74
2014	Bellata	258	Rain moisture	0	5.2	83	276	9-Dec	0	187	1085.06	1132.73
	Boggabri	220	Watered up	7	10.2	122	278	9-Oct	190	188	2515.16	2474.3
	Bourke	88	Pre - irrigated	6	8.7	621-YP	190	24-Sep	240	167	2210.98	1904.53

	Breeza	213	Watered up	3	10.8	119	207	10-Oct	168	193	2070.24	1959.01
	Clermont	254	Rain moisture	0	6	1261	358	4-Dec	50	147	987.45	1041.93
	Croppa Creek	124	Rain moisture	0	5.7	68	278	14-Nov	46	126	612.9	513.02
	Dalby	453.4	Watered up	5	10.5	27	285	21-Oct	230	182	3062.23	2969.16
	Dirranbandi	51	Watered up	9	10.2	155	105	3-Oct	382	151	2805.72	1934.04
	Goondiwindi	98	Pre- irrigated	9	9.7	227	204	24-Oct	398	149	2674.06	2583.26
	Griffith	145	Watered up	9	10.5	697	225	2-Oct	300	191	1943.12	1981.71
	Gurley	110	Rain moisture	0	4	57	320	3-Oct	2	156	513.02	483.51
	Hillston	361.1	Watered up	9	13.1	696	148	5-Oct	230	189	2533.32	2524.24
	Moree	N/A	Watered up	7	7	870	315	17-Oct	0	141	2156.5	1843.24
	Mungindi	205	Watered up	9	10.5	1280	302	9-Nov	302	152	2058.89	1949.93
	Narrabri	260	Watered up	9	9.8	124	357	10-Oct	285	168	2058.89	2358.53
	North Star	136	Rain moisture	0	6.9	236	293	30-Sep	55	147	385.9	388.17
	Spring ridge	297	Rain moisture	0	3.5	94	302	15-Oct	70	187	880.76	860.33
	St George	161	Pre- irrigated	7	11	40	191	11-Oct	240	126	2154.23	2197.36
2015	Bellata	288	Rain moisture	0	7.5	83	276	4-Dec	0	145	939.78	960.21

	Breeza	252	Pre- irrigated	3	10.25	119	207	18-Oct	190	173	2047.54	2426.63
	Clermont	180	Rain moisture	0	10	1261	358	27-Dec	45	135	939.78	960.21
	Moree	231	Watered up	8	11	870	315	7-Oct	290	175	2047.54	2426.63
	Mullaley	256	Rain moisture	0	8.5	1170	258	1-Oct	0	160	2047.54	2426.63
	Spring ridge	292	Rain moisture	0	4.8	94	302	22-Oct	68	165	939.78	960.21